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EXAMINING THE EFFECTIVENESS OF RAINWATER COLLECTION SYSTEMS IN A NIGERIAN LEPER COLONY USING THE BEHAVIOURAL MODEL

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ABSTRACT

Rainwater from roof catchments can be a valuable source of water and can be quite safe to drink when stored in a properly installed and well maintained water storage system. It is noteworthy to observe the capacity intended for rainwater storage because this factor is a determinant to both its initial cost of construction and its effectiveness, especially during the dry season for the isolated lepers who are sited outskirts of towns and cities where the water mains does not get to. This paper examines the effectiveness of rainwater collection systems in a Nigerian leper colony using behavioral method, such that the relationship between the storage and the utility or demand was punctuated in terms of water saving efficiency. The data obtained were used to mathematically simulate the model algorithms using the time interval of an hour, a day and a month. The detailed analysis for the application of these time interval models were expressed in a dimensionless ratio known as the storage fraction, S/AR, where S = storage capacity (m^3), A = roof area (m^2), and R = average annual rainfall (m). The values obtained for the water saving efficiency using the YAS and the YBS algorithms shows that the YBS gives an exaggerated value for the data plots while the YAS operating algorithm showed a conservative estimate and could be use as a standard of comparison and calibration for other models. The hourly models can therefore be most effective for relatively small stores with storage fractions less than 0.014. Daily models can be used more effectively for stores with storage factions above 0.014 while the monthly time model for store capacities with storage fractions greater than 0.13.

Keywords: Rainwater harvesting, collection systems, roof catchment, water saving efficiency, sustainable water source.

List of symbols

R	Average annual rainfall (m)
Yt	Yield (m^3)
Dt	Demand (m^3)
Vt	Volume of rainwater (m^3)
Vt-1	Volume of water in tank from the time interval t–1(m^3)
Qt	Runoff into tank (m^3)
S	Capacity of the tank/ storage capacity (m^3)
A	Roof area (m^2)
D	Annual demand (m^3/yr)
ET	Water saving efficiency at time t
YAS	Yield after spillage
YBS	Yield before spillage
t	Time interval (hour, day, month)

1. INTRODUCTION

A safe and potable water is yearned for globally, one which can be easily harnessed when needed but nevertheless this necessity has proved somewhat difficult for the government and the non-governmental organisations who from day to day strife to meet the daily requirements of the masses. Many lepers communities all over the world are approaching the limits of their traditional water resources as thousands of lepers throughout the world still do not have access to adequate water a basic necessity for well being and development. The situation is even direr in developing country like Nigeria [1, 2, 3, and 4] where even the towns and cities lack adequate water supply [5, 6]. On the other hand, rainwater harvesting has drawn increased attention in many parts of the world as an economic and sustainable water source both for potable and non-potable use [7]. Hence the collection of rainwater from roof catchments and storage is a viable method of reducing water scarcity in leper colonies all over the world. As a general rule, rainfall should be over 50 mm/month for at least half a year or 300 mm/year to make Rain Water Harvesting environmentally feasible [8].

Without extensive treatment required rainwater can be suitable for a range of household chore such as drinking, WC flushing, clothes washing, garden irrrigation, and in some cases bathing. Rainwater harvesting has maintained its importance as water source for small scale agriculture and as a primary water source in the remote locations in the rural areas and islands, so this could be applicable for the lepers who are sited outskirts of cities where the water mains are inaccessible [9, 10]. Rainwater harvesting has become a popular supplement for potable water to reduce the demand on the conventional water supplies even in the cities where the surface water is polluted or the groundwater is over extracted due to rapid increase in population. The cost of rainwater collection tend to be quite small but the largest economic consideration is the initial capital cost to construct the collection system. In lepers' colony, rural areas and even in some urban households where rainwater is valued it could be harnessed with bowls, buckets, jerry cans, tanks etc. But in the case where there is need to utilize this natural water source maximally, the

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construction of a storage system is required and the most important design decision is how much storage capacity to build as it is important to note that the capacity of the rainwater stored is very crucial both economically and operationally. In this paper, a Nigerian leper colony was selected for investigation; the behavioral model was incorporated into the data acquired from the colony such that the time interval was incorporated into the model algorithms to observe the water saving efficiency.

