Analysis of Storage-Estimation Techniques for Optimal Rainwater Reservoir Sizing

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ABSTRACT
Rainwater harvesting (RWH) is an appropriate technology that has been in use for a long time, yet it remains a partial solution to meeting water needs. RWH systems are installed with inefficient rainwater reservoirs unable to supply rainwater year long. As a result, the potential of RWH is not fully realised. In Uganda, wet season RWH is common throughout the country. This paper aims at establishing an optimal rainwater reservoir size for a given rainfall distribution and water demand pattern that can meet water supply needs throughout the year. Mass curve analysis, behaviour analysis and Gould's probability matrix method were the storage-estimation techniques analyzed. Mass curve analysis considers all the input parameters. Behaviour analysis simulates the operation of the reservoir with respect to time by routing simulated inflows through an algorithm that describes the operation of the reservoir. Gould's probability matrix allows for seasonality of flows, serial correlation of inflows and use of non-continuous data. Historical rainfall records and water demand pattern for monthly and daily time-steps were used as inputs into reservoir capacity relationships. Time-based reliability and volumetric reliability were the performance measures that were examined. Traditional rainwater reservoir sizing approaches were also examined. Makerere University main hall was used as a study area and catchment area-demand-storage relationships were presented. As a result, a curve showing the relationship between volumetric reliability and storage capacity was generated as a guide for optimal rainwater reservoir sizing in the region.

Keywords: Demand pattern, Reliability, Reservoir performance, Storage capacity, Time-step

1.0 INTRODUCTION

Several Rainwater Harvesting (RWH) systems are in existence. RWH is a relief to the strain exerted on already stressed water resources (Meera and Ahammed, 2006). The rainwater reservoir is a crucial component in of a RWH system. The analysis of several storage-estimation techniques for the proposed Makerere University Main Hall rainwater reservoir located 2.5km from Kampala city, on Makerere Hill; Kampala, Uganda forms the focus of this study, as shown in Figure 1. The main hall was experiencing interrupted water supply that disrupted the functioning of the water closets. Chilton *et al*. (2000) states that properly designed RWH systems can considerably reduce potable water demand for non-potable water uses. Many rainwater reservoirs are simply installed and they exhibit storage capacity inadequacies with cases of frequent overflow and short term storage periods (Ngigi, 1999). The reservoir affects the economics, performance and operation of the system (Fewkes and Butler, 2000). This creates a need to maximise the use of rainwater through optimising storage. An optimal technique catering for the different variables, which ensures long term storage and satisfies the demand is therefore necessary.

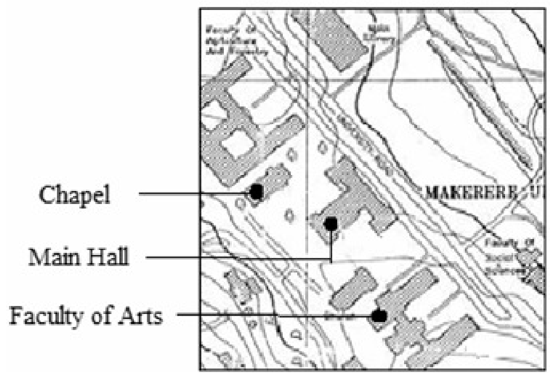

Figure 1: Map showing location of Makerere University Main Hall

2.0 METHODOLOGY

This paper presents the findings of a research effort that analysed storage-estimation techniques for optimal rainwater reservoir sizing (Mutesi, 2009). The study also considers the demand and supply side approaches that have been used to size rainwater reservoirs for a long time. The specific objectives were to investigate the reservoir performance as regards to the different sizing methods, examine the techniques with the aim of recommending the ones most suitable for particular storage requirements, develop a storage yield performance (S-Y-P) relationship for the proposed Makerere University Main Hall rainwater reservoir and estimate the most optimal reservoir size for the specified catchment area. The following were done to achieve the aforementioned objectives:

(i) Information about rainwater reservoir sizing and performance was obtained from various sources.
(ii) Site inspection. The information acquired during the site inspection was (a) the catchment area of the main hall; (b) the historical rainfall records; and (c) the occupancy of the main hall.
(iii) Analysis of the available data about the rainfall, catchment area and water demand pattern.

