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IMPACT OF THE VARIATION OF STORAGE VOLUMES IN CASCADING MULTI-TANK RAINWATER HARVESTING SYSTEMS

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ABSTRACT

Rainwater harvesting is perceived as an acceptable method of supplementing the reticulated service water supply, particularly in water stressed locations. Mostly used as stand-alone types for the provision of service water for secondary purposes such as laundry, the biggest drawback in Rain water Harvesting (RWH) systems is its rainwater storage tank occupying a considerable space depending on the daily demand for water, roof collection area and the average rainfall depth. Attempts have been made to optimize the storage tank capacity for a desired Water Saving Efficiency (WSE) with the aim of reducing the size of the tank which would also allow the tank to be placed just below the roof level to feed the service points through gravity. Still the weight and volume of the tanks can be high particularly for high demand, multi-storey situations. To address the problem, Cascading Multi Tank Rain Water Harvesting (CMTRWH) systems have been introduced with the storage capacity distributed among floor levels where the upper level feeder tank capacities can be restricted to as low as 1 m^3 posing a minimum disturbance to the building envelop, but the parent tank which collects only the excess roof runoff cascading down from the feeder tanks still occupies a considerable space at the ground level. If the storage volume of the parent tank can be further reduced while having a marginal effect on the overall water saving efficiency, it could have a significant impact on minimizing the system cost.

Key words: Rainwater, cascading, multi-tank, energy efficient, parent tank, stand-alone, optimize

INTRODUCTION

The storage tank of a Rain Water Harvesting (RWH) system is the component that by far costing the most compared with the other two main components, namely, the collection surface, which is usually the roof of the building, and guttering which convey the roof collection to the storage tank. Therefore, optimizing the storage tank capacity (S) for a given annual demand (D), roof collection area (A) and an annual average rainfall depth (R) is of importance if RWH systems to proliferate. Taking the daily service water demand is user specific and therefore is constant [3], and that all storage tanks individually and collectively obey Yield After Spillage (YAS) reservoir behavioral algorithm [4] a set of generalized curves which are independent of the spatial and temporal fluctuations of rainfall has been developed for Water Saving Efficiency (WSE) or η of a generic RWH system [2] (Fig. 1). Depicting WSE against location and collection area independent storage fractions S/AR for a given set of demand fractions D/AR, where $0.25 \leq D/AR \leq 2.0$ and $S/AR \geq 0.005$ the curves can be used effectively to determine the optimum storage capacities in RWH systems. Taking into consideration the requirement of providing the harvested rainwater to service points in an energy efficient manner and also with minimum structural and aesthetic disturbance to the building envelop, Cascading Multi-Tank Rain Water Harvesting (CMTRWH) systems have been introduced [6] which are particularly suitable for multi-level buildings.

A CMTRWH system consists of feeder tanks of typically 1 m^3 capacity for each floor level and a parent tank at the ground level to collect the cascading excess roof runoff which is pumped up to the uppermost feeder tank to sustain the cycle, enhancing the overall WSE. The pump is triggered on by a floater switch arrangement monitoring the water level at the lowest level feeder tank. The parent tank capacity (S_P) is usually taken to complement the difference between the cumulative volume of feeder tanks and the storage volume of an equivalent conventional RWH system in order to achieve a comparative WSE. If however, the capacity of the parent tank (S_P) can be optimized with minimum impact on the performance of a CMTRWH system, it will significantly reduce the foot print of the parent tank while reducing the overall cost. The result will be more important for single and two storey houses with cascading two or three tank rainwater harvesting systems.

Since RWH is prolific at household level, the study is focused more on Three Tank and Two Tank models suitable for two and single storey houses respectively.