1.1. Previous work

Rainwater harvesting system primarily consists of collection and subsequent use of captured rainwater as either the principal or supplementary source of water.

All rainwater harvesting systems share a number of common components:

a) A catchment's surface from which runoff is collected e.g. roof surface.
b) A system for transporting water from the catchment's surface to a storage reservoir, known as the delivery systems.
c) A reservoir where water is stored until needed (storage system).
d) A device for extracting water from the reservoir.

The size of the storage tank is the major cost challenge of constructing a rainwater harvesting system and so requires serious consideration. A vivid description and understanding of the behaviour of the system in operation was described by Mitchell [11]. A schematic diagram of the various components of a storage tank is shown in Figure-1.

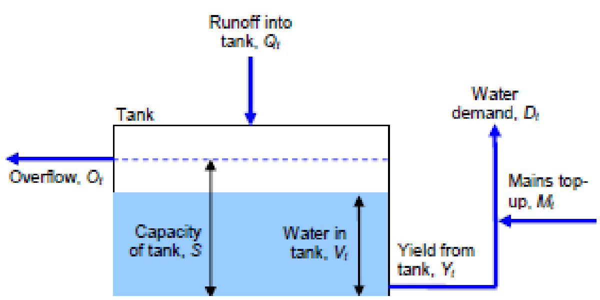

Figure-1. Typical RWH storage tank configuration used in behavioral models (Source: Mitchell, 2005).

Where

Y_t = yield (withdrawal) from the tank in time t (m³)
O_t = overflow from the tank in time t (m³)
M_t = volume of mains top-up required in time t (m³)
V_t, Q_t, D_t and S are as previously defined.

In relation to the operation of the storage device, the following was incorporated; the fundamental water runoff into the tank, Q_t; mains top-up, M_t; overflow, O_t; water demand, D_t; water in the tank, V_t; capacity of tank, S; and yield from tank, Y_t. Tank flux elements consist of the runoff into the tank (inflow), Overflow from the tank and the yield extracted from the tank. The behavioral model used in this paper was first developed by Jenkins [12] using two basic algorithms to describe the performance of a rainwater storage system. The Yield after spillage algorithm rule (YAS) and the yield before spillage operating algorithm rule (YBS):

The YAS rule describes the yield to be the lesser of the demand or the previous volume of water in the store at time t-1 as given in equation (1). It also prescribes the volume in the tank at time t to be the lesser of the sum of the previous volume and discharge less the yield or the store less the yield as shown in equation (2) below.
Mathematically:

$$Yt = min\begin{cases} Dt \\ Vt - 1 \end{cases} \quad (1)$$

$$Vt = min\begin{cases} Vt - 1 + Qt - Yt \\ S - Yt \end{cases} \quad (2)$$

The graphical representation of this algorithm is shown in Figure-2 below. The figure shows that the yield is practically extracted from the tank after the runoff into the tank has been recorded and this is given as the previous volume of water in the tank. After the yield has been extracted with respect to the water demand then the volume at time t was taken. The YBS algorithm prescribes the yield as the minimum of the demand at time t or the sum of the previous volume at time t-1 and the discharge at time t, mathematically shown in equation (3). The volume at time t is given as the minimum of the sum of the previous volume at time t-1 with the discharge at time t less the yield at time t or the value of the capacity of the store as illustrated in equation (4).
Mathematically:

$$Yt = min\begin{cases} Dt \\ Vt - 1 + Qt \end{cases} \quad (3)$$

$$Vt = min\begin{cases} Vt - 1 + Qt - Yt \\ S \end{cases} \quad (4)$$

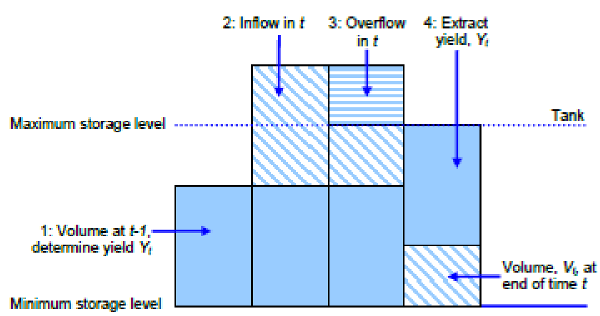

Figure-2. Graphical representation of YAS algorithm (Source: Mitchell, 2005)

