Assessing the Efficiency of a Rainwater harvesting system for meeting water demand in Ibadan: Case Study of an Hospital

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, savings, sensitivity analysis and MonteCarlo simulation were optimised using a Raincycle model. A detailed assessment of the proposed system was carried out, considering seven fixed and eleven variable parameters. The fixed parameters are: catchment area, pump power rating, first-flush volume, storage tank volume, pump capacity, UV unit power rating and operating time while the variables are: filter coefficient, rainfall profiles, runoff coefficient, discount rates, electricity cost, water demand, main water cost, capital cost, disposal and decommissioning cost. The water savings and RWH efficiency were assessed and payback period was estimated. The result of optimising storage capacity reveals that the maximum percentage of demand that could be met was 78.1 %. The analysis of optimising saving showed that there were seven tank sizes with a potential long-term profit. A 12 m^3 tank was found to be the best, predicted to save $51,072 over 50 years and had a payback period of 1 year. The important influence of a given set of conditions on the economic viability 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. There is a high potential of using RWH as an alternative source of water for the Children's ward. This methodology can be adopted to other sections of the hospital such as the accident and emergency unit.

Keywords: 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 used as an alternative source to public water mains for various non-potable water purposes in the home, workplace and garden. An option where conventional water supply systems have failed to satisfy demand is RWH [3]. This technology can serve 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 is beneficial for the attenuation of surface runoff.

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Rooftop rainwater 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, RWH is used mainly as a complementary source for non-potable purposes, such as clothes washing, toilet flushing, irrigation and outside washes [5]. In

developing countries, RWH is used as a control measure for water shortages (potable and non-potable) use [6].

A typical RWHS consist of the catchment surface, the conveyance system; the storage and distribution systems. Although impermeable areas, such as roads, car parks and pavements can be used for collecting runoff [7], the catchment surfaces are commonly roofs [8]. The rainwater quality and quantity are affected by the material of the catchment area. After collection of rainwater, it goes through the conveyance system to treatment. There is more pollutant in the initial 'first-flush' of runoff with time than subsequent flows and there is an exponential reduction in the quantity of contaminants associated with a given rainfall event [9]. Thus, the need to divert the initial 'first-flush' away from the storage device to enhance the quality of water entering storage while subsequent treatment can be reduced or even eliminated [10]. As rainfall events occur more erratically than system demand, a storage device is required to collect and hold catchment 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 was revealed for scenarios simulated in a university accommodation building [12]. A payback period of 21 years and savings of $259 was found for the hydrological performance 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 and workmanship.

In Nigeria, less than 30% of the population have access to safe drinking water. In 2007, only 47% of the total population had access to water from improved sources [14]. Successive Nigerian governments have spent several billions of dollars providing safe drinking water, but most of these projects failed due to fraud. Hence, most people are left with no choice than drinking water contaminated with iron sulphide and bacteria, germs and suspended matter, all capable of causing disease.

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 water saving efficiency of implementing this technology in Ibadan. The evaluation was carried out using rainfall data, roof area and average daily water demand of an hospital block.

Study area

The study was carried out on the Children out-patient ward of the University College hospital in Oyo state. Oyo State is reputed to be the largest City in Africa in the south-west, south of the Sahara (longitude $3^0$45'-$4^0$00'E, latitude $7^0$15'-$7^0$30'N). Ibadan is the Capital of Oyo State with a population of 2,559,853 in 2007 [15]. It is the second largest city in Nigeria with a land area of 400 km^2 [16]; consisting of 11 Local Government areas. In addition, the University of Ibadan founded in 1948 has the best equipped teaching hospital in West Africa (University College Hospital), presented in Figure 1. However, this hospital lacks adequate water supply for the daily need of both staff and patient.

In Nigeria, rainfall is regular for six months of the year, with a mean annual fall of 1200-2250 mm so RWH is practised in the south [17]. The rainy season is from May/June to September/October, depending on the rainfall pattern each year while other months are dry, with cool Harmattan winds between January-March. 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].

