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Modelling Rainwater System Harvesting in Ibadan, Nigeria: Application to a Residential Apartment

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Abstract Reduction of water consumption associated water wastage in the residential sector is a rapid pressing issue. The residential sector is a substantial consumer of water in every country and therefore constitutes a focus of water consumption efforts. Since the water consumption, characteristics of the residential sector are complex and inter-related, comprehensive models are needed to assess the technical and economic impacts of adopting rainwater harvesting (RWH) as a sustainable system suitable for residential applications in developing countries. This paper has presented the hydraulic and financial modelling of a RWH system using a residential apartment in Ibadan, Nigeria. With a RWHS being site-specific, 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, taking into account 18 parameters. Seven of these are fixed parameters- catchment surface area, first-flush volume, storage tank volume, pump power rating, pump capacity, UV unit power rating and UV unit operating time while 11 are variable parameters- rainfall profiles, runoff coefficients, filter coefficients, additional inputs (if any), discount rate, electricity cost, mains water cost, water demand, disposal cost, capital cost and decommissioning cost. 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 70.6% with a tank size of 4 m^3. Optimising saving analysis showed that there were four tank sizes with a potential long-term profit. The best was 4 m^3 tank which was predicted to save $259 over 50 years and had a payback period of 21 years, which is typical for a current domestic system. The results show that significant reductions in the total fresh water consumption and the total cost can be obtained. A Monte Carlo simulation shows an important influence of a given set of conditions on the economic viability of RWH systems.

Keywords: *rainwater harvesting, water savings, payback period, residential apartment, Ibadan Nigeria*

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1. Introduction

One of the UN millennium Development Goal is to reduce by half the proportion of people without access to safe drinking water. In some countries, this goal will not be achieved by 2015. Some one billion people do not have access to safe drinking water [1]. Due to inadequate water supplies, over 25,000 people die daily from their use of contaminated water and many millions; more suffer from frequent and devastating water-borne illness [1]. About half of the people in developing countries lack access to safe drinking water and 73% have no sanitation. Thus, their drinking water supplies are eventually contaminated by their wastes, leading to health problems [2]. Water scarcity is faced by several parts of the globe, most notably in Africa, it is estimated that by 2025 two thirds of the world's population will face water related challenges [3]. As water is a key at-risk resource, improved water management is essential as resource optimization benefits the economy, environment and society [4,5].

In Nigeria, the largest environmental challenge is water scarcity. The current water use already exceeds the renewable supply. To increase the sources of water supply; many methods have been suggested and one of these alternative sources is rainwater harvesting (RWH). Little attention has been given to rainfall harvesting from rural/urban catchments. RWH from roads, parking lots and rooftops can increase water supply for various domestic uses, thus help in combating the chronic national water shortage. In urban areas, the inadequacy of public water systems and ineffective functioning of water facilities have made it impossible for most of the population to have access to sufficient potable water. About 52% of the population do not have access to improved drinking water supply [6]. An attractive solution for resolving water scarcity in various parts of the world is the use of water harvesting systems for runoff water collection and storage [7,8].

In optimizing water management, two main categories of solution exist; reduction of water consumption and identification of new water sources. The former recommends solutions that promote changes in consumption habits and the adoption of lower consumption devices, such as low-flush toilets. The latter explores alternative sources for water supply. In general, for building and residential buildings in particular, rainwater is one of the most common alternative sources- the scope of the research work. The paper reviews the most relevant technical and economic issues in designing domestic RWH systems, evaluating the technical and economic feasibility of implementing this technology in Ibadan. The evaluation is performed on a residential apartment from data collected on rainfall, roof area and average daily water demand.

2. Literature Review

2.1. General Context of Rainwater Harvesting

RWH primarily consists of the collection, storage and subsequent use of captured rainwater, either as the principal or supplementary source of water. It is applicable both for potable and non-potable purposes [9]. In developed countries such as Belgium, France, Germany, Japan, New Zealand, Singapore or United States, RWH is used mainly to complement conventional systems for non-potable use, namely for clothes washing, toilet flushing, irrigation and outside washes [10-15], but also for potable uses in Australia [16]. In developing countries such as Bangladesh, Botswana, China, India, Kenya, Mali, Malawi or Thailand [4,17], RWH is used mostly to cope with water shortages for potable and non-potable use [18].

In Nigeria, RWH is practised in the south, as rainfall is regular for eight months of the year, with a mean annual fall of 1200-2250 mm. 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 November-March. RWH is practised at individual, household, commercial and occasionally at local or state government level, to augment dwindling water supplies to urban centres.

Some of the most relevant obstacles to the implementation of RWH system are initial cost, social acceptance and treatment requirement. The most relevant factors governing the use of RWH as an alternative water source are sustainability concerns, which include water scarcity issues (climatic changes, pollution, and population growth) and the total costs of public water supply (investment, operation, maintenance and rehabilitation/replacement or disposal).

2.2. Rainwater Harvesting Solutions

The components of a RWH system differ between developed and developing countries, a typical RWH system comprises of three basic elements: the catchment surface, the conveyance system; the storage and distribution systems. The catchment surfaces are commonly roofs [9,19] although runoff can also be collected from other impermeable areas, such as roads, car parks and pavements [20]. The material of the catchment area affects the rainwater quality and quantity. After collection, rainwater goes through the conveyance system (which includes the first flush diverter and a filtration device) to treatment. The initial ‘first-flush’ of runoff is more polluted than subsequent flows and the concentration of contaminants associated with a given rainfall event tend to reduce exponentially with time [21]. Thus, the quality of water entering storage can be improved by diverting the initial portion of runoff generated by a storm away from the storage device and the need for subsequent treatment can be reduced or even eliminated [22,23]. After filtration, a storage device is required to collect and hold catchment runoff because rainfall events occur more erratically than system demand [9]. In order to balance out the difference between supply and demand, water storage capacity is required [24]. Underground tanks are the most commonly used storage device in the developed world [25]. Other types of reservoir structures used include the above-ground tanks and ponds [26].

A RWH system may have distinct or combined storage and distribution tanks. One of the tanks should be connected to another water source, usually the public main supply if it exists, to ensure supply when rainwater is insufficient. To prevent contamination of the public main supply, an air gap must be guaranteed. A pumping system may be required to provide adequate water pressure at delivery and at the end-use point depending on the location of the tanks (surface or underground tank). An option is to provide additional treatment stages before the storage tank to ensure rainwater quality, however this is not generally required for non-potable uses.