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The graphical representation of the YBS algorithm is given in Figure-3 and it shows that the yield is extracted directly from the runoff such that the volume at time t is at maximum i.e., equal to the capacity of the store and the previous volume of water in the store is the volume that exists initially in the store and it is assumed that water demand is met for that period without substantial reduction in the volume at time t which would be available for use in the future. A number of researchers have investigated the YAS/YBS operating algorithms for the sizing of rainwater tanks [12, 13, 14, 15, 16, and 11], amongst others. This work has further extended the use of the operational algorithm for predicting the effectiveness of rain water storage in a Nigerian leper colony.

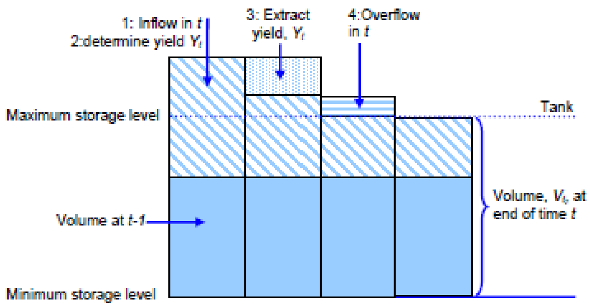

Figure-3. Graphical representation of YBS algorithm (Source: Mitchell, 2005).

2. METHODOLOGY

2.1. Investigation approach

The performance of rainwater collector depends on the size of the collection system. Behavioral model use a mass–balance transfer principle and are based upon a discrete time interval of a minute, hour, a day or month [14]. The present investigation extends the use of the model to access the water saving efficiencies of water collection systems in a Nigerian leper colony, using a range of available store capacities and two adoptable roof areas of 248 m^2 and 131m^2, respectively. Seven ranges of store capacities were adopted for each roof area and the dimensionless ratios were evaluated for each. The water saving efficiency of the installation was measured over a monitoring period of six months. Results obtained were simulated into the model algorithms using the hourly, daily and monthly time intervals and compared with the measured water saving efficiencies of the system. Two dimensionless ratios namely the demand fractions and the storage fractions were used to express the combination of roof areas and store capacity.

The demand fraction given as D/AR,

Where

D = annual demand (m^3)
A = roof area (m^2)
R = rainfall (m)

The storage fraction is given as S/AR,

Where

S = storage capacity (m^3)
A and R as described above

These dimensionless ratios were used because each demand fraction and storage fraction represents many different combinations of demand area and storage [7, 17]. It is of importance to note that the demand fractions were chosen to be representative of the range of roof collection areas encountered in the study area. The demand was obtained from the acqisition of raw data from the study area. Data such as; the average water consumption (litres per person) and the water consumption of the number of persons that withdraw water from the store daily (person/day) were obtained from the lepers. These values were multiplied and were used to obtain the given demand in litres per day.

However, having obtained the storage fractions for the different sizes of stores under consideration, the volume of water in each of the tanks at the time interval under consideration was taken (Vt). The value of this volume at time (t) was used to determine the previous volume at a time interval before t given as t-1 as given in the equation for the model algorithms; the previous volume obtained was now used to evaluate the yield as given in equations (1) and (3) for the YAS and YBS, respectively.

2.2. Study area

A Nigerian leper colony with an average of eight months yearly rainfall and mean annual rainfall of 1, 400mm was selected, a twenty year annual rainfall data for the study area is as shown in Figure-4. All the lepers in this colony depends extremely on rainfall as their source of potable water and have the rainwater harvesting systems at their residence for easy access due to the inability to walk far distances as a result of disability in the limbs (fore and hinge). Two roofs area was selected which serves 16 and 18 lepers respectively. The average annual rainfall for the location was obtained from the Nigerian Metrological Agency in 2010 as shown in Figure-4 and was used to estimate the average annual rainfall for the study area.

