Modelling Rainwater Harvesting System in Ibadan Nigeria: Application to a University Campus Office block

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Abstract
Rainwater harvesting (RWH) is a popular supplementary water supply source for various purposes, including drinking, sanitation and irrigation. This paper presents the hydraulic and financial modelling of a RWH system using an office block. A Raincycle model was used to optimise tank size and savings. Sensitivity analysis and Monte Carlo simulation were also carried out. The analysis consists of a detailed assessment of the proposed system, considering of seven fixed and 11 variable parameters. The RWH and water savings efficiency were assessed, and payback period was estimated. Optimising tank size and savings reveal that the maximum percentage of demand that could be met was 75 % with a tank size of 10 m^3 and savings of $ 2,564 over 50 years. It had a payback period of 8 years, which is typical for a commercial system. This method can be used for other offices in the Departments/Faculties on the University campus.

Keywords: rainwater harvesting, water savings, payback period, office block, Ibadan, Nigeria

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1. Introduction

About 5 – 20 % of the global population is predicted to live under severe water scarcity to an increase of 2^0Cin global temperature and this percentage tends to increase with a further rise in temperature (Scheme *et al*., 2014). The impact of climate change will result in water scarcity in different parts of the world, hence the global search for alternative water sources (USGCRP, 2012). Interest in Rainwater harvesting (RWH) as a green infrastructure practice in the face of adaptation to climate change is increasing (USGCRP, 2012; Ghimire *et al*., 2014).

RWH technology is a tool for poverty eradication and for improving women's livelihood as they are directly involved in the provision of water for household use. It is less time consuming than groundwater and surface sources and produce water at a decreased distance to sources of supply.

RWH consist of the collection, storage and transportation of rainwater either as the principal or supplementary source of water. It can be used for both potable and non-potable purposes (Fewkes, 2006). RWH is a simple and ancient concept of collecting water in a small system by attaching a water butt to a rainwater downspout or collection in a large complex system from many hectares to serve many communities (Leggett *et al*., 2001a).

Studies worldwide have explored RWH: in the south-eastern USA, computer models were developed to simulate system performance for 2081 rain barrels. The result revealed that rain barrel was used to meet household irrigation demands and overflow during rainfall events (Matthew *et al*., 2010). The potential for potable water savings using rainwater for washing vehicles in petrol stations was evaluated in Brasilia, Brazil (Ghisi*et al*., 2009).

A feasibility study on the use of rainwater in high-rise residential envelope was conducted in four Australian cities (Melboure, Sydney, Perth and Darwin). The result found Sydney had the shortest payback period compared with other cities with 3 Ampere rated appliances (8.6 years) or Ampere once installed (10.4 years)(Zhang *et al*., 2009). The components of the microbiological and chemical characteristics of harvesting rainwater and reservoir water as an alternative water resource was studied in South Korea. The study found that all harvested rainwater met the requirement for greywater, but not drinking water (Ju *et al*., 2010). A method for establishing the probabilistic approach relationship between storage capacities and deficit rates of RWHS was developed in the City of Taipei, Taiwan. A set of curves revealed the relationships between storage capacity and water supply deficit which was used by engineers to decide the storage sizes under current deficit rates [Ming-Daw *et al*., 2009)]. A GIS-based decision support system for rainwater harvesting (RHADESS) was built in selected part of South Africa to assist decision-makers and stakeholders to indicate the suitability of RWH and quantify the potential impacts associated with its adoption at the catchment scale(Mwenge *et al*., 2009).

A RWHS was designed in the Otukpa community, Benue State, Nigeria using local material. Rooftop RWH is a common practice in most households, the supply is still inadequate for sustenance through the dry season (Onoja*et al*., 2010).The quality of rainwater from four roofing materials (asbestos, aluminium, concrete and corrugated plastic) was analysed in Ogbomosho, Oyo State. The analysis revealed that boiled harvested water could be used for domestic purposes, if gutters and catchment areas were cleaned regularly to remove animal droppings and leaves from over-hanging trees (Olaoye& Olaniyan, 2012). The use of rainwater harvested from rooftops to recharge groundwater in a household well was studied in Ibadan which resulted in water conservation through reduced evaporation. The experimental well yields water all year round compared to the control well that dried up during the dry season (Lade *et al*., 2012). The potential for RWH was evaluated in Kanai (Mali) district in Kaduna State. The quantity of rainwater harvested was enough to supplement the needs of

rural communities if community involvement in RWH activities could be increased (Lekwot*et al*., 2012). A RWHS was designed and constructed for household with no public main supply in Ibadan. RWH proved to be a cheap and viable water supply option for domestic, industrial and agricultural purposes in both rural and urban areas (Shittu *et al*., 2012).
Rainwater water harvesting can be used in optimizing water management through reduction of water consumption and identification of new water sources. Rainwater is one of the most commonly explored alternatives for buildings, which is the scope for this research work. This paper evaluates the technical and economic feasibility of implementing RWH for an office block in a University campus using data collected from average daily water demand, rainfall and roof area.