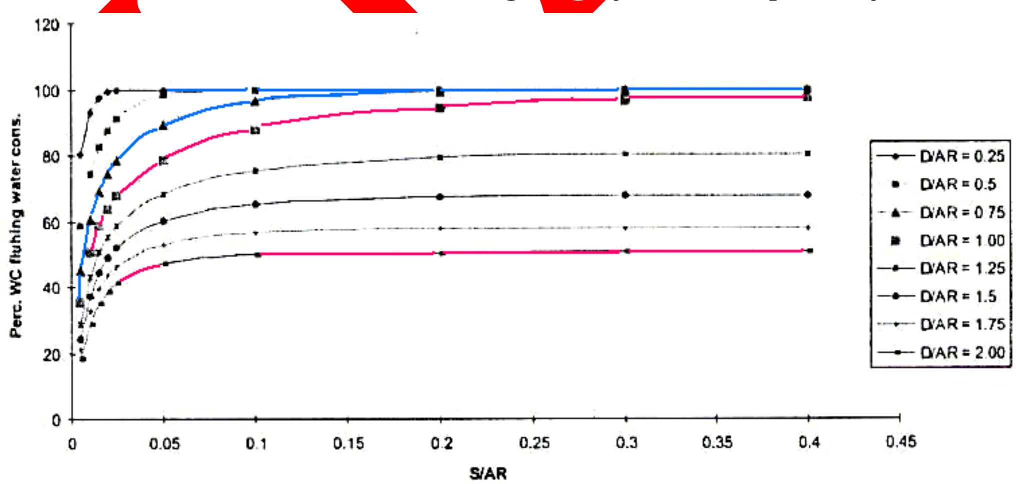

Figure 1: Generalized curves for WSE

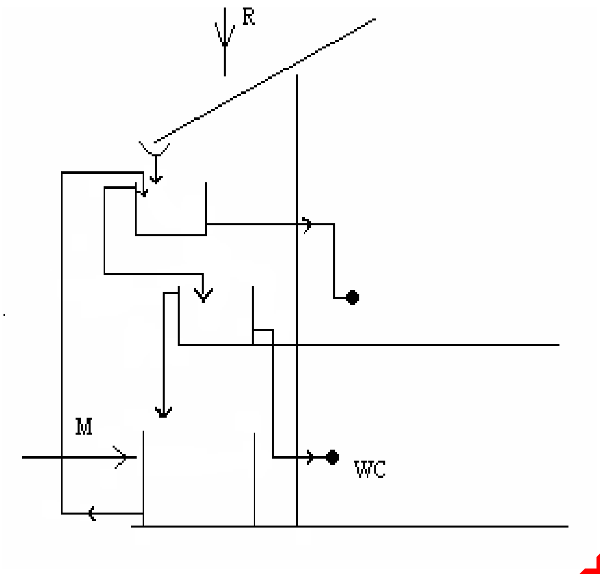

Figure 2: CMTRWH system for a two storey house

OBJECTIVE

The objective of the study is to investigate the impact of the variation of the storage capacity of parent tanks (S_P) on the quantities of collected rainwater that can be pumped up (Q) and therefore on the overall WSE of cascading two and three tank rainwater harvesting systems in single and two storey houses. The study also attempts to determine the threshold values for S_P for D < AR, D = AR and D > AR scenarios for given D, A, and R values while maintaining the feeder tank capacities at 1 m^3 for the minimum disturbance on the building envelop.

CALCULATIONS

In CMTRWH systems, for a given set of parameters D, A, R, S_P and feeder tank capacity at the i^{th} level S_i, the quantity of collected rainwater that is possible to be pumped up from the parent tank (Q) is given by,

$$Q = \eta_P \left\{ \sum_{i=1}^{n} Di - \sum_{i=1}^{n} Di\eta i \right\} \quad (1)$$

For which the effective roof collection at each level is,

$$(AR)i = AR - \sum_{i=i+1}^{n} Di * \eta i \quad (2)$$

Where D_i, and η_i are the demand and WSE at the feeder tank at the i^{th} level and η_P is the WSE of the parent tank. For an equal demand at each floor level, (1) and (2) can be modified as,

$$Q = \eta_P D\{1 - 1/n \sum_{i=i+1}^{n} \eta i \} \tag{3}$$

$$(AR)_i = AR - D/n \sum_{i=i+1}^{n} \eta i \tag{4}$$

For $n \geq 2$ where 'n' is the number of floor levels.