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

2. Performance of System Component

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

2.1 Precipitation

Factors such as location, season and year have a significant impact on precipitation. The variance of precipitation is influenced by factors such as 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 areas that receive just 0-1350mm [19]. The North receives less rainfall (~800 mm), than the south. Rainfall data of 30-years was collected from various 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 rainfall depths contained within the data set is presented in Figure 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 calculated by comparing the volume of water that runs off a surface to the total volume of rain falling on it [20]. Data of several months or years are gathered to calculate the coefficient, which can 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 rainfall falling on a catchment surface in time t is given by multiplying the intensity of rainfall in time t by the effective catchment area, which is calculated by multiplying the catchment horizontal length by the horizontal width (Figure 4). Thus, producing the plan area and not the actual area. The rainfall is assumed to fall vertically onto the roof surface.

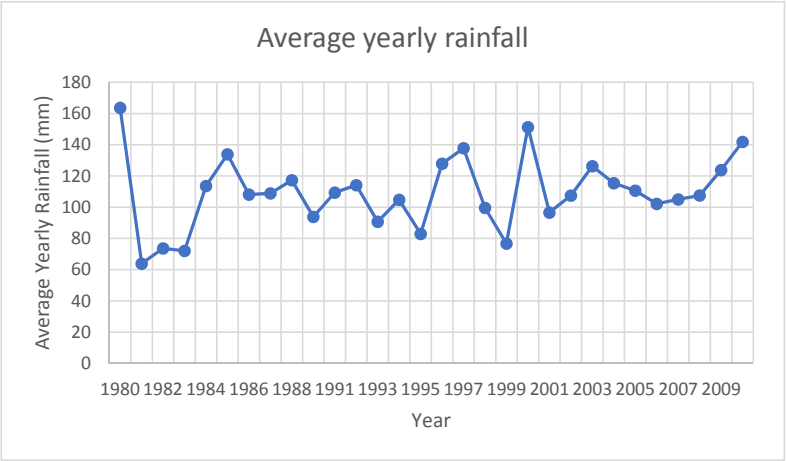


Fig. 2. Ibadan City average yearly rainfall pattern 1980-2009
Source: [17]

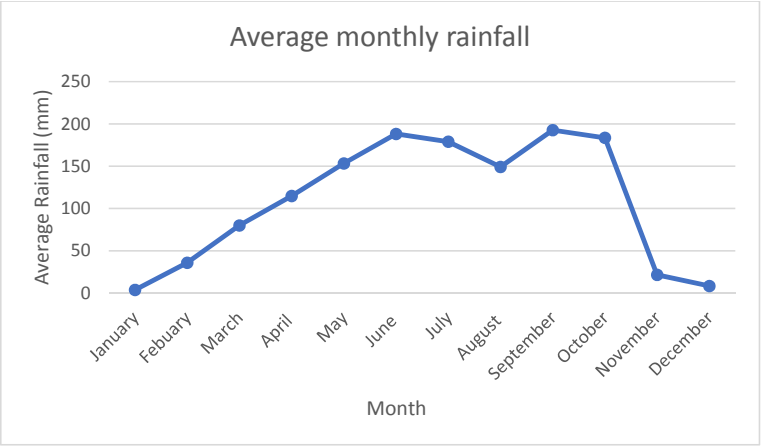


Fig. 3. Ibadan City Average monthly rainfall pattern 1980 – 2009
Source: [17]

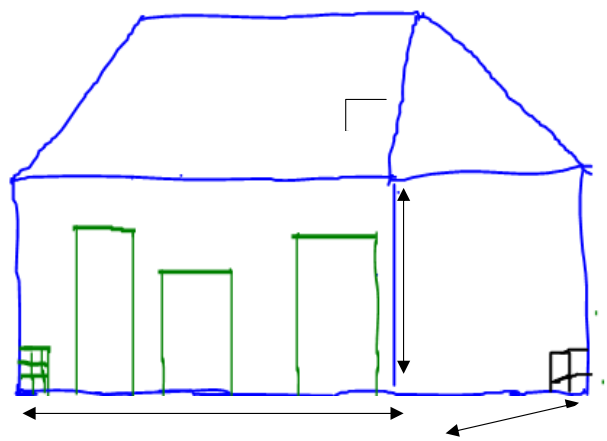


Fig. 4. Calculating the catchment plan area

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

After calculating the effective area of the catchment (equation 2), 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:

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 RWHS installed in hospital blocks, roof (plan) areas as a function of occupancy is needed since the level of occupancy strongly influences total water demand within a dwelling [21].

2.5 Pump

A pump can be modelled hydraulically with the amount 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 multiplying the pump energy usage by the unit cost of electricity, which depends on the amount charged by the relevant energy utility.