2.3. Previous Studies

The literature reviewed identifies existing methods for assessing the performance of RWH system at the single building scale, in terms of water saving reliability (i.e. the methods that can be used for determining volume of potable water that can be substituted by harvested rainwater). Numerous methods for predicting the performance of a RWHS exist: ranging from the relatively simple such as the ‘rule-of-thumb’ approaches to the more complex, such as statistical methods and sophisticated computer programs. There are various techniques; some consider only a single building, whilst others investigate the impacts of wider implementation such as at the development or catchment scale [27]. These are often with the aid of Geographical Information Systems [28]. Some methodologies focus solely on hydrological performance, whilst others include additional elements such as economic/financial measures [29] and in some instances assessment of system ‘sustainability’ [30]. A common practise among drainage engineers and researchers is the use of computer software for modelling hydraulic behaviour of both traditional urban drainage systems and sustainable urban drainage system [31]. Computer based methods offer several advantages over manual calculations, such as greater speed and flexibility, sophisticated data handling capabilities, simulation of specific designs under a wide range of circumstances, optimisation, and assessment of associated risk and identification of potential failure routes.

A study on the use of harvested rainwater resulted in fresh water savings of up to 19.7% [32]. The use of slow sand filter and solar technology was proposed for treatment of rainwater in agriculture and households applications [33]. Another study recommends a type of roof for maximizing the availability and quality of harvested rainwater [34]. An evaluation for the physicochemical properties for harvested rainwater showing the adequacy of using in several human activities was presented [35]. A study obtained savings from the required fresh water and energy through an optimization model for rooftop rainwater harvesting [36]. A significant reduction of fresh water consumption was obtained at low cost by carrying out a simulation for a large-scale water harvesting system [37]. A model for evaluating the performance of RWH was presented [38]. A RWH system for domestic use using an optimization model was designed [39]. The application of a geospatial and multi-criteria analysis techniques for planning the recollection of rainwater in a basin was investigated [40]. A RWH system was simulated using economic analysis technique [41]. A review of some specific evaluation studies on RWH for domestic use is presented in Table 1.

Table 1. Specific rainwater harvesting evaluation studies

Reference	Description
[10]	Performed a study in Germany that revealed the potential for potable water savings in a house varies from 30-60%, based on demand and roof area.
[44]	Investigated the use of rainwater in 27 houses in Newcastle, (Australia); and concluded that rainwater usage would promote potable water savings of 60%.
[45]	Investigated the use of roof water from Nanyang Technological University, China, to supply water to toilets in the whole campus. This reduced potable water consumption by 12.4%.
[46]	A significant saving in potable water was made through use of rainwater collected from roofs for flushing toilets. The performance of a rainwater collector installed in a house in Nottingham (UK) was monitored and a mean water saving efficiency of 57% was obtained.
[47]	Studied roof water harvesting from high-rise buildings in Singapore where >84% of the population lives. The study reveals that a monthly saving of about £9,187 in water expenditure was realised with this system.
[48]	Studied the quality of harvested water on different catchment systems in rural areas of Southern Nigeria. The potential of RWH as a reliable source of potable water is high and ~90% of rooftop catchments in Nigeria are composed of corrugated sheets.
[49]	Evaluated the potential for potable water saving using rainwater in 62 cities in South-eastern Brazil. The mean potential for potable water saving through RWH was 41%.
[50]	Investigated the potential for potable water saving in south Brazil. Some 34-92% of cities have potential for potable water saving using rainwater, depending on potable water demand.
[51]	Evaluated the potential for potable water saving using rainwater for washing vehicles in petrol stations in Brasilia, Brazil. The potential for potable water saving through RWH was 9.2-57.2%, with a mean of 32.7%.
[52]	Conducted a feasibility study on the use of rainwater in high-rise residential envelope in four Australian cities (Melbourne, Sydney, Perth and Darwin). Sydney had the shortest payback period compared with other cities with 3 Ampere (A) rated appliances (8.6 years) or 5A once installed (10.4 years).

In Nigeria, this topic has received little attention so far. The potential for non-potable water savings using rainwater for flushing and laundry in Abeokuta, Nigeria was estimated [42]. The potential for water savings was 90% (flushing) and 50% (flushing and laundry). The potential for potable water savings in residential houses, estimating water savings of 52.7% for a household of 5 people depending on demand conditions was evaluated [43]. The present paper extends the findings of this research using a computer based model instead of estimation method.

From studies on water savings and quality, it was found that local conditions and system configurations influence the savings potential and economic viability of RWH and level of pollution of the harvested rainwater. All studies confirm the viability of using harvested rainwater for non-potable purposes and its potential for potable without requirement for extensive treatment.

2.4. Modelling System Component

The section describes how each of the RWH components mention in section 2.2 can be represented within a conceptual RWHS hydrological model.

2.4.1. Precipitation

Precipitation varies with location, season and year. Factors such as distance from the coast and local topology strongly influence precipitates variability [53]. Annual rainfall depths in Nigeria vary from 0-2400 mm, with the bulk of population living in areas that receive just 0-1350 mm [54]. The south and south-west receive comparatively more rainfall than most other areas, whilst the north receives less (~800 mm). For the RainCycle model to be functional, a suitable method of representing the actual rainfall profile in the city of interest i.e. Ibadan, had to be found. There are two broad categories of incorporating rainfall data into the analysis: historic and stochastic. Empirical rainfall data series obtained from weather monitoring stations are contained in the historic category, whilst rainfall data generated using some technique that has a random/probabilistic element are contained in the stochastic category.

In Nigeria, rainfall data of this type is often available from various sources such as the Meteorological office, Nigerian Airport Authority, International Institute of Tropical Agriculture (IITA), Universities and research institutions. Most common is the collection of rainfall data at an hourly or daily timescale, the collection of short duration rainfall data is rare [55]. Average monthly rainfall (using a daily rainfall data of 30-years) was input, and the rainfall wizard was used to define the rainfall pattern.

2.4.2. Catchment Surface

Several catchment surfaces (e.g. roads, pavements and car parks) can be used for runoff harvesting, but in urban areas, the most rainwater surface types are restricted to roofs. Thus, this paper is limited to roofs rainfall/runoff characteristics only. The level of actual runoff is influenced by the type of surface material, surface wetting, ponding in depressions, absorption and evaporation.

2.4.3. Runoff coefficient

The runoff coefficient represents the proportion of rainwater collected from an actual roof compared with an idealised roof from which no losses occur [9]. It is the ratio of the volume of water that runs off a surface compared to the total volume of rain falling on it [24]. In order 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, (CR), can be expressed (equation 1) [24].

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

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

The volume of rain falling on a catchment surface in time period 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 [56] (Figure 1). This gives the plan area and not the actual area. It assumes that the rainfall falls vertically onto the roof surface.

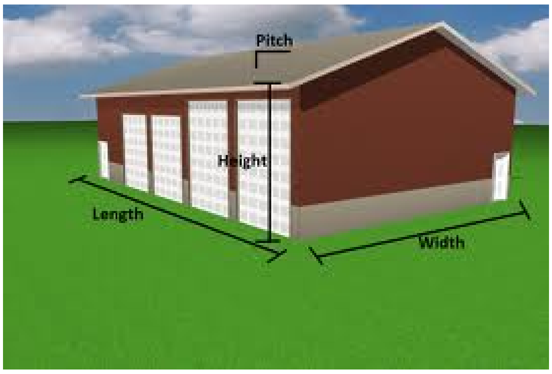

Figure 1. Calculating the plan area of a catchment

$$\text{Catchment area} = \text{Length x Width} \qquad (2)$$

After calculating the effective area of the catchment, a suitable runoff coefficient should be determined. Then, the volume of runoff occurring in time period t can be calculated using equation 3.