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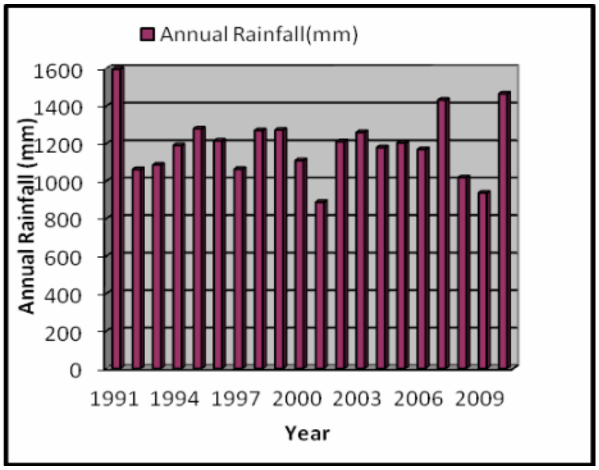

Figure -4. Annual rainfall for the study area (1991-2010)

3. RESULTS AND DISCUSSIONS

3.1. Rainfall data and estimation of daily water demand

Daily demand per head per day was estimated as shown in Table-1. However, due to none availability of large storage the lepers make do with the available stores within the colony to charter for immediate need. Table-2 shows the average pattern of rainwater usage by daily activity per head per day.

Table-1. Approximate daily water consumption.

Activity	**Water usage** (l/h/day)
Bathing	20
Cloth washing	20 – 30
Dish washing	5 – 10
Food washing	10
Food preparation	10
Drinking	2
Total	67 – 82

Table-2. Typical average rainwater utilized by activity.

Rainwater usage	**Volume** (Liters /h/day)
Cooking	10
Dish washing	6
General washing	12.5
Drinking	2
Total	30.5

Table-3 shows two different roof areas with varying store capacities as expressed in terms of two dimensionless ratios, namely the demand fraction and the storage fraction. The performance of rainwater harvesting system with the demand fractions of 0.504 and 1.072 with storage fractions ranging from 0.00071 - 0.03619 and 0.00179 - 0.0911 for roof 1 and roof 2, respectively were examined with annual rainfall R = 1.426 m/yr.

Table-3. Demand and storage fraction for roof 1and 2.

S (m^3)	**D/AR = 0.504 D = 178.12 m^3/yr A = 248 m^2 S/AR**	**D/AR = 1.072 D = 200.39 m^3/yr A = 131 m^2 S/AR**
0.25	0.00071	0.00179
1.00	0.00283	0.00712
3.20	0.00947	0.02280
5.00	0.01410	0.03560
6.40	0.01810	0.04550
10.00	0.02827	0.07120
12.80	0.03619	0.09110

3.2. Water saving efficiency

The performance of a rainwater collection system was evaluated relative to its water saving efficiency which is given as (ET). This is the amount of water that has been conserved in the mains in comparison to the overall demand of water. In this case it is assumed that the water in the collection system is used only for activities identified in Table-2 while other usage are sort for from other available sources and the overall demand is how much water is withdrawn from the storage tank in the various time intervals considered.

Water saving efficiency is usually expressed as a percentage, which is given as:

$$ET = \sum Yt / Dt \times 100$$

It is pertinent to determine the percentage of the water saving efficiency of each store because this will assist in knowing how sufficient a given capacity can satisfy a given demand. The values of the water saving efficiency for each store under the YAS and the YBS operating algorithms were determined and represented in Figures 5-8 where these values were juxtaposed with the storage fractions to plot the set of curves that was used to predict the effectiveness of the collection systems.