2. Modelling System Component

In this section, the RWH components was represented within a conceptual RWHS hydrological model.

2.1 Precipitation

Precipitate variability is strongly influenced by factors such as distance from the coast and local typology (Thomas, 2002). In Nigeria, the annual rainfall depths vary from 0- 2400 mm, with most of the population residing in areas receiving 0 – 1350 mm(NPC, 2006). The Northern part of the country receives less rainfall (~ 800 mm) compared to the south and south-west which receives more rainfall than other areas. For the Rain Cycle model to be functional, historic and stochastic rainfall data of the city was incorporated into the analysis. The historic data consists of empirical rainfall data series obtained from weather monitoring stations; whist stochastic data consists of rainfall data generated using some technique that has a random/probabilistic element.

2.2 Catchment surface

Catchment surfaces such as roads, pavements and car parks can be used for harvesting runoff. In urban areas, the most common rainfall surface is restricted to roof rainwater harvesting. This paper is limited to roofs runoff/rainfall collection only. Factors such as surface material, ponding in depressions, surface wetting, absorption and evaporation influenced the level of actual runoff.

2.3 Runoff coefficient

The proportion of rainwater collected from an actual roof compared with an idealised roof from which no losses occur is called the runoff coefficient (Fewkes, 2006). It is the ratio of the volume of water running off a surface compared to the volume of rain falling on it (Gould & Nissen-Peterson, 1999). Data of several months or years are gathered to calculate the coefficient, which may include many storm events. The runoff coefficients are combined for each storm event, to give mean value (Zhu & Liu, 1998; Fewkes, 1999a).
The dimensionless runoff (CR), can be expressed (equation 1) (Gould & Nissen-Peterson, 1999)

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

where t is the time period over which the measurement is made
The volume of rain falling on a catchment in time period t can be derived by multiplying the depth of rainfall in time t by the effective catchment area, which is calculated by multiplying the horizontal length of the catchment by the horizontal width (Environmental Agency, 2003b). This provides the

plan area (Figure 1) and not the actual area with the assumption that rain falls vertically onto the roof surface.

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

A suitable runoff coefficient can be determined after calculating the effective area of the catchment. 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.