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

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.

2.4.4. Roof Areas for Residential Houses

A range of realistic roof (plan) areas as a function of household occupancy is needed in order to conduct simulations of domestic RWH system installed in residential houses. This is necessary because the level of occupancy strongly influences total water demand within a dwelling [57].

2.4.5. First-flush Diverters

The first-flush is a fixed amount of roof runoff requiring separation [58]. A set figure for a given building type or a variable figure based on the catchment area is often recommended. For domestic dwellings, the first 20-25 litres of effective runoff should be removed, whilst the first 2 mm of rain falling on the roof surface should be removed in commercial/industrial buildings. Although, there is no universally agreed volume of runoff that should be captured, [59] recommended diverting the first 5 litres of runoff for small roofs. These types of approaches have dominated the modelling and design of first-flush devices [60].

2.4.6. Pump

A pump can be modelled hydraulically in a simple fashion, by considering the amount of water requiring pumping per unit time and the rate at which it is able to pump that water. The manufacturers usually give pump performance data in the form of a head versus discharge relationship for a pump of a given type and power ratings. The required 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 calculated from this, by multiplying P_UEn_t by the unit cost of electricity, which depends on the amount charged by the relevant energy utility.

$$C = Pu_{POW} x Pu_{TIME} \qquad (4)$$

where:
P_UEn_t= pump energy usage in time t (kWhrs)
Pu_{POW}= pump power rating (kW)
Pu_{TIME} = pump operating period in time t (hrs).

For a given head, the pump algorithm used in the research assumes that the power consumption and flow rate are constant.

2.4.7. Potable (mains) Water Supply and Sewerage Systems

When available harvested rainwater cannot satisfy demands, the extent to which public water supply is incorporated into RWH models is usually restricted to the measurement of mains top-up required. For models incorporating financial assessment, the associated volumetric mains and sewerage charges would be included. The primary indicator of financial performance (known as 'avoided costs') used is the value of the mains supply substituted by harvested water. This is the primary way in which RWHS are potentially able to save money [61].

2.4.8. Storage Tanks

A relation exists 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 [9]. A rainwater tank can be considered as a storage reservoir that receives stochastic inflows (effective runoff) over time and is sized to satisfy system demands [9]. The designer controls the tank size, hence some techniques to determine the size that will provide the optimum level of service is required [62].

3. Methodology

To evaluate the economic viability of the installation of a RWH system, the time period- called the payback period is to be estimated. The lower the payback period, the more attractive the investment becomes. Several factors make an investment un-attractive. A timescale of 50 year is common for buildings, which makes the investment economically viable with payback periods of several years of decades.

A comparison of the expenditure with savings determines the payback period. In this paper, savings result from the reduction of cost on potable water as a decrease in public water supply consumption and its impact on total charges is considered. As expenditures are associated with investment and operational costs of the RWH system, only direct costs were accounted for using market values of the RWH components. In the following sections, the methodology assumed to compute the water savings and costs are detailed.

3.1. Water Savings

There are several standards and guidelines on rainwater harvest system design [63,64,65]. Some standards such as German Abbreviation Method [66], the English Method [63] and Azevedo Neto Method [67] indicate estimation methods for tank sizing. In addition, several alternative methods exist [68]: (i) simplified approaches based on user-defined relationships [69,70]; (ii) continuous mass balance simulations or behavioural models [41]; (iii) non-parametric approaches based on probability matrix methods [71] and (iv) statistical methods.

The water savings were determined from the balance between daily water consumption and harvested rainwater following the approach represented schematically in Figure 2. A behavioural approach was chosen and use of YAS for design purposes was recommended [72] because it gives a conservative estimate on system performance. However, in estimating time reliability, YBS rules were used in preference to YAS.

In general YAS/YBS algorithm was incorporated into the Raincycle model adopted in this work with the storage operating parameter ϴ set to zero (YAS) as the default mode of operation. However, research suggested that as long as certain constraints regarding the selected time-step are employed, then YAS models are capable of modelling system performance within 10% of that predicted by a more accurate hourly time-step model and this was considered to be an acceptable margin of error [72].

3.1.1. Water Availability

The available rainfall depends on the precipitation pattern, the catchment surface and the water losses. A continuous 30 year daily rainfall record covering the years 1980-2009 was obtained from [73,74]. Figure 2. shows annual rainfall depths contained within the data set. Note the extreme marked on the graph, which correspond to the 1980 floods, which affected much of Ibadan.

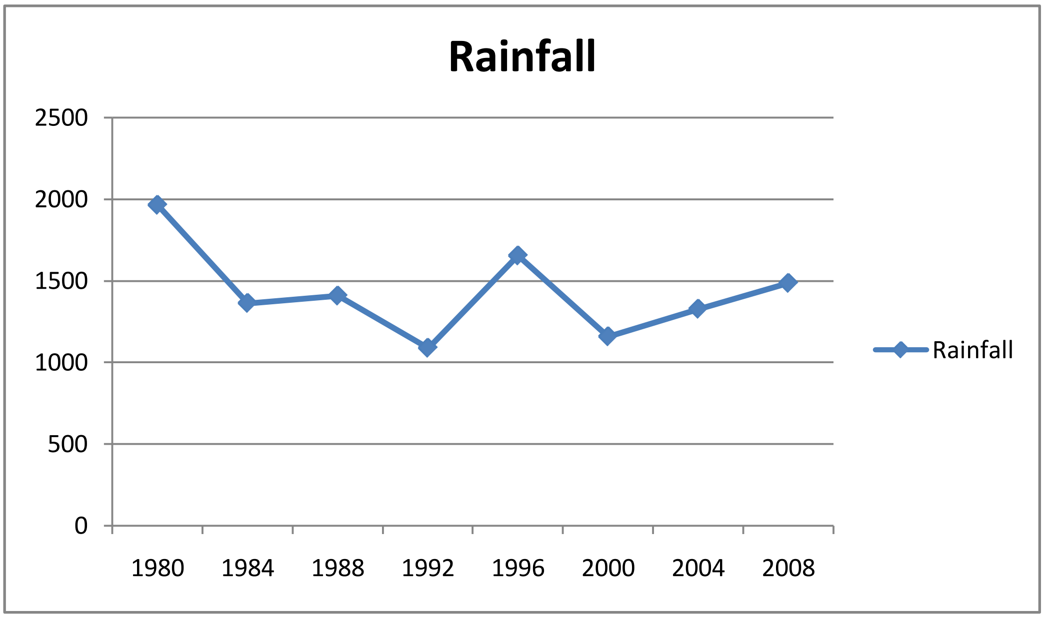

Figure 2. Ibadan City historic annual rainfall depths 1980-2009 (Source: [73])

3.1.2. Water Consumption

In this study both potable (drinking and cooking) and non-potable uses (toilet flushing, clothes washing and outdoor irrigation) were considered for rainwater. Collection of valid information on water usage in a developing country like Nigeria is difficult. Attempts were often made to estimate water demand, by quantifying the amount of water use in terms of number of 8-litre buckets used per day [75]. Figure 3 reports the volume of water used per person per day. The standard water consumption per person per day is 50 litres [76].