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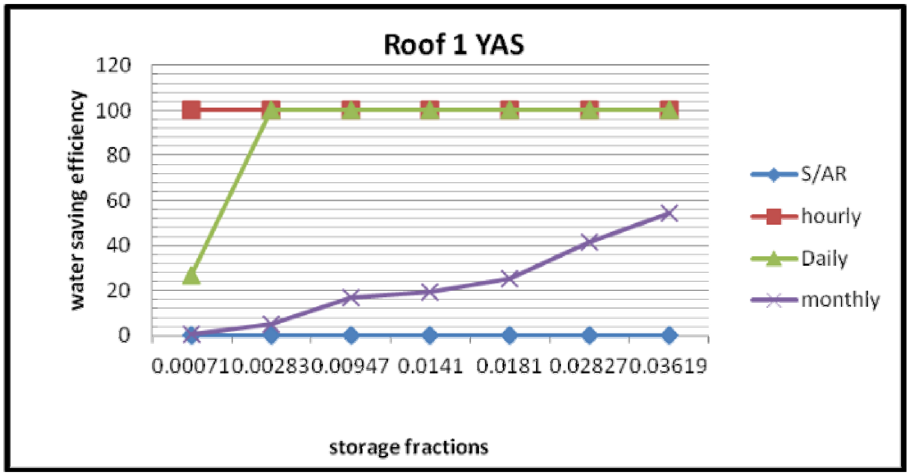

Figure-5. Water saving efficiency against the storage fractions at different time intervals.

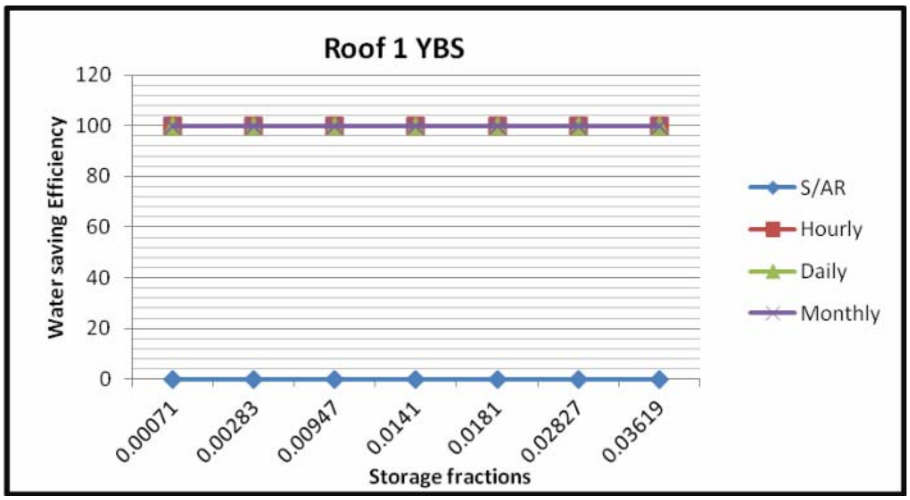

Figure-6. Water saving efficiency against the storage fractions at different time intervals.

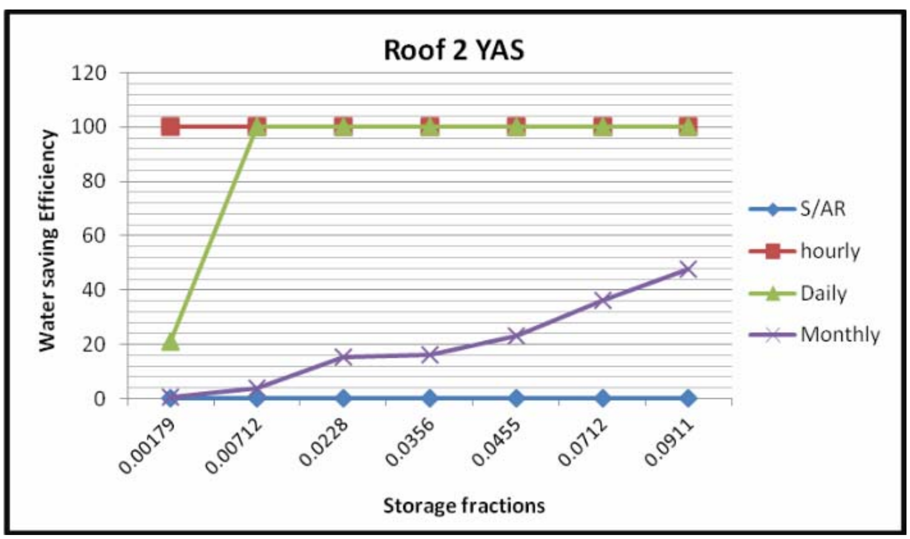

Figure-7. Water saving efficiency against the storage fractions at different time intervals.