For a CMTRWH system with a feeder tank for each floor level and a parent tank, the demand on the parent tank can be given by,

$$D_P = D - \sum_{i=i+1}^{n} Di * \eta i \tag{5}$$

When modified for equal demand loading at each floor level, (5) can be given as,

$$D_P = D - D/n \sum_{i=i+1}^{n} \eta i \tag{6}$$

D_P, therefore, is the gross shortfall in the total yield, which requires to be satisfied by the quantity of collected rainwater that can be pumped up from the parent tank (Q).

Therefore, $(D_P - Q)$ is the effective shortfall in the yield (ESY) and when taken as a percentage of the total demand, indicates a measure of the overall WSE of the system. A high overall WSE is indicated by a low ESY% and vice versa.

$$ESY\% = (D_P - Q)/D \tag{7}$$

Analyzing the variation of (ESY%) with respect to the reduction of parent tank capacities, (ΔS_P) as a percentage of the original capacity S_P (i.e. $\Delta S_P / S_P\%$), for scenarios of D < AR, D = AR and D > AR, threshold values for S_P can be found for the minimum impact on overall WSE.

To investigate the optimum values for the parent tank capacity S_P with respect to system parameters D, A, R, S_P and S_i, hypothetical cases of cascading Three Tank and Two Tank RWH systems installed at two storey and single storey houses located in a tropical setting receiving annual average rainfalls of 2000 mm are selected. With an effective roof runoff area of 50 m^2, feeder tank capacities are taken as 1 m^3 each, the parent tank capacities are selected as 8 m^3 for the Three Tank model and 9 m^3 for the Two Tank model to ensure that the total capacity ($\sum S_i + S_P$) is 10 m^3 satisfying the condition $S \geq 0.1AR$ for maximum WSE values for a given D/AR value [2].

For constant daily demands of 200, 300 and 400 Liters, (D_P – Q) values are calculated for S_P values of 12, 8, 4, 2 and 1(in m^3) for Three Tank model and 9, 6, 4, 2, 1 and 0.5 (in m^3) for Two Tank models. The daily demands are selected to suit the three scenarios of D < AR, D = AR and D > AR. (D_P – Q), identified as the Effective Shortfall in Yield (ESY) is tabulated as a percentage of the total demand D against ΔS_P/ S_P% where ΔS_P is the variation introduced to the parent tank capacity and S_P is the original capacity of the parent tank (in this case 8 m^3) (Tables 1-6).

Table 1: Three Tank model – D < AR scenario

S_P (m^3)	η_P	Q(m^3)	ESY%	$\Delta S_P/S_P$%
8	0.90	14.8	2	0
6	0.89	14.6	2	25
4	0.89	14.6	2.5	50
2	0.87	14.3	3	75
1	0.80	13.1	4.5	88

Table 2: Three Tank model – D = AR scenario

S_P (m^3)	η_P	Q(m^3)	ESY%	$\Delta S_P/S_P$%
8	0.71	21.4	8.5	0
6	0.69	20.8	9	25
4	0.67	20.2	9.5	50
2	0.65	19.6	10	75
1	0.60	18.1	11	88

Table 3: Three Tank model – D < AR scenario

S_P (m^3)	η_P	Q(m^3)	ESY%	$\Delta S_P/S_P$%
8	0.30	22	35	00
6	0.29	21	36	25
4	0.27	19.7	37	50
2	0.26	18.9	37.5	75
1	0.23	17.1	38	88

Table 4: Two Tank model – D > AR scenario

S_P (m^3)	η_P	$Q(m^3)$	ESY%	$\Delta S_P/S_P$%
9	1	25.6	0	0
6	1	25.6	0	33
4	1	25.6	1	56
2	0.95	24.3	2	78
1	0.90	23	4	89
0.5	0.75	19.2	9	94

Table 5: Two Tank model – D = AR scenario

S_P (m^3)	η_P	$Q(m^3)$	ESY%	$\Delta S_P/S_P$%
9	0.78	38.5	10	0
6	0.77	38	10	33
4	0.75	37	11	56
2	0.68	33.5	14	78
1	0.58	28.6	19	89
0.5	0.45	22.2	25	94