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

where:

Pu_{POW}= pump power rating (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 storage reservoir that receives effective runoff over time [8]. There exists a relationship between the performance of a storage capacity and characteristics of the contributing rainfall, catchment, capacity and demand on the system [8].

The mass curve method has formed the basis of many adaptations [20], such as in sizing fresh water supply reservoirs. The critical periods in the data are identified when the difference between cumulative inflows (rainfall) and cumulative outflows (demand) are at a maximum. The maximum volume for future use is represented by this difference and hence the necessary storage capacity required maximising supply. For the storage reservoir in a RWHS to perform adequately the relationship shown in equation 5 must be satisfied [8].

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

where $t_1 < t_2$ and:

S = storage capacity (m^3).

Dt = demand during time interval t (m^3).

Qt = inflow during time interval t (m^3).

t = time of measurement

3. METHODOLOGY

The economic viability of installing a RWHS can be evaluated by calculating the payback period. Lower payback period makes the investment more attractive. The payback period is determined by comparing the expenditure with savings. In this paper, savings resulting from decrease in the cost of potable water as public water supply consumption reduces and its impact on total charges is considered. The market values of the RWH components was used to account for the direct cost as expenditures are associated with investment and operational costs. The methodology to compute the water savings and costs are presented in the following sections.

3.1 Water Savings

The water savings were determined from the balance between daily water consumption and harvested rainwater. For this study, a behavioural approach was chosen and use of YAS was recommended [22] due to the conservativeness of the estimate given on system performance. However, time reliability was estimated using YBS rules in preference to YAS. The Raincycle model adopted in this work incorporates YAS/YBS algorithm with the storage operating parameter Θ set to zero (YAS) as the default mode of operation. However, research suggested that YAS models are capable of modelling system performance within 10% of that predicted by a more accurate hourly time-step model and this was an acceptable margin of error if certain constraints regarding the selected time-step are employed [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 Figure 3.

3.1.2 Water Demand

Potable (cooking and drinking) and non-potable uses (toilet flushing and clothes washing) were considered in this study. In a developing country like Nigeria, it is difficult to collect valid information on water usage. Water demand were estimated by quantifying the amount of water use in terms of number of 8-litre buckets used per day [25]. The volume of water used per person per day is presented in Figure 5. The standard water demand per person per day is 50 litres [26].

3.1.2.1 Predicting Non-potable Domestic Demand

Factors such as household size, time of the year, type of property and ages of household residents have impact on per capita consumption [27]. To achieve the lowest level of compliance, a minimum per capita consumption of 120 litres per day is required for internal use. Thus, a daily per capita consumption of 120 litres was adopted throughout this work.

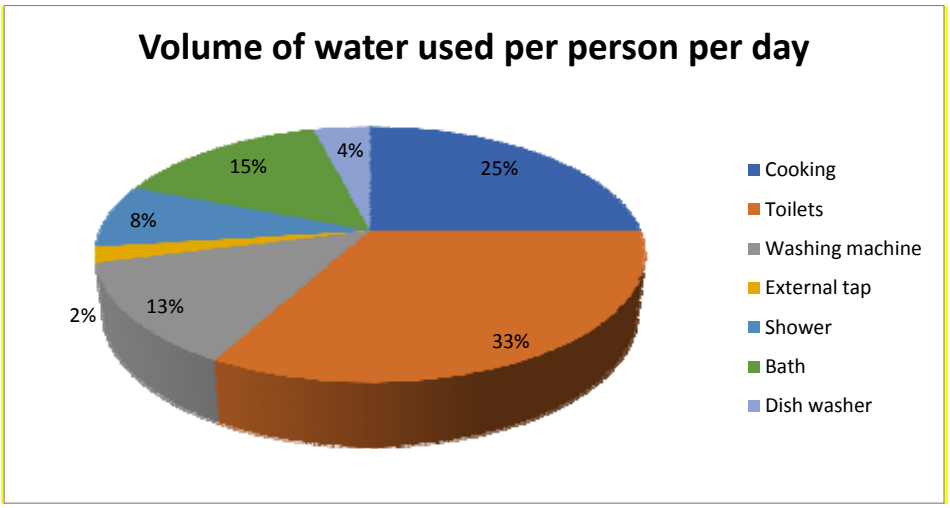


Fig.5. A typical household daily water use in Nigeria (2002)
Source: [25]

3.1.2.2 Water Closet Demand

Existing data based on past monitoring studies was used as an acceptable indicator of future behaviour as there is no cause for WC usage frequency to increase or decrease significantly. The mean value equals 4.59 flushes per person per day (Table 1). However, a per capita usage of 6 times/day assumed for weekends (Saturday and Sunday) was used for the study since it is an hospital block. A linear relationship exists between household occupancy and frequency 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 permitted for single flush WCs.