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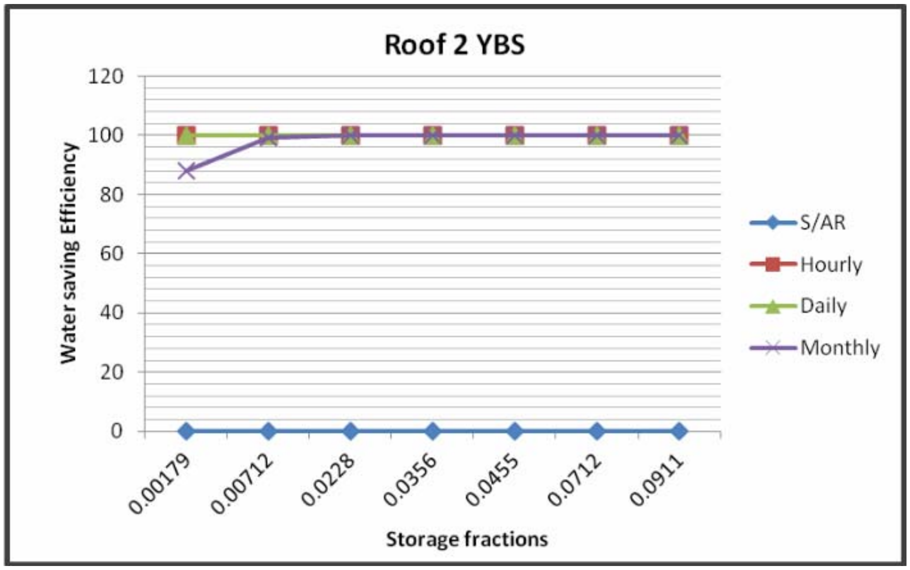

Figure-8. Water saving efficiency against the storage fractions at different time intervals.

The hourly and the daily plots appear to coalesce at a point for the YAS and are continuous along the graph having an increasing water saving efficiency that tends towards an optimum reliable effectiveness of 100%. On the other hand, the monthly performance exhibited a low efficiency with small stores, though the efficiency increases with larger stores but less than 100% throughout compared to the hourly and the daily performance as it is seen in the performance curve (Figures 4 and 6). This can be attributed to the fact that relatively small stores were under consideration and available for the purpose of this study.

It can also be deduced analytically from the performance curves that as the values of the storage fractions increases the monthly efficiency also increases and it is assumed that a point of increment would be reached when the monthly efficiency would be a hundred percent efficient for YAS algorithm given that the storage capacity is large enough to produce a maximum value of storage fraction. The YBS on the other hand gives almost the same water saving efficiency irrespective of the storage fraction (Figures 5 and 8) except for the initial small store which gave a low monthly efficiency from the second roof (Figure-8). The YBS has been found to give an exaggerated value for the performance of a rainwater harvesting system, this can be attributed to the fact that the YBS model conserves the water in the store such that volume at time t remains the volume of the store after the yield is extracted. The hourly and daily model maintains a consistency in efficiency as the store capacity increases unlike the monthly time model.

3.3. Theoretical evaluation of the collection system

This method was adopted for the purpose of comparison with the behavioral model. It is simple enough and direct unlike the behavioral model and can be easily understood. This was evaluated by calculating the hourly, daily and monthly water demand in comparison to the volume of rainwater stored in each of the tanks, for a particular interval of time from each of the roofs.

Table-4. Demand at different time interval from the two roofs.