The rainwater reservoir sizing methods were limited to the mass curve, behaviour analysis and Gould's probability matrix for their inherent qualities that catered to the study area and design. The variables that were necessary to describe the reservoir dynamics were as defined in Koutsoyiannis (2005).

3.0 RESULTS

The following paragraphs summarize the findings of the site inspection and data collection.

3.1 Consistency Test

A linear relationship was observed in the double mass curve plotted indicating that the trend in Makerere Weather Station rainfall data was solely due to meteorological conditions and independent of gauging.

3.2 Rainfall Data

The maximum peak daily rainfall was decreasing with increasing years and took a period of 7 to 8 years to re-occur see Figure 2.

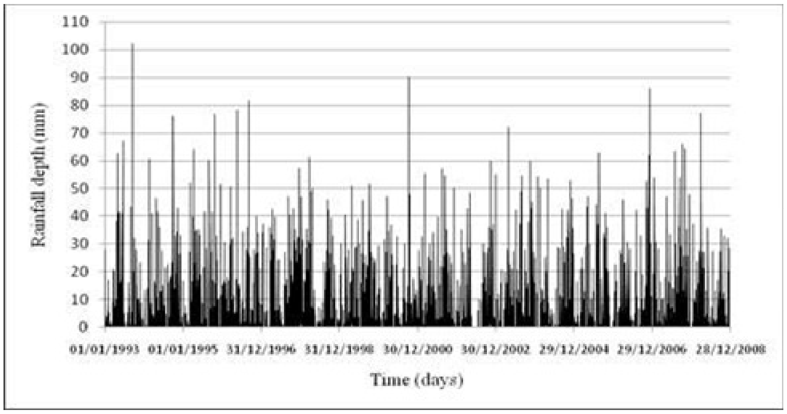

Figure 2: Daily rainfall hyetograph.

3.3 Catchment Area

A catchment area of 1954 m^2 was available to act as catchment area. Initial losses, *I* of 0.32mm and runoff coefficient, C_R of 0.9 were considered.

3.4 Water Demand

The rainwater harvested from the rooftop is for non-potable water use. Figure 3 shows the water demand pattern.

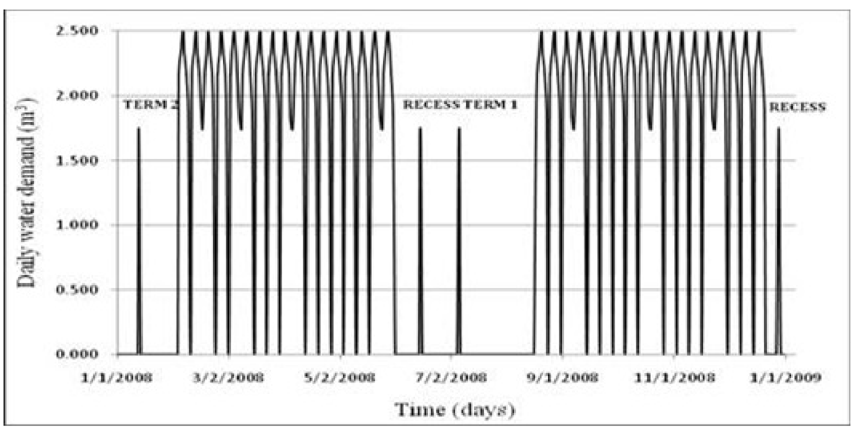

Figure 3: Variation of daily demand per year

4.0 ANALYSIS OF RESULTS

4.1 Mass Curve Analysis

In the storage capacity calculations, symbols as defined in Butler and Memmon (2006) were used, where S is the storage capacity, D_t is demand during time interval t, and Q_t is the inflow during time interval t. The storage capacities obtained through a simulation of Equation 1 were 333 m^3 and 179 m^3 while using the monthly time-step and daily time-steps respectively.

$$S \geq \max\left\{\int_{t_1}^{t_2} [D_t - Q_t]dt\right\},\ t_1 < t_2 \tag{1}$$

A comparison of storage sizes obtained using daily and monthly rainfall data was obtained for various sizes of catchment area, as shown in Figure 4. In daily time-step calculations, an increase of $0.09m^3$ in storage capacity per unit catchment area was experienced. For small catchment areas, the storage capacity obtained using the monthly time-step increases at the same rate as storage capacities obtained using daily time-steps. At approximately 25 percent of the total catchment area, the increase in storage capacity doubles. 0.25 increments of the total catchment area corresponding to unit increments of constant water demand within which the variable water demand lies may be used to size the reservoir.