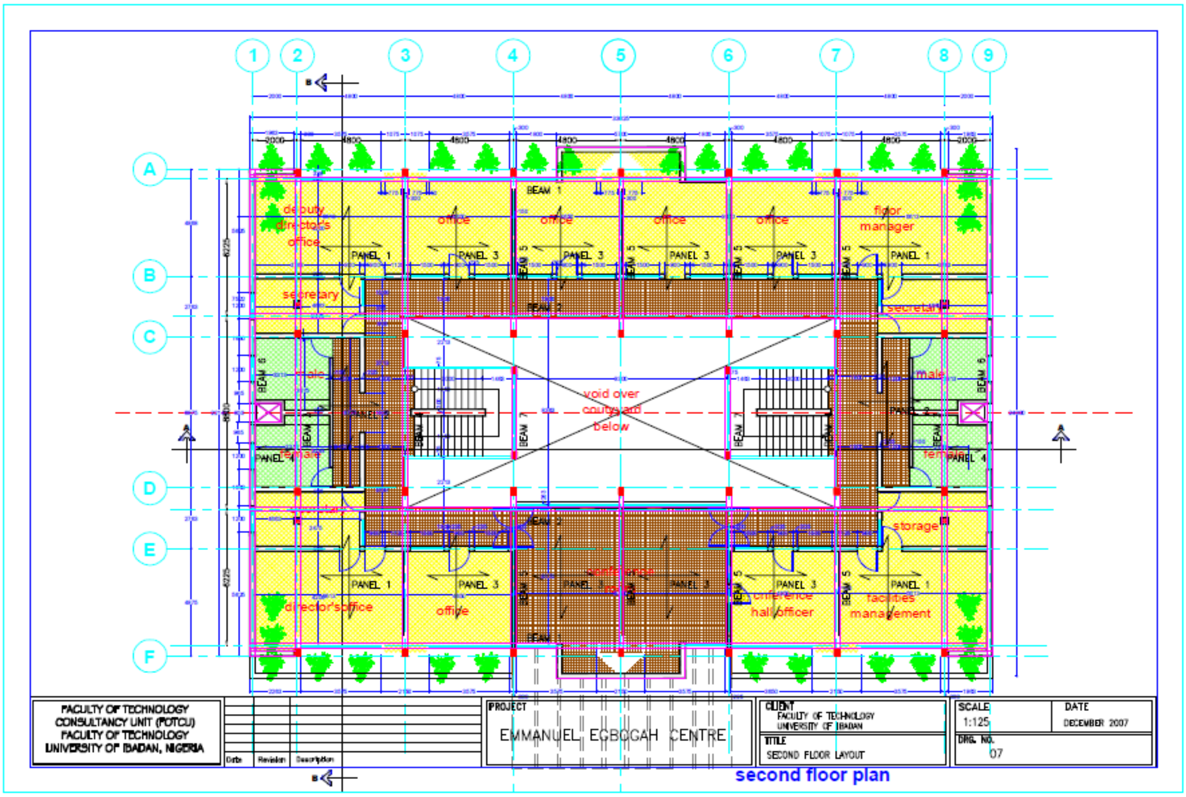


Figure 1 Roof plan for the office block at Dr Egbogah Building (Department of Civil Engineering, University of Ibadan)

2.4 First-flush diverters

A fixed amount of roof runoff requiring separation is known as first-flush (Mitchell *et al.*, 1997; Cunliffe, 1998). Figures from a given building type or variable figure based on the catchment area is often recommended. In commercial building/industrial buildings the first 2 mm of rain falling on the rooftop should be removed, whilst in domestic dwellings, the first 20-25 litres of effective runoff should be removed. Although, no universal agreed volume of runoff should be captured, it was recommended that the first 5 litres of runoff should be diverted for small roofs(Yazizet *al.*, 1989). An average domestic roof in Australia should capture 20-25 litres initial flow (Cunliffe, 1998)which has dominated the modelling and design of first-flush devices(Coombes, 2002).

2.5 Pump

A pump can be modelled hydraulically by considering the amount of water that requires pumping per unit time and the rate at which the water can be pumped. The pump performance data is usually provided by the manufacturers in the form of a head versus discharge relationship for a pump of a given type and power rating. The required operating period from which the energy usage of the pump can be determined (equation 4). The operating cost per unit time can be calculated by multiplying $P_UEn_t$by the unit cost of electricity, which depends on the amount charged by the relevant energy utility provider.

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

where:

P_UEn_t = pump energy usage in time t (kWhrs)

Pu_{POW} = pump power rating (kW)

Pu_{TIME} = pump operating period t (hrs)

2.6 Potable (mains) Water Supply and Sewerage Systems

When the harvested rainwater cannot meet the demand, the level of incorporating public water supply into the RWH models depends on the quantity of mains top-up required. Models incorporating financial assessment will include the associated volumetric mains and sewerage charges. The value of the mains supply substituted by harvested water is used as the primary indicator of the financial performance. In this way, RWHS are potentially able to save money (Ghisi& Ferreira, 2007).

2.7 Storage tanks

A rainwater tank is a storage reservoir that receives stochastic inflows (effective runoff) over time and is sized to meet the systems demands (Fewkes, 2006). The tank size is controlled by the designer, hence the provision of some techniques to determine the optimum level of service is required (Fewkes, 1997).

3. Methodology

In order to estimate the economic viability of the installation of a RWHS, the payback period needs to be estimated. Lower payback period attracts more investment. In buildings, a timescale of 50 years is common which makes the investment economically viable with payback periods of several years. The payback period can be determined by comparing the expenditure with savings. In this paper, savings was achieved by reducing the cost on potable water through decrease in public water consumption and consideration of its impact on total charges. Only direct costs were accounted for using market values of RWH components as expenditures are associated with operational costs and investment. The methodology used in computing the water savings and cost are detail in the sections below:

3.1 Water savings

The water savings were determined from the balance between daily water consumption and harvested rainwater based on the chosen approach. The behavioural analysis approach was chosen using either the yield after spillage (YAS) or yield before spillage (YBS) operating rule. The YAS rule was recommended for design purpose because it gives a conservative estimate on system performance (Fewkes& Butler, 2000) while the YBS rule was used in investigating time reliability.

In this study, the YAS/YBS algorithm was incorporated into the Raincycle model with the storage parameter θ set to zero (YAS) as the default mode of operation. Research has suggested that the YAS models are capable of modelling system performance within ±10% of that predicted by a more accurate hourly time-step model if certain constraints regarding the selected time-step are employed (Fewkes& Butler, 2000).

3.1.1 Water availability

The available rainfall is determined by factors such as: precipitation pattern, the catchment surface and the water losses. Average monthly rainfall data of 30-years (1980 – 2009) was input, and the rainfall wizard was used to define the rainfall pattern (DMS, 2010). The average monthly rainfall data is presented in Figure 2.