3.1.2.1. Predicting Non-potable Domestic Demand

Per capita consumption varies with household size, type of property, time of the year and ages of household residents [77]. Increases in household demand are primarily driven by population growth, levels of affluence and household occupancy [78,79]. In modern developments, the UK Code for Sustainable Homes Standard [80] may act as a significant driver for reduction in domestic water use. In order to achieve the lowest level of compliance, a minimum per capita consumption of 120 litres per day is required for internal water use and this may come to represent the minimum standard for new housing stock. For these reasons, a daily internal per capita consumption of 120 litres was adopted throughout this work. About 55% of total household demand could be met through domestic RWHS, if used for non-potable applications, such as WC flushing, laundry washing and garden irrigation.

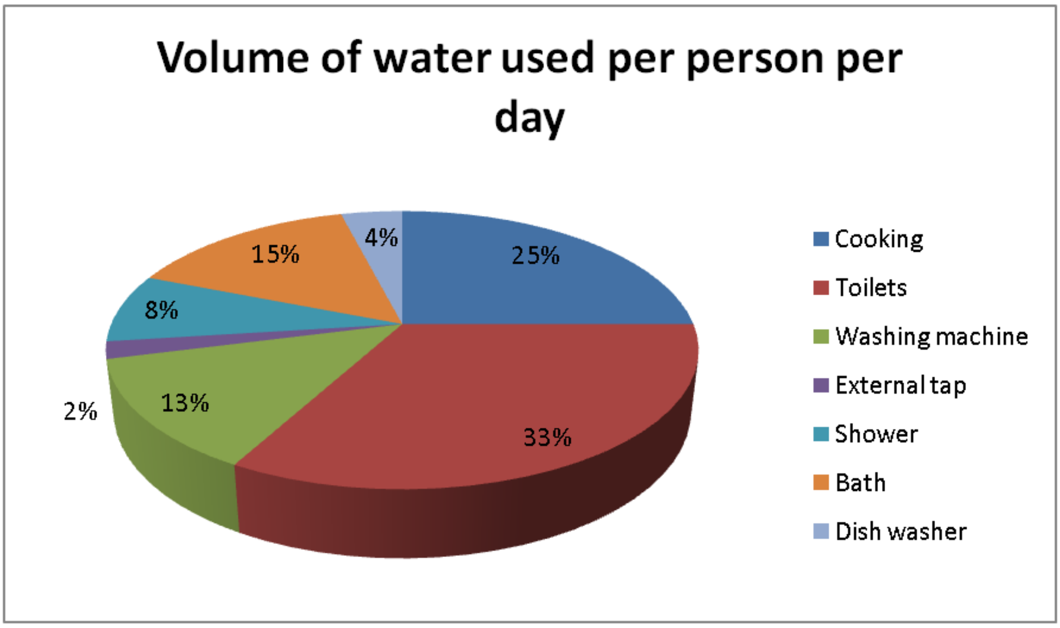

Figure 3. A typical household daily water use in Nigeria (2002) (Source [75])

3.1.2.2. Water Closet Demand

There is no cause to believe that WC usage frequency will increase or decrease significantly and so existing data based on past monitoring studies was used as an acceptable indicator of future behaviour. In Table 2, the mean of the values equal to 4.59 flushes per person per day. However, it is impossible to flush a toilet 4.59 times, so a per capita usage of 4times/day was assumed for weekday (Monday-Friday), whilst a per capita usage of 6times/day was assumed for weekends (Saturday and Sunday). An essentially linear relationship was found between household occupancy and frequency of WC flushes [81]. Therefore, an acceptable approach for calculating household usage is to multiply the household occupancy rate by the capita usage frequency. In the current regulations, a maximum flush volume of 6 litres is permitted for single-flush WCs [82]. This assumes higher weekend usage, which is reasonable, and gives mean rate of 4.57/person/day, which is close to the actual average of 4.59. A full flush ratio of 1:2 was adopted in this work.

Table 2. Range of domestic WC usage frequencies

Uses/person/day	References
3.3	[83]
3.7	[81]
5.25	[84]
6-8*	[85]
4.3	[78]
4.8	[86]
4.8	[80]
4.59	Mean (of above)

* Fewkes noted that one of the monitored WCs often required two flushes to clear the pan, which may explain the higher than average values. The higher value was ignored when calculating the mean.

3.1.2.3 Washing machine demand

A range of washing machine (WM) use frequencies is shown in Table 3. Anticipated future per capita use frequencies will probably not differ much from those occurring at present. In Table 4, the mean is 0.21 uses per person per day (~ once every 5 days). This latter figure was used as a standard value for domestic simulations. This is a general relationship between frequency of WM usage and household occupancy [83]. Thus, to determine household usage the per capita frequency can simply be multiplied by the household occupancy rate.

Table 3. Range of domestic washing machine usage frequencies

Uses/person/day	References
0.16	[81]
0.18	[84]
0.157	[78]
0.34	[80]
0.21	Mean

Table 4. Range of modern domestic washing machine water usage volumes

Volume/use (litres)	References
100	[84]
27/kg of wash load	[82]
45	[87]
80	[77]
49	[80]
40-80	[78]
35-40	[88]

* Maximum allowable under current regulations.
** 30-40 litres per 5 kg load probably technical limit due to rinse performance requirements.

3.2. Costs

The cost of water from a public main 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 in Table 5 were input into the model.

3.3. 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-Figure 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