Table 6: Two Tank model – D > AR scenario

S_P (m^3)	η_P	$Q(m^3)$	ESY%	$\Delta S_P/S_P$%
9	0.52	49.4	31	0
6	0.50	47.5	33	33
4	0.48	45.6	34	56
2	0.44	41.8	36	78
1	0.40	38	39	89
0.5	0.28	26.6	47	94

RESULTS AND DISCUSSION

When the Effective Shortfall in Yield as a percentage of the total demand (ESY%) quantities are plotted against the percentage change in the parent tank capacity ($\Delta S_P / S_P\%$), in the D = AR scenario, in both Three Tank and Two Tank cases only a marginal increase in ESY% can be observed till $\Delta S_P / S_P\%$ reached a value of 50% indicating a parent tank half the capacity of the originally selected tank of 8 m^3 is sufficient to maintain the cascading cycle without significantly affecting the WSE of the system (Chart 1.0).

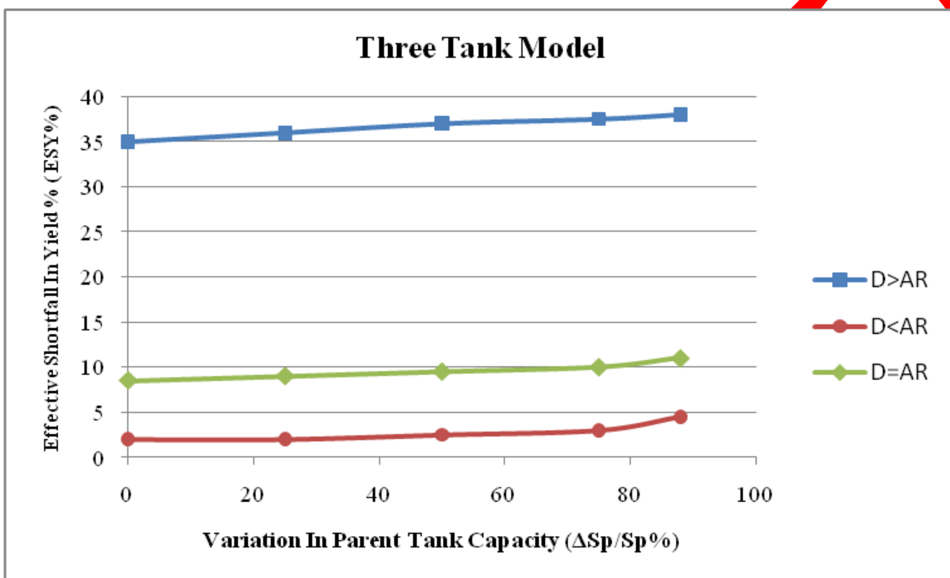

Figure 3: Effective Shortfall in Yield versus Variation in parent tank capacity – Three Tank Model