Demand	Roof 1	Roof 2
Hourly demand (litre / hour)	20.3	22.88
Daily demand (litre / day)	488	549
Monthly demand (litre /month)	15,128	17,019

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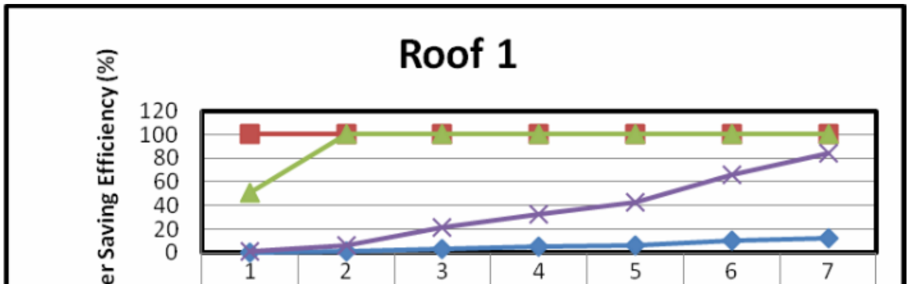
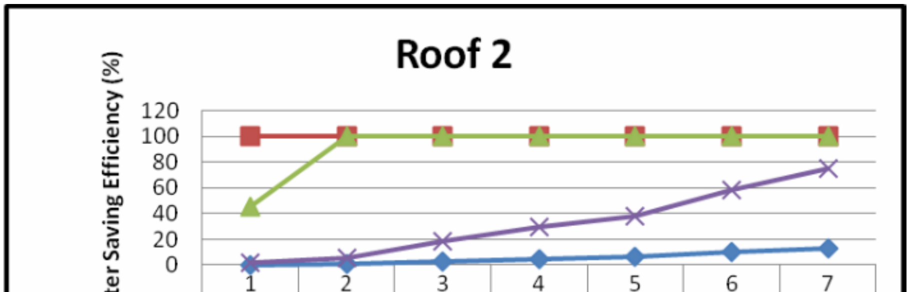


	1	2	3	4	5	6	7
S(m3)	0.25	1	3.2	5	6.4	10	12.8
Hourly	100	100	100	100	100	100	100
Daily	51.23	100	100	100	100	100	100
Monthly	1.65	6.61	21.15	33.05	42.31	66.1	84.61

Figure-9. Water saving efficiency against different storage capacity.



	1	2	3	4	5	6	7
S(m3)	0.25	1	3.2	5	6.4	10	12.8
Hourly	100	100	100	100	100	100	100
Daily	45.54	100	100	100	100	100	100
Monthly	1.47	5.88	18.8	29.38	37.61	58.76	75.21

Figure-10. Water saving efficiency against different storage capacities.

It can be seen that Figures 9 and 10 is comparable and is similar with the YAS algorithm (Figures 5 and 7), though the daily and monthly water saving efficiency were lower for the YAS algorithm, the algorithm is quite useful for designing and planning a rainwater storage structure.

Generally in comparison to the time models which involves a more standard and complex calculations it was seen that the results were highly predictive of a reliable performance and in agreement to the practical direct approach method which describes how well the store can perform even after the rainfall period has elapsed.

4. CONCLUSIONS

The effectiveness and performance of rainwater collection systems in a Nigerian leper colony was examined with behavioural model. The model incorporates different time intervals applied to a range of demand and storage fractions using different reservoir operating algorithms which were applied to a range of operational conditions. The hourly and the daily time intervals predicted astounding performances for the storage fractions but the monthly time interval predicted a less water saving efficiency, though water saving efficiency increases with increase in stored capacity. The values obtained for the water saving efficiency using both operating algorithms YAS and the YBS with respect to the performance curves shows that the YBS gives an exaggerated or ambiguous value for the data plots. In most cases the YAS operating algorithm is usually sufficient for the generation of the curves to predict the performance of a rainwater harvesting system but a comparative study of both algorithms gives a more reliable and precise solution.

Hourly model can be used effectively for stores with small ranges of storage fractions less than 0.014, daily model can be used more effectively for the determination of stores with storage factions above 0.014 while the monthly time interval can be used most effectively for store capacities with storage fractions greater than 0.13. Results indicated that the YAS model could be used as a standard of comparison and could be used to calibrate other models. It is important to note that the YAS reservoir operating algorithm gives a conservative estimate of the water saving efficiency irrespective of the model time interval and is therefore preferred to the YBS operating algorithm for design purposes in this study area. However, appropriate rain water treatment and system operation should be incorporated into the design and planning of a rainwater storage system.

It is recommended that subsequent work be extended to other regions of Nigeria having spatial rainfall patterns and also to regions having a more recurrent rainfall pattern outside the study area so that comparison can be made with the same model.

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