Table 5. Financial details

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

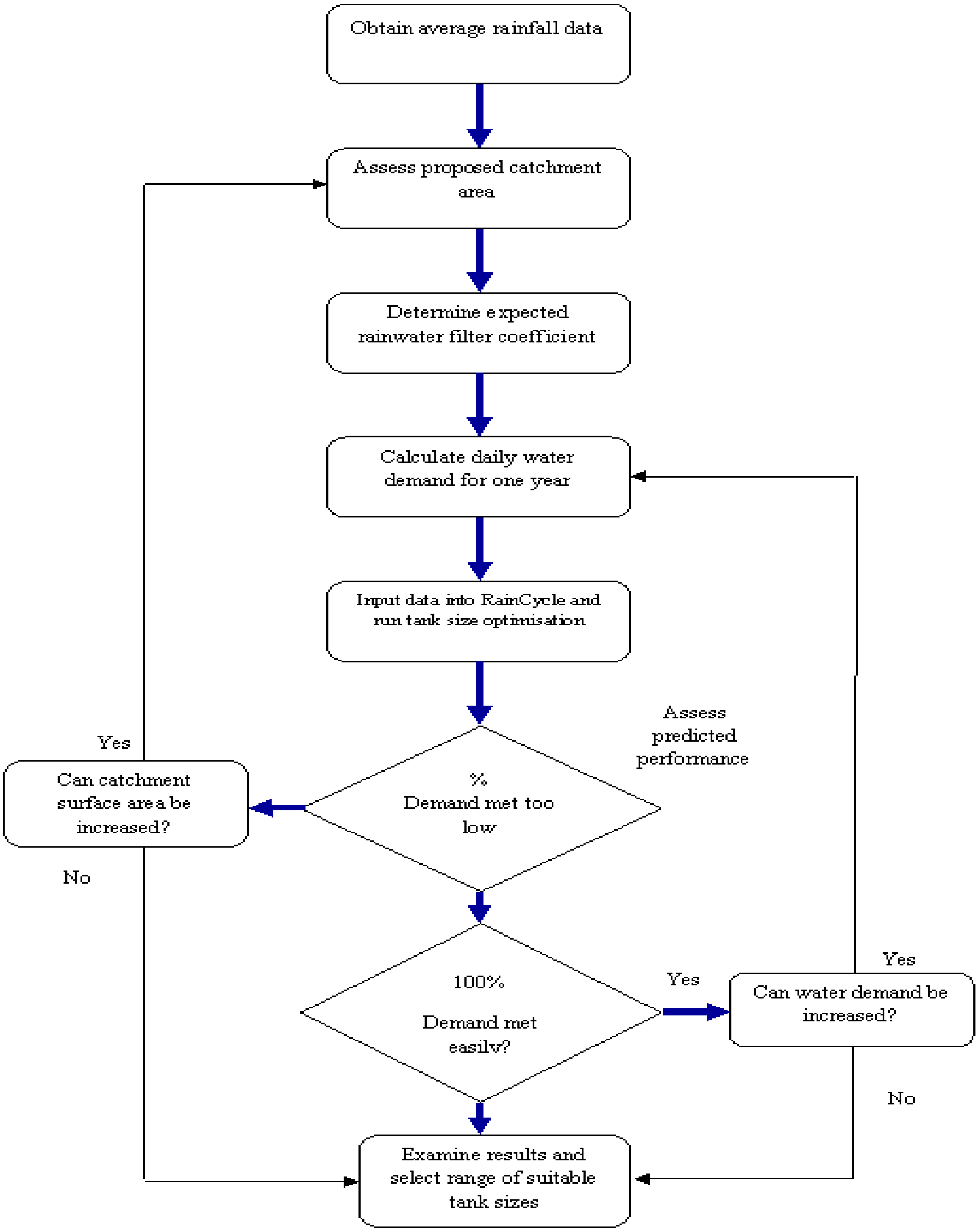

Figure 4. Determining range of suitable tank sizes

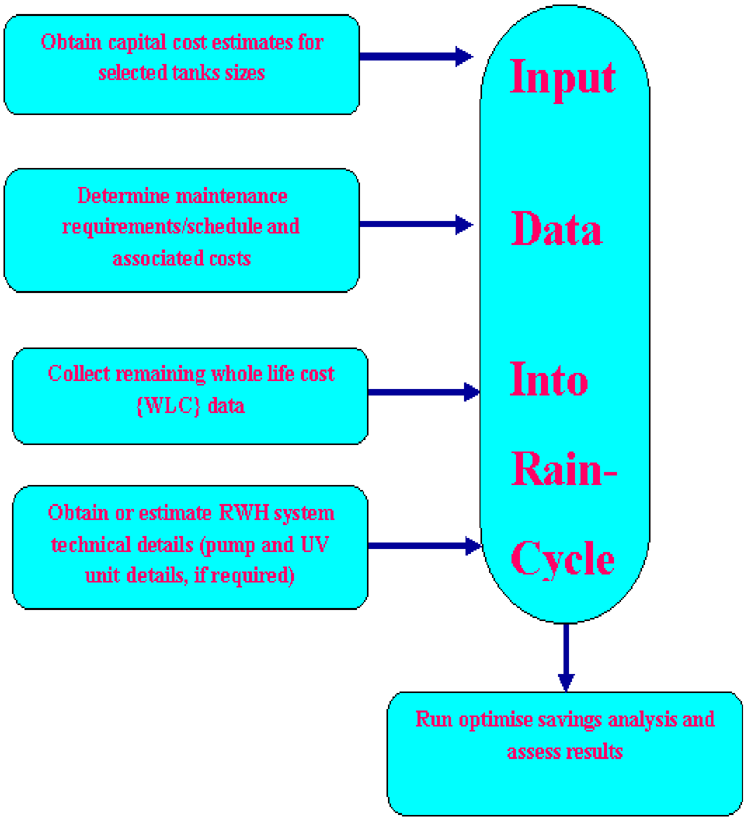

Figure 5. Determining cost savings of tanks and choosing optimum size

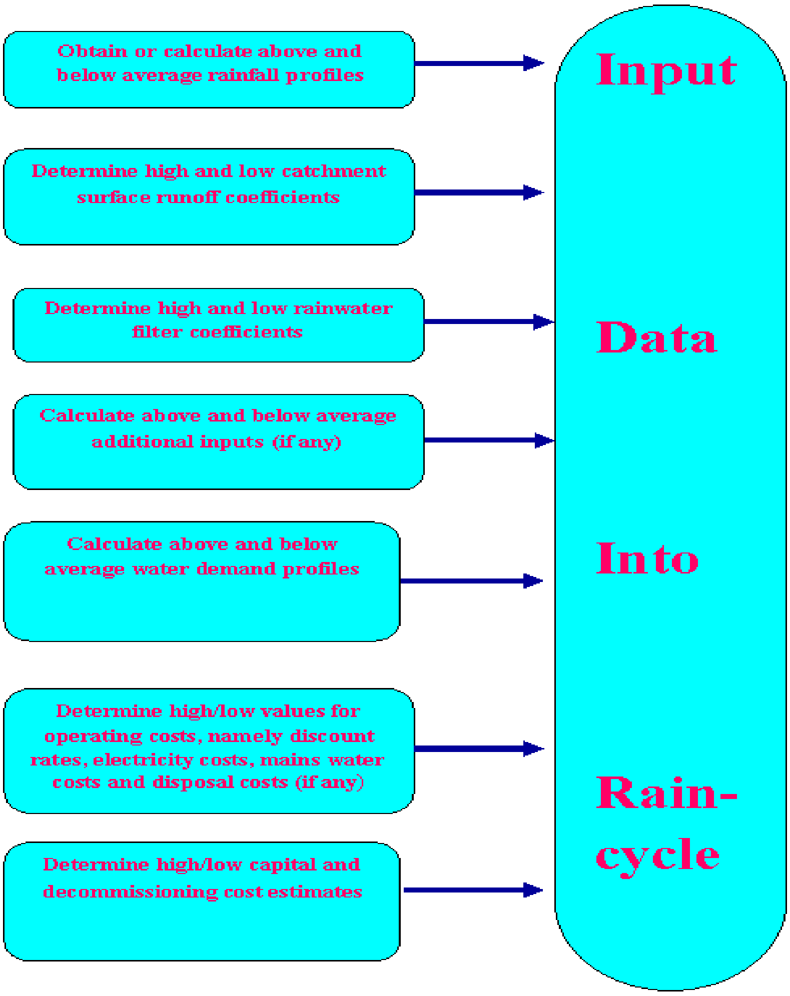

Figure 6. Assembling data required for detailed analysis

3.4. System Details: A Household of 12 Occupants

This building- a twin semi-detached bungalow is designed and build intended to provide residential facilities for 12 people (Figure 8). It has a roof area of 195.69 m^2. A proprietary RWH system has been proposed for the scheme to reduce mains water demand for W.C. flushing. Table 4-Table 5 show the data required in order to carry out the assessment. The data on hydraulic detail of the system is presented in Table 6. The expected operational life of the building is at least 50 years and so this was used as the time frame for the analysis.

4. Discussion of Results

Both short-and long-term hydraulic and financial assessments are included in these analyses. The analysis consists of a detailed assessment of the proposed system, taking into account 18 parameters. Seven of these are fixed parameters (Catchment surface area, first-flush volume, storage tank volume, pump power rating, pump capacity, UV unit power rating and UV unit operating time) while 11 are variable parameters (rainfall profiles, runoff coefficients, filter coefficients, additional inputs (if any), discount rate, electricity cost, mains water cost, water demand, disposal cost, capital cost and decommissioning cost).

For each variable parameter, there are three possible values: above average/high, average/expected and below average/low. It is possible to assess the system under study in more detail by allowing a range of values to be used in the assessment than would otherwise be possible if only one set of values was used. This allows variations in system performance (hydraulic and financial) under a range of conditions to be tested, leading to a more robust assessment and increased confidence in predicted future performance. For example, by allowing a range of scenarios such as best, expected and worst-case to be analysed, confidence in the results is higher than would otherwise be if only one set of values was used.

4.1. Mean Per-year Results

Mean per-year results use one set of parameters (fixed and variable) to assess the mean yearly savings that can be expected from the RWHS. All costs are summed and then divided by the number of years that the analysis was run to give the mean yearly running cost, as well as the savings that can be expected compared to relying solely on mains water.