3.1.3 Washing machine demand

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

Table 1. Range 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 retrieved from Water Corporation of Oyo State (WCOS) while the cost of the rainwater system components was obtained from a market survey. The data on financial details were input into the model (Table 2).

Table 2. Financial details

Parameter	Probable value
Capital cost	$496.00
Decommissioning cost	$0.00
Discount rate	3.5%
Electricity cost	0.1 c/KWh
Main water cost	$0.83/m^3

3.3 Payback 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 sequence of logical steps is followed to increase the likelihood of creating a successful design in a RWHS. The steps are as follows (Figure 6-9):

Step 1: Estimate tank sizes.
Step 2: Estimate cost savings of tanks
Step 3: Gather data required for detailed analysis.
Step 4: Carry out detailed analysis and examine results

3.2.1 System detail: a hospital block

The Ward provide facilities for 203 patients and nurses (Figure 1). Direct measurement was carried out to determine the length and width of the building as a detail roof plan is not available. The hydraulic detail 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. New values for the variable parameters were randomly generated and a system analysis was run with the new values. The results of hundreds and thousands of simulations was used to assess RWHS response to a wide range of conditions.

Each parameter requires three values: highest most probable value, most probable and lowest value. For each iteration, a new set of variable parameter values are generated by random sampling of set probability distributions.

The results of such iteration 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.

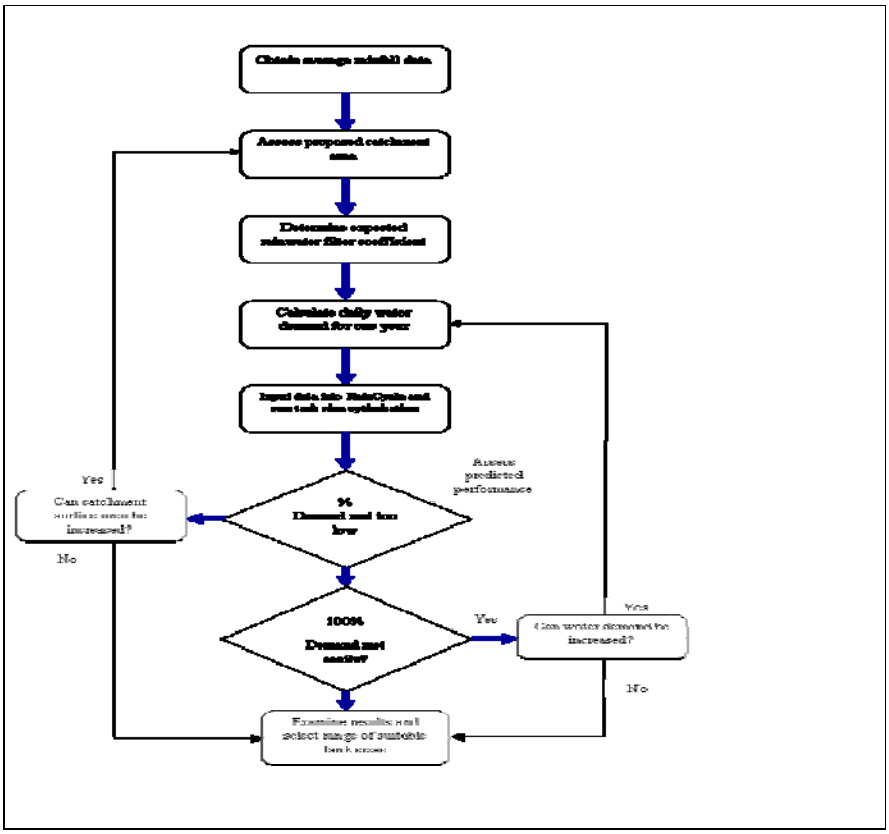


Fig. 6. Determining range of suitable tank sizes
Source: [35]

4.2 Optimising storage capacity

The results of optimising storage capacity (Figure 10) reveals that the maximum percentage of demand that could be met was 78.1% with a tank size of 12 m^3. The limiting factor was the amount of water available, hence, increasing the storage capacity above 12 m^3 would have little (if any) benefit.