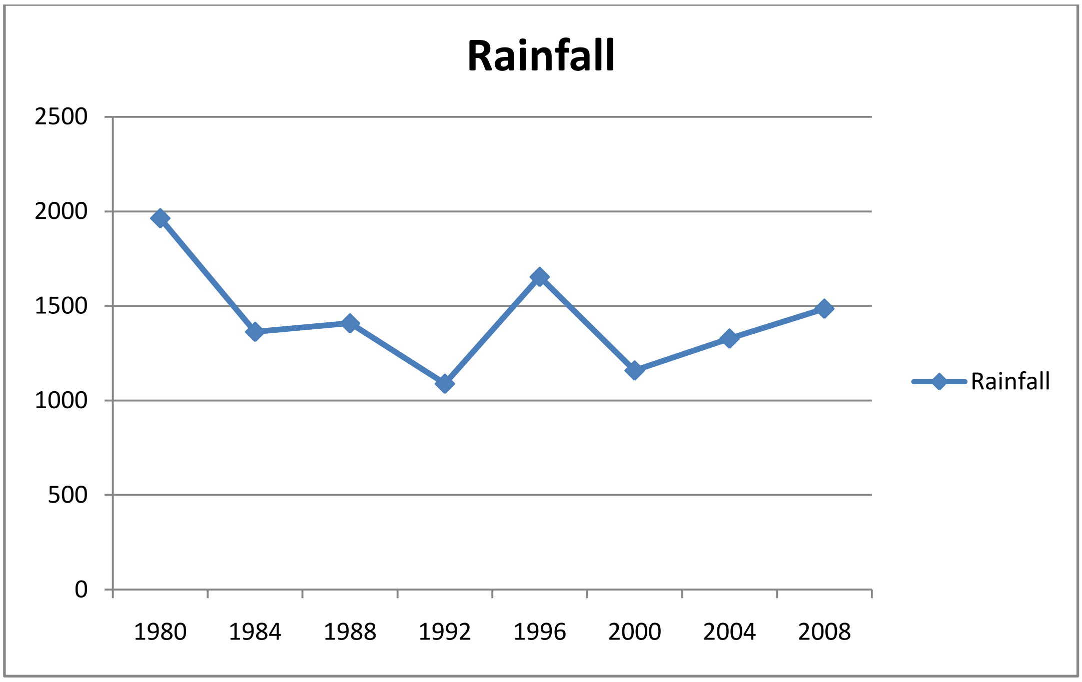


Figure 2 Ibadan city historic annual rainfall depths 1980 – 2009

3.1.2 Water consumption

Potable and non-potable water uses were considered for this study. In developing countries like Nigeria, valid information on water usage were not available. Hence, water demand was estimated by quantifying the amount of water use in terms of a8-litre buckets used per day(Adekalu*et al*., 2002). The standard water consumption per person per day is 50 litres (UN, 2002).

3.1.2.1 Predicting non-potable domestic demand

Factors such as household size, type of property, time of the year and ages of household residents are determinants of per capita consumption(Memon& Butler, 2006). Increasing population growth, levels of affluence and household occupancy affects household demand(Environmental Agency, 2001). In modern developments, a significant driver to reduction of domestic water use is the UK code for Sustainable Homes Standard (DCLG, 2007). To achieve the lowest level of compliance, a minimum per capita consumption of 120 litres per day is required for internal water use which was adopted in this study.

3.1.2.2 Water closet demand

In this study, an acceptable indicator of future behaviour was based on existing data from past monitoring studies since the possibility of WC usage frequency increasing or decreasing significantly is low. The mean of the values equal 4.59 flushes perperson per day, presented in Table 1 was adopted in this study.

Table 1 Range of domestic WC usage frequencies

Uses/person/day	References
3.3	Thackray*et al*., 1978
3.7	Butler, 1991
5.25	SODCON, 1994
6-8*	Fewkes, 1999a
4.3	Environmental Agency, 2001
4.8	Chambers *et al*., 2005
4.8	DCLG, 2007
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.

3.2 Costs

The cost of public main water supply and rainwater system components were obtained from Water Corporation of Oyo State (WCOS) and market survey respectively. The data on financial details presented in Table 2 were input into the model.

Table 2 Financial details

Parameter	Probable value
Capital cost	$1,047.00
Decommissioning cost	$0.00
Discount rate	3.5 %
Electricity cost	0.1 c/KWhr
Mains water cost	0.83 $/ m^3

3.3 The Raincycle analysis process

In order to design a RWHS, a systematic step is followed to create a successful design. The analysis and design are divided into four steps:

- Step 1: Determine suitable tank sizes (Figure 3)
- Step 2: Determine cost savings of tanks from (1) and choose optimum size
- Step 3: Gather data required for detailed analysis
- Step 4: Perform detail analysis and critically examine results