4.2. Long-term Results

Long-term results use one set of parameters (fixed and variable) to assess the long-term savings that can be expected from the RWHS. The total cost of the RWHS is presented, along with the cost of an equivalent mains-only system. These values are used to deduce the long-term savings of the RWHS.

Hydraulic model validation

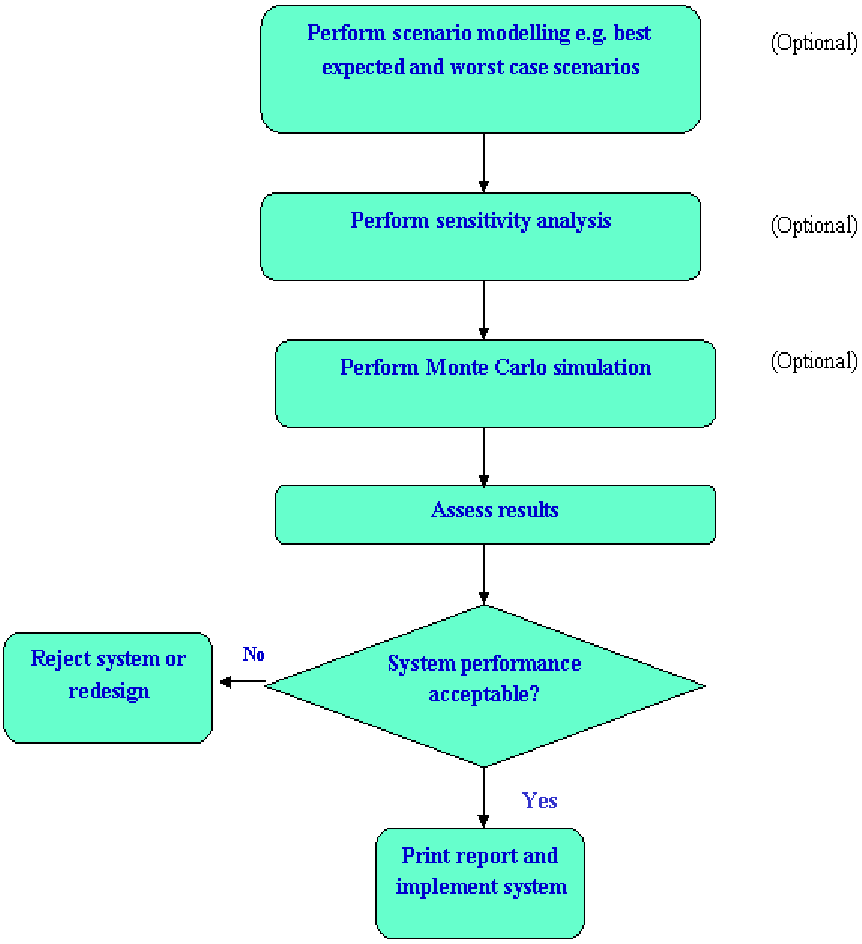

Figure 7. Performing detailed analysis and critically examine results

4.3. Sensitivity Analysis

A sensitivity analysis determines how susceptible the performance of a system is to changes in parameter values. The dependence of system performance on each variable parameter is determined. Systems that show a high variability for changes to a given parameter are sensitive to changes in parameters. System that shows a low variability is insensitive to changes (robust).

Figure 8. A semi-detached twin bungalows at Akobo, Ibadan

Table 6. Hydraulic details

Parameter	Probable value
Rainfall profile	1,311mm/yr
Catchment area	196m^2
Runoff coefficient	0.85
Filter coefficient	0.90
Storage tank volume	4.00m^3
Pump power rating	0.8KW
Pumping capacity	60 litres/min
UV unit power rating	0 W
Water demand	214m^3/yr

4.4. Monte Carlo Simulation

Monte Carlo (MC) simulation is a well-established technique that involves the use of random numbers and probability distributions in order to solve problems. MC simulation is used in science and engineering fields for uncertainty analysis, system optimisation and reliability based design [89]. In this instance, it was used to randomly generate new values for the variable parameters and then to run a system analysis using the new values. Many hundreds or thousands of simulations (iterations) were run and the results used to assess RWHS response under a very wide range of conditions.

Three values are required for each parameter: highest most probable value (above average/high), most probable value (average/expected) and lowest most probable value (below average/low). From these three values and for each iteration the program generates a new set of variable parameter values by randomly sampling from set probability distributions (in this case triangular probability distributions). As an example, suppose there are 3 catchment surface runoff coefficients: high = 0.90, expected = 0.85 and low = 0.75. The most probable value is 0.85 and so the selected number is most likely to be close to 0.85 (it will not equal 0.85 exactly) with a diminishing (but never zero) probability that the value will be closer to 0.75 or 0.90.