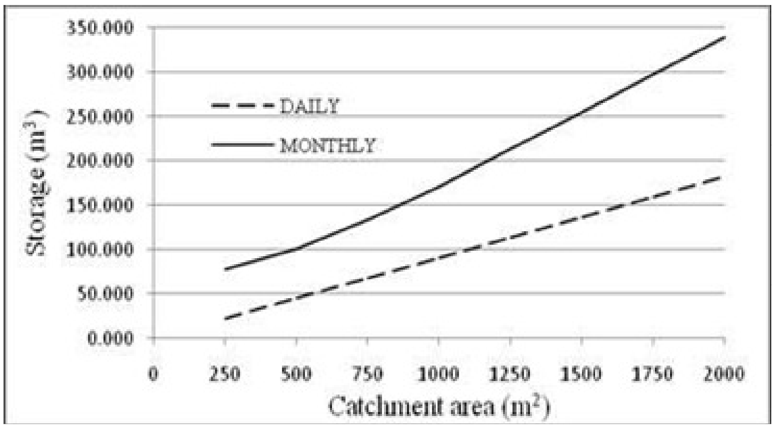

Figure 4: Comparison of storages obtained using daily and monthly time-steps

Storage capacities obtained were also influenced by the historical rainfall data period. The more years used in the analysis, the greater the storage sizes obtained. For every additional 2 – 4 years historical period increment, a $0.01m^3$ increment in storage capacity per unit area was experienced.

4.2 Behaviour Analysis

In the storage capacity calculation, symbols as defined in Liaw and Tsai (2004) were used, where S is the storage capacity, D_t is demand during time interval, t, Q_t is the inflow during time interval, t, Y_t is the yield during time interval, t as shown in Figure 5. The storage capacities obtained through a simulation of Equation 2 were 122 m^3 and 74 m^3 while using the monthly time-step and daily time-steps respectively.

$$Y_t = \min\begin{cases} D_t \\ V_{t-1} \end{cases} \qquad V_t = \min\begin{cases} V_t + Q_t - Y_t \\ S - Y_t \end{cases} \tag{2}$$

The storage capacities needed to satisfy the constant water demands are reducing in size with increase in catchment area size, see Table 1. The contribution of the low rainfall depths received is increased thus decreasing the need to have larger reservoir sizes.

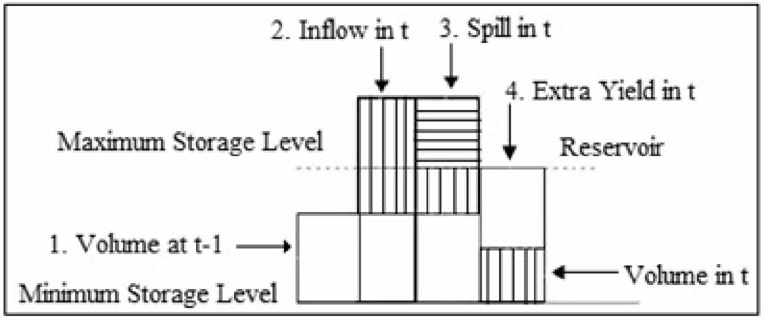

Figure 5: Yield After Storage (YAS) algorithm

Table 1: Catchment area-demand-storage relationship

Catchment Area (m^2)	250	500	750	1000	1250	1500	1750	2000
Constant demand(m^3/day)			Storage (m^3)					
1	958	74	65	61	57	52	48	45
2	6772	1916	173	147	136	130	126	121
3	12586	7730	2874	317	230	220	209	199
4	18400	13544	8687	3831	600	345	303	293
5	24214	19358	14501	9645	4789	1218	488	391

The performance of the rainwater reservoir for various storage sizes was established using monthly rainfall data and daily rainfall data, see Table 2 and Table 3 respectively.