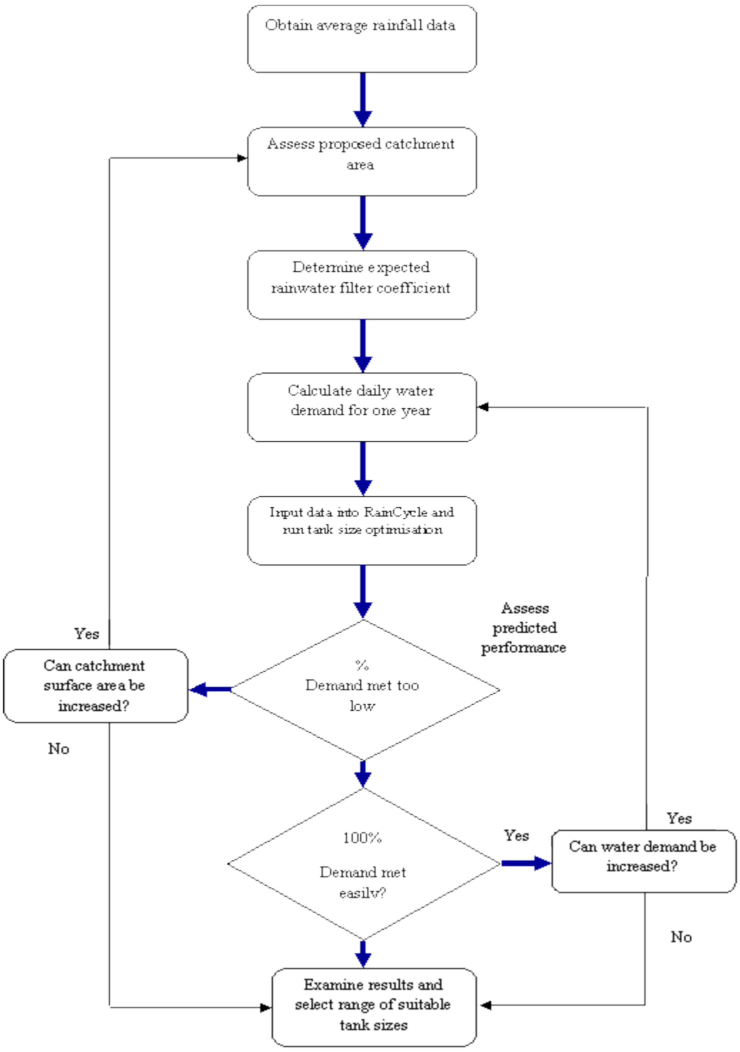


Figure 3 Determining range of suitable tank sizes

3.4 System details

This building is a two-floor storey designed and build to provide office facilities for University of Ibadan Staff. It has a roof plan of566 m^2. Table 3 shows the data required to carry out the hydraulic and financial assessment of the system. The time frame of 50 years which is the expected operational life of the building was used for the analysis.

Table 3 Hydraulic details

Parameter	Probable value
Rainfall profile	1,311 mm/yr
Catchment area	566 m^2
Runoff coefficient	0.85
Filter coefficient	0.90
Storage tank volume	10.00 m^3
Pump power rating	1.2 KW
Pumping capacity	65 litres/min
UV unit power rating	0 W
Water demand	441 m^3/yr

4. Discussion of results

This analysis includes both short and long-term hydraulic and financial performance of the system. It consists of a detailed assessment of the proposed system considering 18 parameters. 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), while 7 are fixed parameters (catchment surface area, first-flush volume, storage tank volume, pump power rating, pump capacity, UV unit power and UV unit operating time).

There are three possible values for each variable parameter: above average/high, average/expected and below average/low. This will allow the system under study to be assessed in more detail using a range of values instead of using only one set of values. The variation in the system performance under a range of conditions could be tested, thus providing a more robust assessment and increased confidence in future performance.

4.1 Mean per-year results

One set of parameters (fixed and variable) are used to assess the mean yearly savings expected from the RWHS. The mean yearly running cost as well as savings compared to relying solely on mains water is estimated by summing all costs and dividing by the number of years that the analysis was run.

4.2 Long-term results

One set of parameters (fixed and variable) is used to assess the long-term savings that can be expected from the RWHS. The long -term savings of the RWHS is deduced from the total cost of the RWHS as well as the cost of an equivalent mains-only system.

4.3 Sensitivity analysis

Sensitivity analysis is carried out to deduce the susceptibility of the system to changes in parameter values. The dependence of system performance on each variable parameter is determined. Systems showing high variability for changes in each parameter are sensitive to changes in parameters while system showing low variability are insensitive to changes (robust).

4.4 Monte Carlo simulation

Monte Carlo (MC) simulation involves the use of random numbers and probability distributions in order to solve problems. MC is used for uncertainty analysis, system optimisation and reliability-based design (Wittwer, 2003). In this study, it was used to randomly generate new values for the variable parameters and then to run a system analysis using the new values. The results of many hundreds or thousands of simulations was 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). For this analysis, the three values assigned to each parameter are shown in the data input table.