Hundreds of such simulations were run, the results were used to predict the probability of the modelled RWHS meeting a given set of conditions (e.g. the probability that long-term savings are equal to or greater than a given amount or that system pay-back occurs within a given timescale).

4.5. Optimising Tank Size

Optimising tank size results (Figure 9) reveals that the maximum percentage of demand that could be met was 70.6% with a tank size of 4 m^3. Therefore the limiting factor was the amount of water available and so increasing the tank size above 4 m^3 would have little (if any) benefit.

4.6. Optimising Saving Results

Optimise saving analysis (Figure 10) showed that there were four tank sizes with a potential long-term profit. The best was 4 m^3 tank which was predicted to save $259 over 50 years and had a pay back period of 21 years, which is typical for a current domestic system. Percentage demand met was also good for a domestic system at 70.6% of predicted demand.

The 4 m^3 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 were examined. Figure 11 and Figure 12 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 $0.37

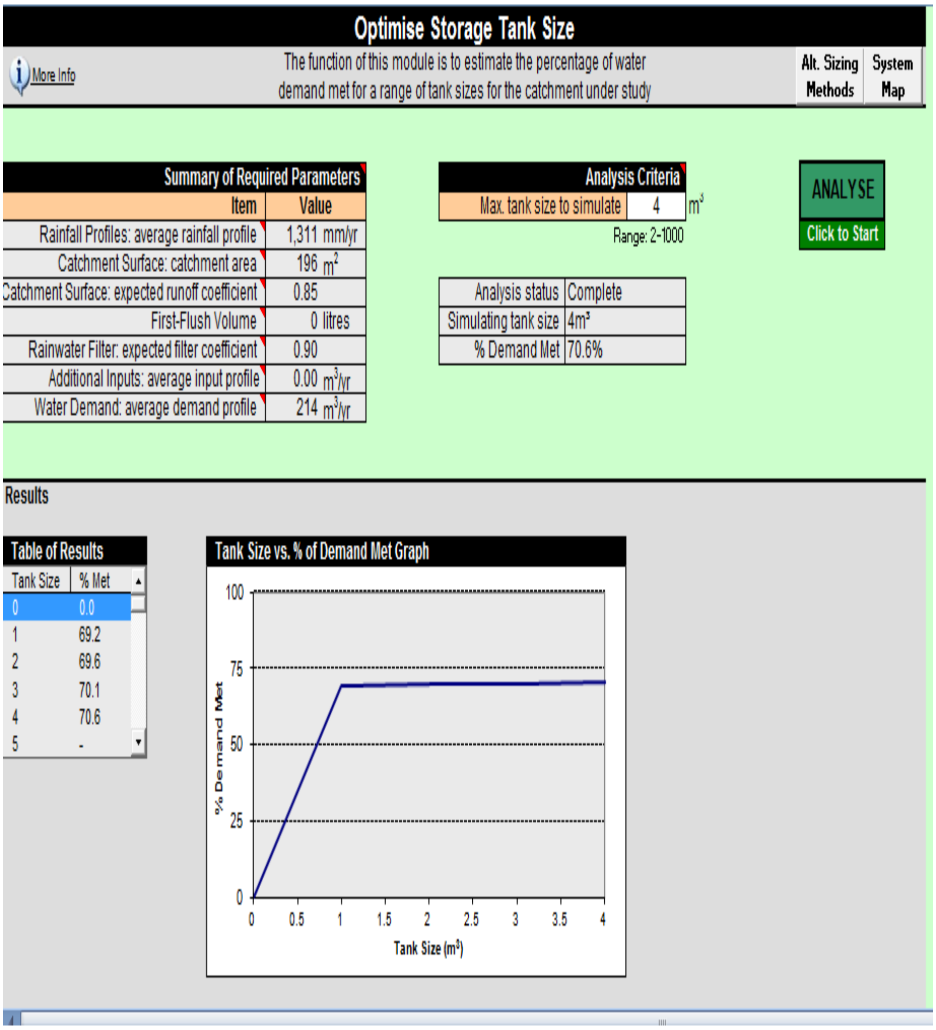

Figure 9. Results from optimising tank size

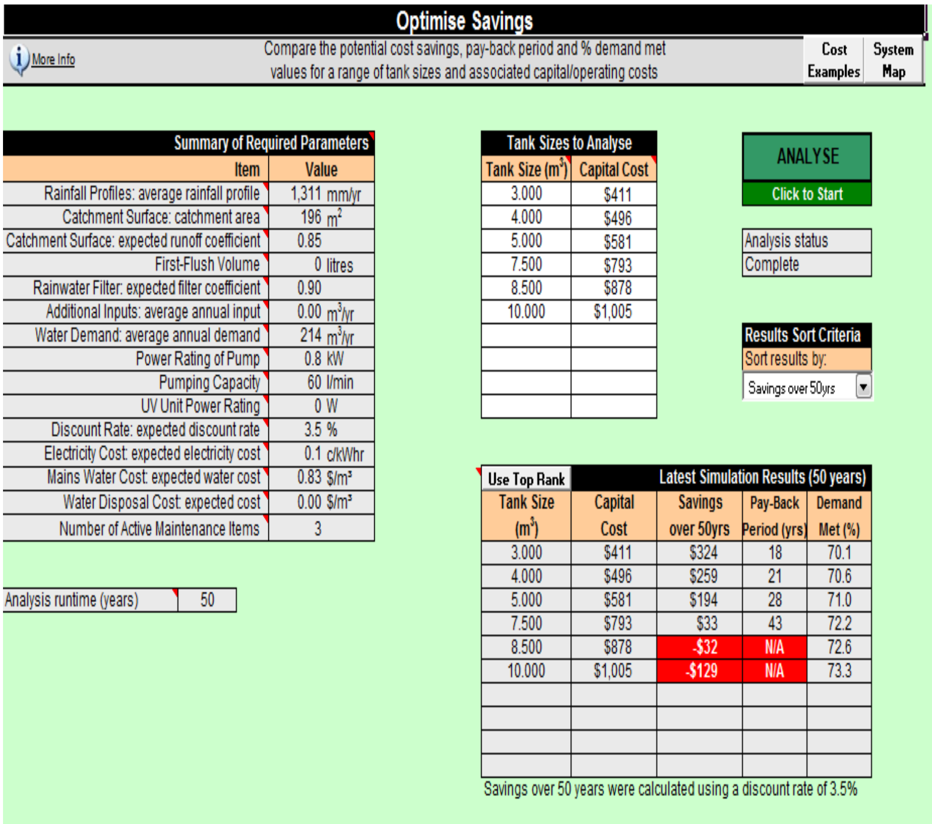

Figure 10. Results from optimising savings

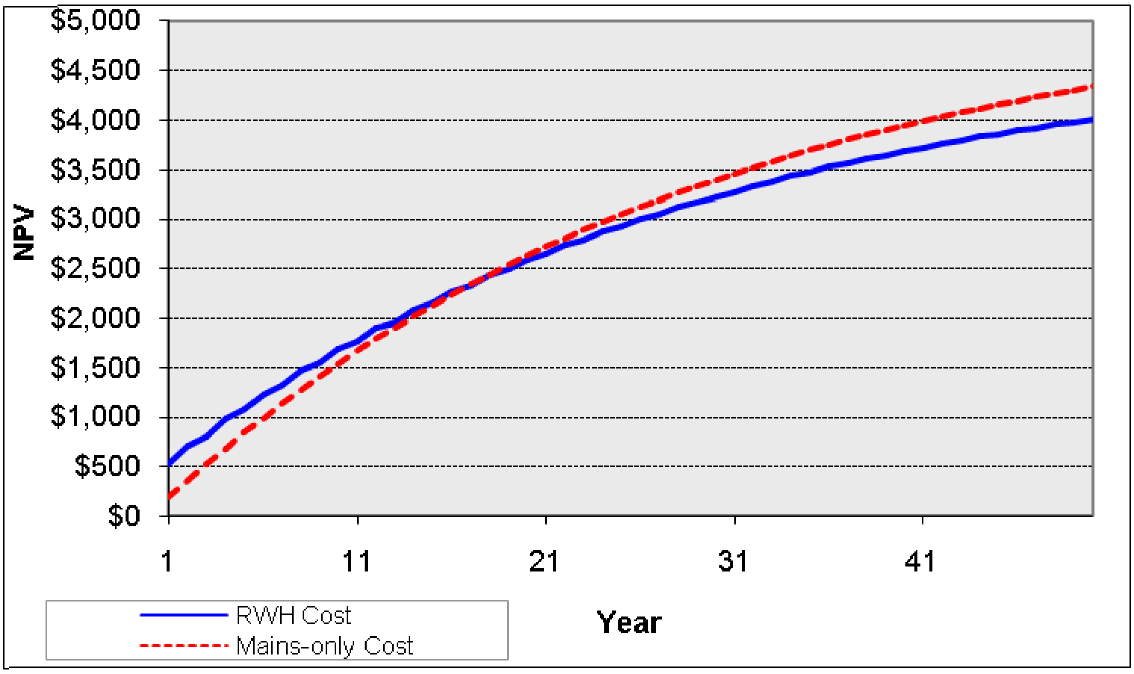

Figure 11. Cumulative long-term analysis cost comparison

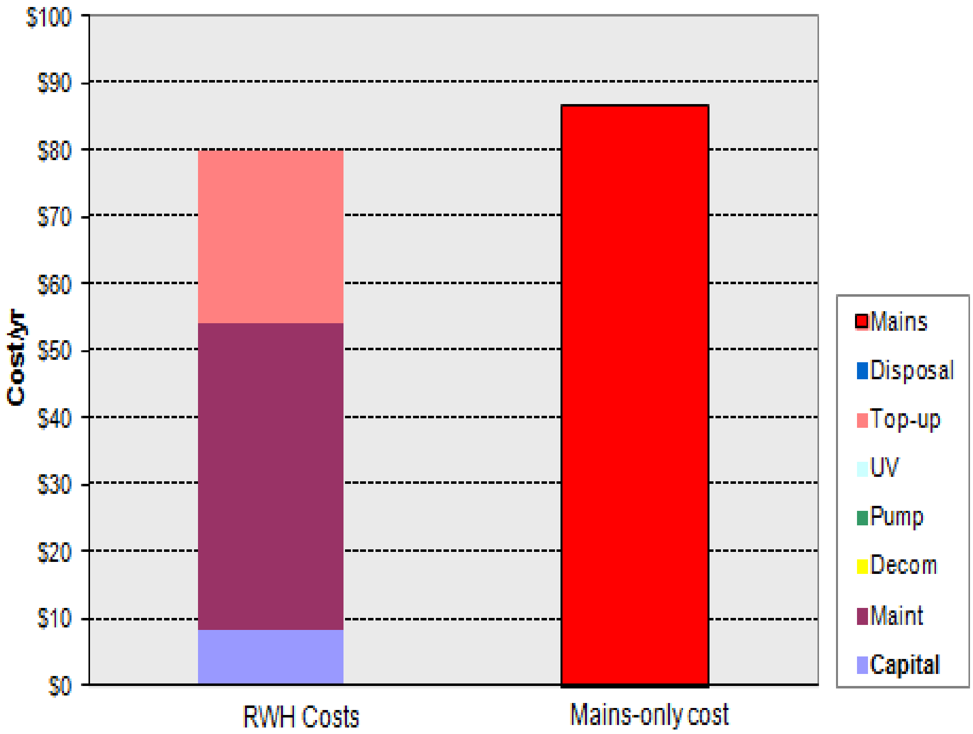

Figure 12. Average yearly cost comparison (discounted at 3.5%)

5. Conclusions

The hydraulic and WLC performance of RWH systems has been investigated using a computer based modelling tool. Case study result from a residential apartment indicated that both water and monetary savings are possible in the long-term. However, the current methodologies used by many RWH system suppliers to predict future performance appear to be inadequate in scope and detail, overestimating the amount of demand that can be met by the harvested rainwater and also the level of financial savings achievable. This is mainly due to the use of models that oversimplify the hydraulic processes involved and financial techniques that take little account, if any, of system requirements and do not use any discounting methods to calculate the true NPCV.