Table 2: Reservoir performance using monthly rainfall data

Storage sizes (m^3)	25	50	75	100	125
Time-based reliability, R_{mtd}	0.25	0.33	0.42	0.67	1
Volumetric reliability, R_v	0.27	0.49	0.70	0.88	1

Table 3: Reservoir performance using daily rainfall data

Storage (m^3)	10	20	30	40	50	60	70	80
Time-based reliability(storage) R_{dts}	0.86	0.95	0.98	0.99	1	1	1	1
Time-based reliability (demand) R_{dtd}	0.83	0.95	0.98	0.99	1	1	1	1
Volumetric reliability, R_v	0.77	0.93	0.97	0.99	1	1	1	1

Using the monthly time-step, the volumetric reliability, is greater than the time-base reliability, because of the lumping of the water demand. When using daily rainfall data in the simulation, time-based reliabilities are approximately equal.

4.3 Gould's Probability Matrix Method

In the storage capacity calculation, symbols as defined in McMahon and Mein (1978) were used. Using monthly rainfall data, the storage capacities as obtained using behaviour analysis were checked using Gould's probability Matrix method shown in Table 4.

Table 4: Reservoir performance using Gould's probability matrix method

Storage size (m^3)	**25**	**50**	**75**	**100**	**125**
Time-based reliability(storage), R_{dts}	0.995	0.995	0.995	0.995	0.995
Time-based reliability (demand), R_{dtd}	0.286	0.365	0.447	0.682	1.000
Volumetric reliability, R_v	0.302	0.511	0.709	0.882	1.000

4.4 Traditional RWH System Storage Sizing Approaches

Rainwater reservoir sizing methods as defined in Pacey and Cullis (1986) were used. Using the Demand Side Approach, the storage capacity required was 50m^3. The Supply Side Approach yielded a storage capacity of 1844 m^3.

5.0 DISCUSSION

Mass curve analysis was sensitive to variable demand patterns, shown in Table 5. The volumetric reliability was the determining reservoir performance measure.

Table 5: Comparison of mass curve analysis and behaviour analysis

Analysis using daily rainfall data								
Behaviour analysis								
Catchment area (m^2)	250	500	750	1000	1250	1500	1750	2000
Storage (m^3)	2843	114	82	80	78	77	75	74
Mass curve analysis								
Catchment area (m^2)	250	500	750	1000	1250	1500	1750	2000
Storage (m^3)	23	46	69	92	115	137	160	183

When traditional approaches were used, they did not consider the variability of the demand and rainfall. There is an under estimation of storage size when using the demand side approach and over estimation of size when using supply side approach as compared to when daily time-step was used in behaviour analysis.

6.0 CONCLUSIONS

From the foregoing analysis and discussion, it can be concluded that:

(i) The Mass curve analysis could not compute a storage size for a given reliability. Small rainwater reservoir sizes need to be computed using the daily time-step.

(ii) Mass curve analysis maximised storage with increasing rainfall runoff. Behaviour analysis and Gould's probability matrix method achieved optimality in storage while incorporating seasonality of inflows.

(iii) The volumetric reliability was found to be the reservoir performance determining measure, see Figure 6.

(iv) The most optimal size for the rainwater reservoir is 74 m^3 obtained from the behaviour analysis method using daily rainfall data.

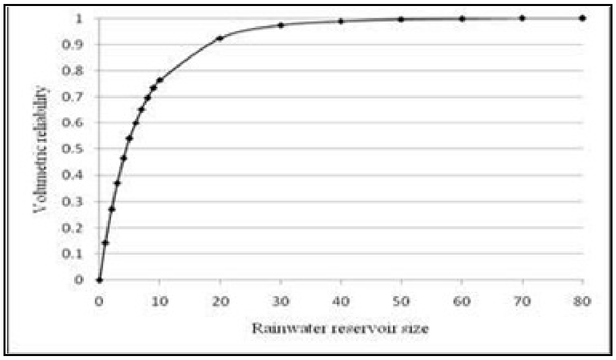

Figure 6: Storage yield performance relationship

Basing on the analysis carried out rainwater harvesting is a viable option for water supply to main hall. It is recommended that research be carried out on how to incorporate reservoir performance into mass curve analysis technique and a solar water pumping system should be designed to enable distribution of water.

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