For each iteration the program generates a new set of variable parameter values by randomly sampling from set probability distributions from these three values. 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 with a diminishing probability that the value will be closer to 0.75 or 0.90. By running enough iterations (say at least several hundred) and the results plotted, then the frequency of values chosen will resemble a triangle. That is, most generated values will be clustered around the most likely value of 0.85 with the number of values either side diminishing the closer to 0.75 or 0.90. When hundreds of such simulations are run, the results can be used to predict the probability of the modelled RWHS meeting a given set of conditions.

4.5 Optimising tank size

Optimise tank size results (Figure 4) reveals that the maximum percentage of demand that could be met was 75.0% with a tank size of 10 m^3. Therefore, the limiting factor was the amount of water available and so increasing the tank size above 10 m^3 would have little benefit.

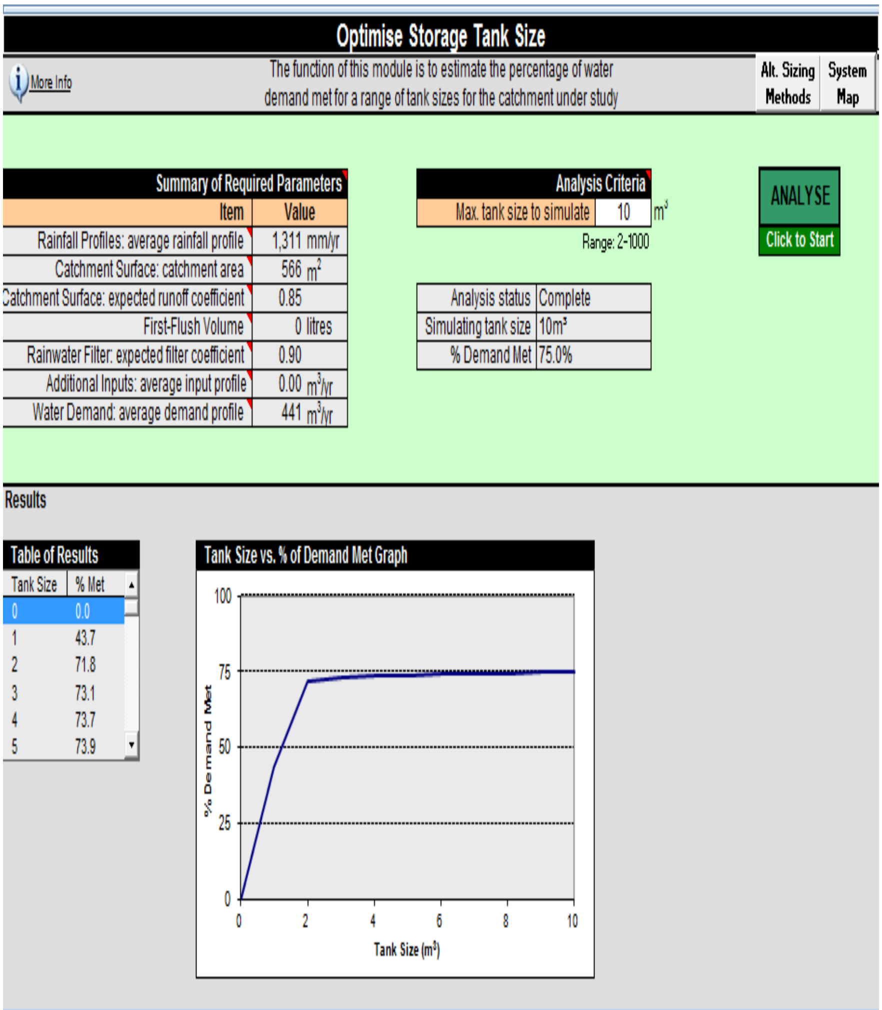
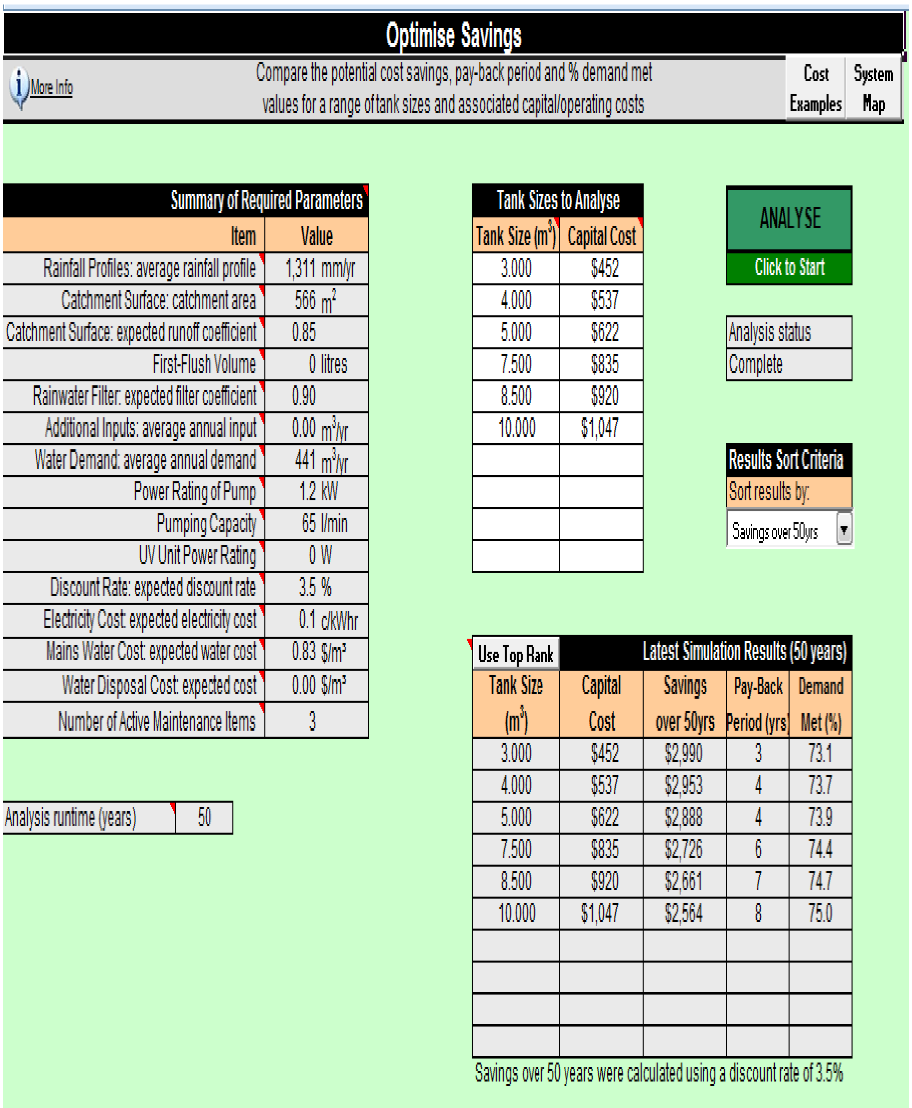