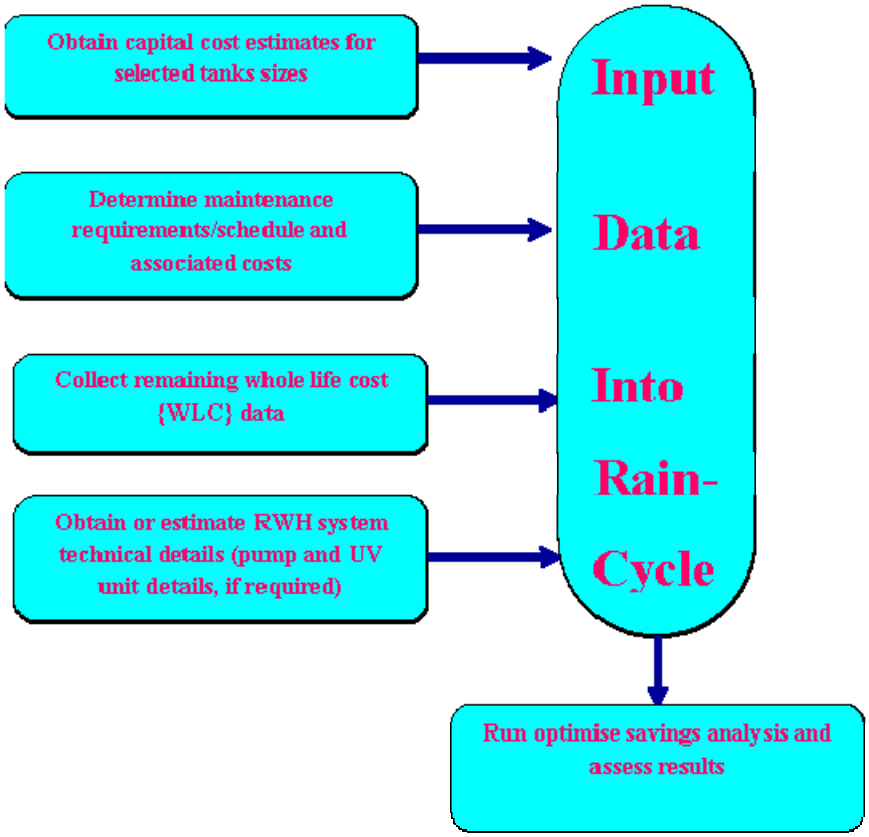


Fig. 7. Estimating cost savings of tanks and choosing optimum size
Source [35]