This paper has presented the hydraulic and financial modelling of a RWHS using a residential apartment in Ibadan, Nigeria. With a RWHS being site-specific, 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, taking into account 18 parameters. Seven of these are fixed parameters (Catchment surface area, first-flush volume, storage tank volume, pump power rating, pump capacity, UV unit power rating and UV unit operating time) while 11 are variable parameters (rainfall profiles, runoff coefficients, filter coefficients, additional inputs (if any), discount rate, electricity cost, mains water cost, water demand, disposal cost, capital cost and decommissioning cost). The evaluation of the hydraulic and financial performance of a RWH system of a residential apartment in Ibadan, Nigeria is presented. The water use and precipitation pattern was monitored.

Analysis of the case Study reveals that the maximum percentage of demand that could be met was 70.6% with a tank size of 4 m^3. A savings of $259 over 50 years and a payback period of 21 years were predicted, which is typical for a current domestic system. The results show that significant reductions in the total fresh water consumption and the total cost can be obtained. A Monte Carlo simulation shows an important influence of on the economic viability of RWH systems in a residential house in Ibadan, namely when compared to changes in the consumption pattern.

The use of Raincycle tool to model a proposed building system in detail and taking into account all associated cost items revealed a less optimistic, but more realistic set of results. The results indicated that RWH is a viable way of reducing reliance on mains water and also provide a monetary saving in the long-term under favourable conditions and in any case reduce downstream impacts on the drainage system.

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