Figure 4 Results from optimising tank size.

4.6 Optimising saving results

Optimise saving analysis (Figure 5) showed that there were six tank sizes with a potential long-term profit. The best was the 10 m^3 tank, which was predicted to save $ 2,564 over 50 years and had a pay-back period of 8 years, which is typical for a current commercial system. Percentage demand met was good for a commercial system, at 75.0 % of predicted demand.

The 10 m^3 gave acceptable results and so the data for this tank was input into the Storage Tank module and WLC Details module and then the result in the Analysis System module examined. Figures 6 and 7 show the cost comparison graphs for both the long-term and average per-year analyses for this system.



Summary of Required Parameters	
Item	Value
Rainfall Profiles: average rainfall profile	1,311 mm/yr
Catchment Surface: catchment area	566 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	441 m^3/yr
Power Rating of Pump	1.2 kW
Pumping Capacity	65 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

Tank Sizes to Analyse	
Tank Size (m^3)	Capital Cost
3.000	$452
4.000	$537
5.000	$622
7.500	$835
8.500	$920
10.000	$1,047

Use Top Rank	Latest Simulation Results (50 years)			
Tank Size (m^3)	Capital Cost	Savings over 50yrs	Pay-Back Period (yrs)	Demand Met (%)
3.000	$452	$2,990	3	73.1
4.000	$537	$2,953	4	73.7
5.000	$622	$2,888	4	73.9
7.500	$835	$2,726	6	74.4
8.500	$920	$2,661	7	74.7
10.000	$1,047	$2,564	8	75.0

Figure 5 Results from optimising savings.