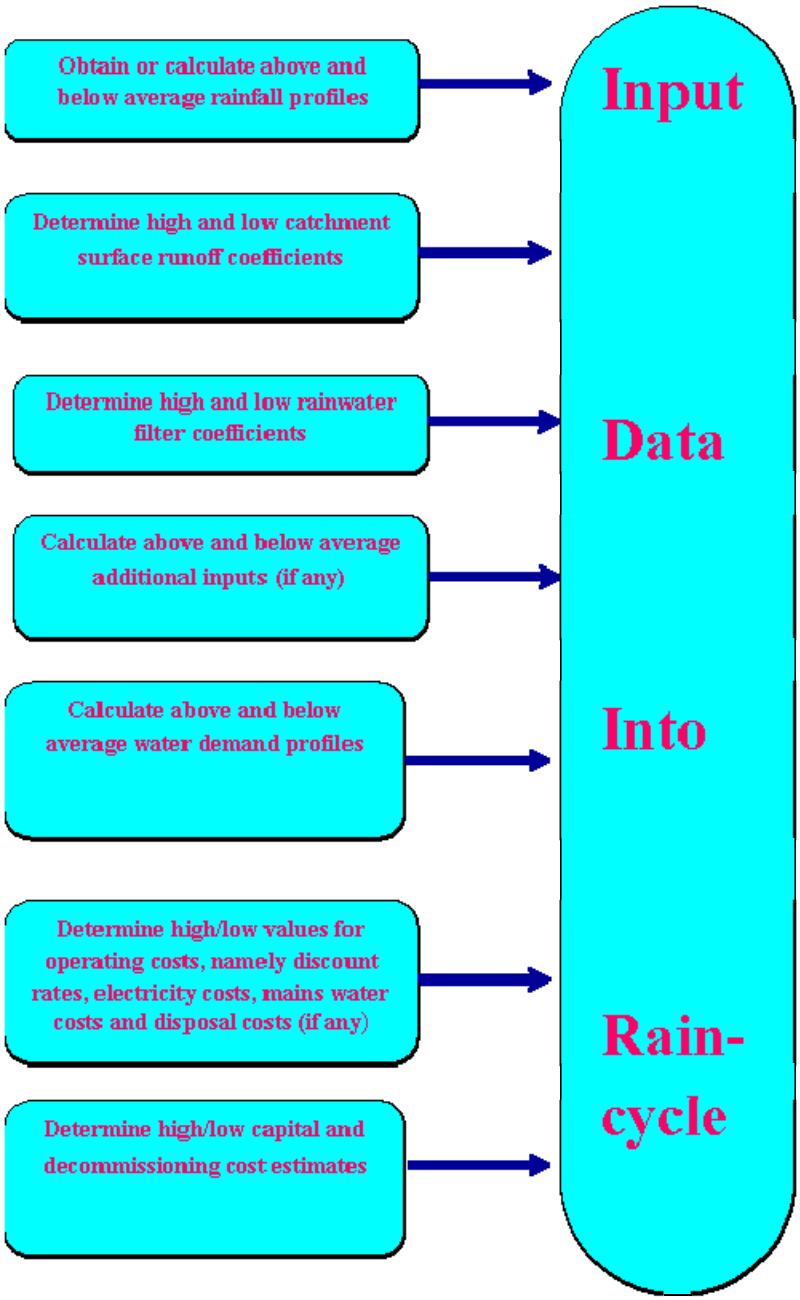


Fig. 8. Assembling data required for detailed analysis
Source: [35]

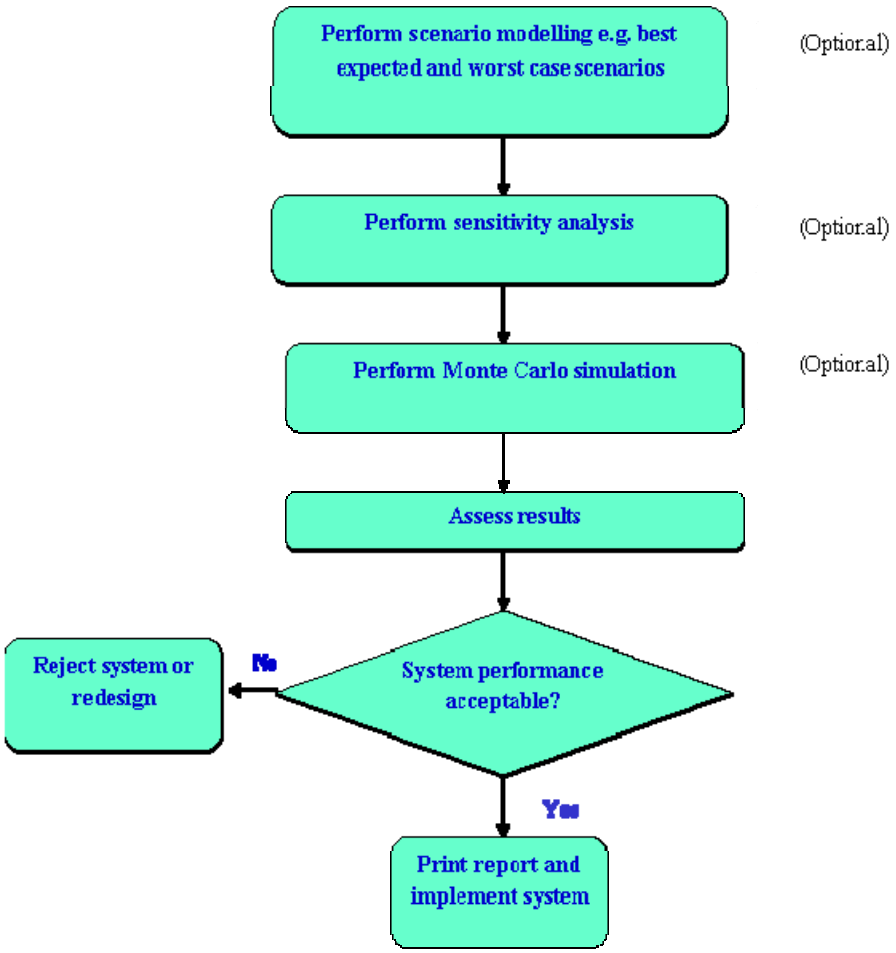


Fig. 9. Carrying out detailed analysis and critically examine results
Source: [35]

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
Storage capacity	12 m^3
Power rating of pump	1.4 KW
Capacity of pump	60 litres/min
UV unit power rating	0 W
Water demand	4,704 m^3/yr

4.3 Optimising water saving

In optimising water saving (Figure 11), seven tank sizes with a potential long-term profit were revealed. The best with a storage capacity of 12 m^3 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. 78.1 % of the predicted demand was met which was very good for a commercial system.

The tank size of 12 m^3 gave acceptable results and so the data for this tank was input into the Storage Tank module and WLC Details module and the result was examined in the Analysis System module. Figures 12 and 13 The cost comparison graphs for both the long-term and average per-year analyses for this system were presented in Figures 12&13.

Costs of Water Supplied	
Main water cost/ m^3	$0.40
Harvested water cost/m^3	$0.14

The potential of potable water savings using rainwater was evaluated in 195 cities of South-eastern Brazil [36]. The result revealed potable water savings of 12–79 % per year for the cities 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. 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 investigated the financial variability of an hospital block in Nigeria with a payback period of 1 year which was similar to the study by [38]. He examined the financial variability of domestic RWHS in high rise buildings in four cities in Australia and found Sidney had the shortest pay-back period (8.6 years). The financial variability of domestic RWHS in single and multi-family buildings was investigated in Barcelona, Spain [39]. Pay-back periods were varied between 30-60 years.

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

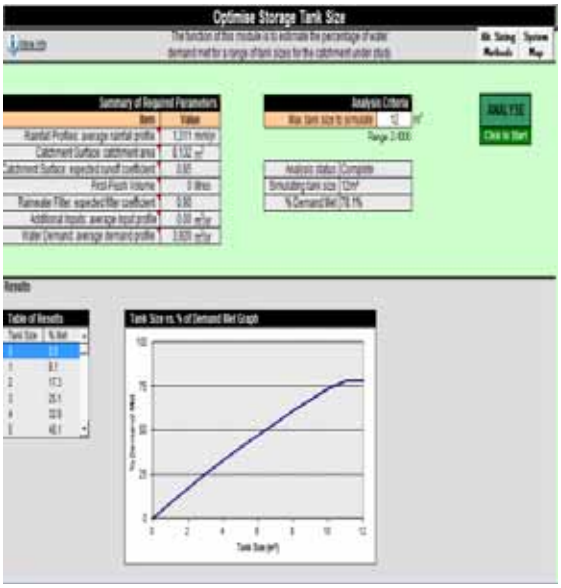
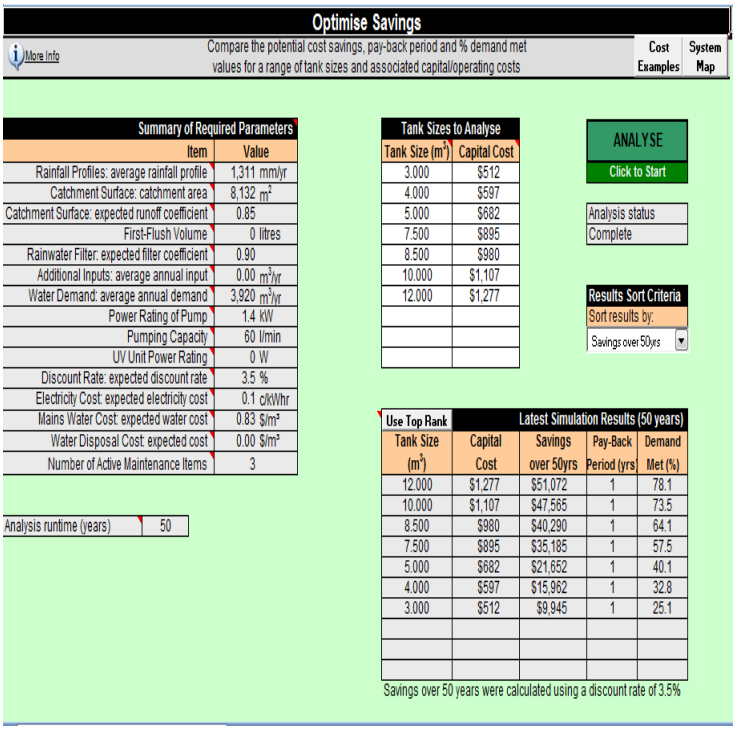