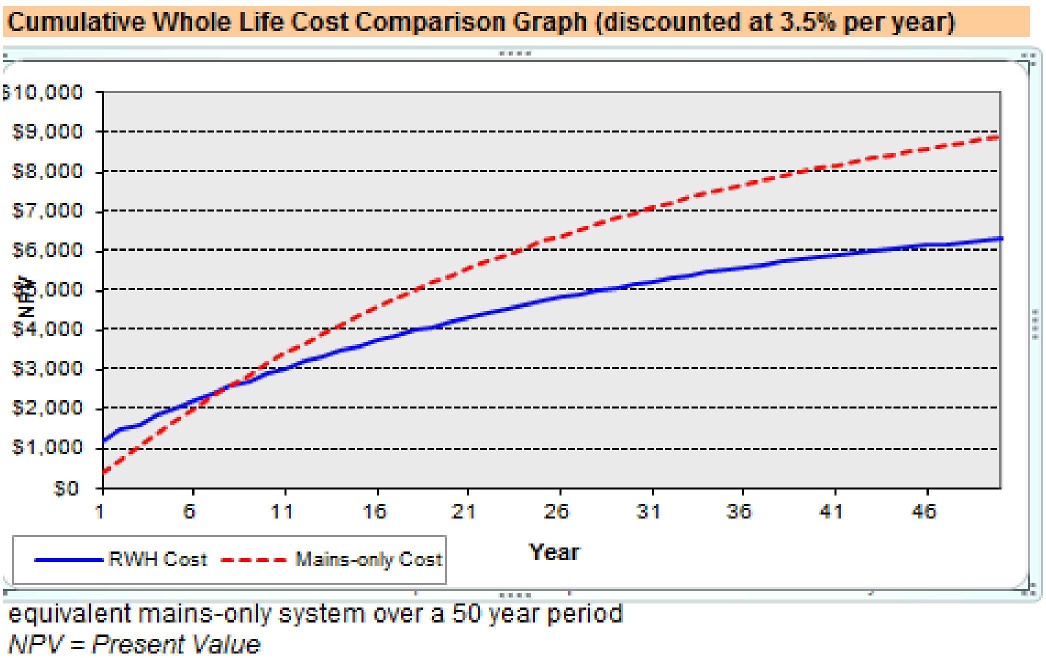


Figure 6 Cumulative long-term analysis cost comparison.

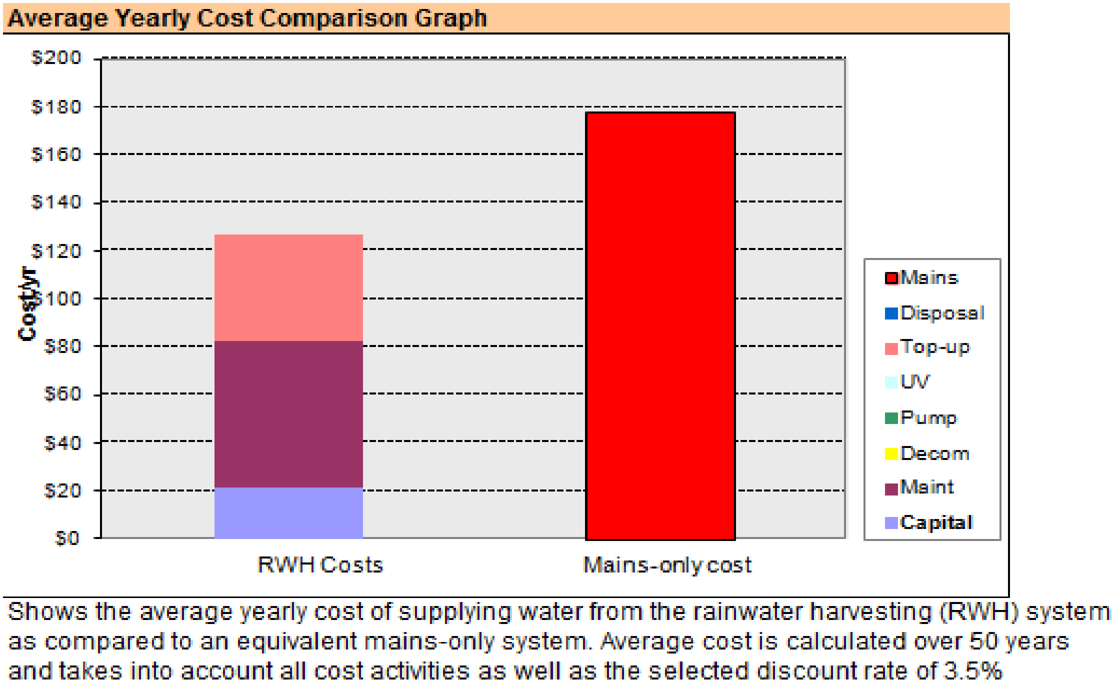


Figure 7 Average yearly cost comparison.

5. Conclusions

This study has presented the hydraulic and financial modelling of a RWHS using an office block with two floors in a University campus. A Raincycle model was used to optimise tank size and savings. Sensitivity analysis and Monte Carlo simulation were also carried out.

The proposed system was assessed using seven fixed and eleven variable parameters. The fixed criteria are: catchment surface area, first-flush volume, storage tank volume, pump power rating, pump capacity, UV unit power rating and UV unit operating time while the variable parameters are: 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.

Analysis of the case study reveals that the maximum percentage of demand that could be met was 75.0% with a tank size of 10 m^3. A savings of $2,564 over 50 years and a payback period of 8 years were predicted, which is typical for a current commercial system.

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