Fig. 10. Results from optimising storage capacity



Optimise Savings

More Info

Compare the potential cost savings, pay-back period and % demand met values for a range of tank sizes and associated capital/operating costs

Cost Examples | System Map

Summary of Required Parameters	
Item	Value
Rainfall Profiles: average rainfall profile	1,311 mm/yr
Catchment Surface: catchment area	8,132 m^2
Catchment Surface: expected runoff coefficient	0.85
First-Flush Volume	0 litres
Rainwater Filter: expected filter coefficient	0.90
Additional Inputs: average annual input	0.00 m^3/yr
Water Demand: average annual demand	3,920 m^3/yr
Power Rating of Pump	1.4 kW
Pumping Capacity	60 l/min
UV Unit Power Rating	0 W
Discount Rate: expected discount rate	3.5 %
Electricity Cost: expected electricity cost	0.1 c/kWhr
Mains Water Cost: expected water cost	0.83 $/m³
Water Disposal Cost: expected cost	0.00 $/m³
Number of Active Maintenance Items	3

Analysis runtime (years)	50

Tank Sizes to Analyse	
Tank Size (m^3)	Capital Cost
3.000	$512
4.000	$597
5.000	$682
7.500	$895
8.500	$980
10.000	$1,107
12.000	$1,277

ANALYSE

Click to Start

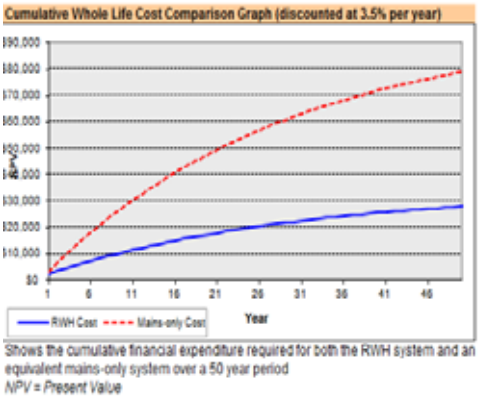
Analysis status
Complete

Results Sort Criteria
Sort results by:
Savings over 50yrs

Use Top Rank	Latest Simulation Results (50 years)			
Tank Size (m^3)	Capital Cost	Savings over 50yrs	Pay-Back Period (yrs)	Demand Met (%)
12.000	$1,277	$51,072	1	78.1
10.000	$1,107	$47,565	1	73.5
8.500	$980	$40,290	1	64.1
7.500	$895	$35,185	1	57.5
5.000	$682	$21,652	1	40.1
4.000	$597	$15,962	1	32.8
3.000	$512	$9,945	1	25.1

Savings over 50 years were calculated using a discount rate of 3.5%

Fig. 11. Result from optimising water savings



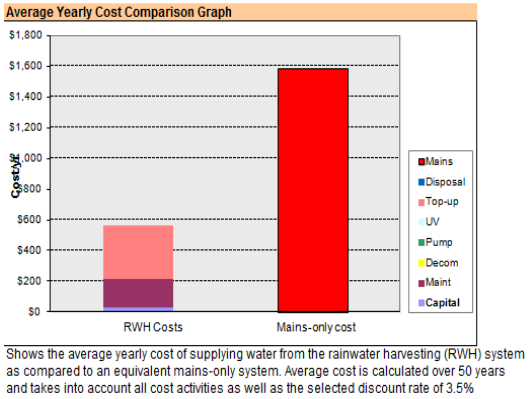


Fig. 12. Cost comparison of cumulative Long-term analysis

Fig. 13. Yearly cost comparison

5. CONCLUSION

Comment [O2]: So my friend what have you recommended ??????????

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

The result of optimising storage capacity reveals that the maximum percentage of demand that could be met was 78.1 %. The analysis of optimising saving showed that there were seven tank sizes with a potential long-term profit. A 12 m^3 tank was found to be the best, predicted to save $51,072 over 50 years and had a payback period of 1 year. The important influence of a given set of conditions on the economic viability of a RWHS was revealed by MonteCarlo simulation.

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