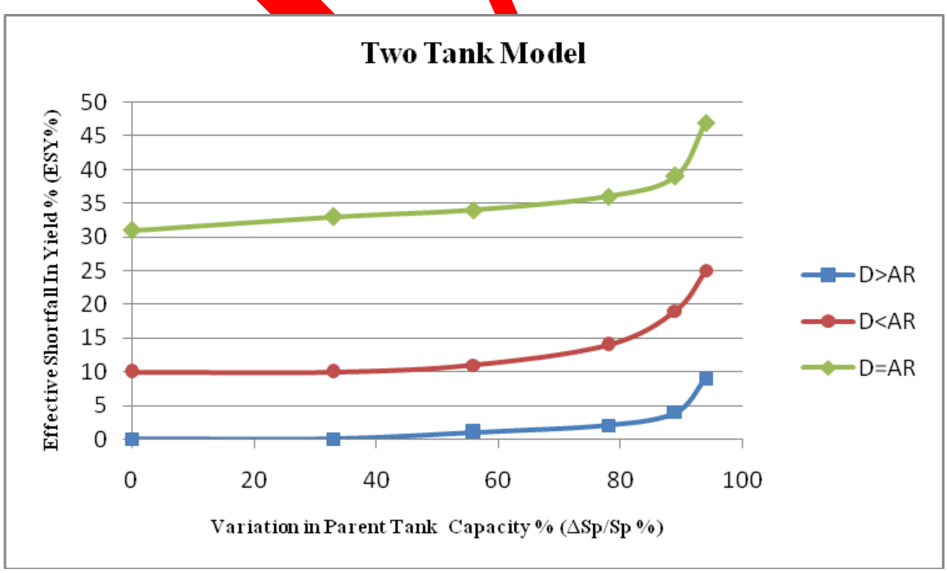

Figure 4: Effective Shortfall in Yield versus Variation in parent tank capacity – Two Tank Model

Comparing the Three Tank and Two Tank models it is seen that the ESY% values corresponding to $\Delta S_P / S_P$% at the optimal D = AR scenario are lower in the Three Tank model whereas the Two Tank model outperforming the Three Tank model at sub optimal D < AR and D > AR scenarios.

Further, when the demand is varied, for both D > AR and D < AR scenarios, the respective curves for Three Tank and Two Tank models, even though show a slight increase in ESY% values for the increase of $\Delta S_P / S_P$% values, maintain the same shape characteristics. Comparing the curves for the Three Tank and Two Tank models, it can be seen that at D = AR, the Three tank model showing lower ESY% values and in all other scenarios, the Two Tank showing marginally lower ESY% values. In the D < AR scenario, the behavior can be attributed to the relatively high roof runoff to the parent tank resulting in high η_P, hence Q, resulting in low ESY%. In the D > AR scenario comparatively, both D_P and Q drop, lowering the ESY%.

When D > AR, for both Three Tank and Two Tank models efficiencies of the individual feeder tanks drop for given S_i values, pushing the D_P values high. Further, in this scenario, the effective runoffs to the parent tanks (AR_P) are small compared to D < AR, D = AR scenarios, hence increasing the D_P/AR_P ratio resulting in low η_P values. As a consequence therefore, (D_P – Q) increase, hence high ESY% values for all corresponding $\Delta S_P / S_P$%. The rapid increasing of ESY% values with increasing $\Delta S_P / S_P$% can also be attributed to the behavior of η_P decreasing rapidly with increasing D_P/AR_P ratio.

In all situations a rapid increase in ESY% is seen for ($\Delta S_P / S_P$%) over 80%, i.e. when $S_P < 1\ m^3$, where the parent tank capacity is less than that of feeder tank capacity. In that scenario, since S_P/AR_P values getting positioned in the sensitive region of the generalized WSE curves, a rapid drop in η_P makes low Q hence resulting in high ESY%. This trend is slightly mitigated in the D > AR scenarios due to drop in AR_P values, keeping the S_P/AR_P values away from the sensitive region of the WSE curves.

CONCLUSION

In both cascading Three Tank and Two Tank models the effect on ESY% for the variation of ($\Delta S_P / S_P$%) are less than 3% and therefore are marginal up to 50% for all three scenarios of D < AR, D = AR and D > AR. Since ESY% is a measure of the overall WSE of the system, it can be concluded that reduction of parent tank capacity by as much as 50% is possible without a significant impact on the system performance. Of the three scenarios, the rate of increase of ESY% for the reduction of S_P is highest when D > AR, highlighting the continued underperformance of an under designed system. On the other hand D < AR scenario corresponds to an over designed system while in the optimum D = AR scenario, less than 10% ESY values in both Three Tank and Two Tank models, indicating a small drop in WSE can be justified by the expected cost saving due to reduction of the parent tank capacity S_P by as much as 50%.

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It can also be recommended that the reduction of S_P should not be below 1 m^3 for the risk of high inefficiencies (η_P) resulting in high ESY% values and hence low system performances. Further, since the equations used for the calculation of ESY% are based on the equations developed for CMTRWH systems, the above findings can be extended to multi tank models as well. Comparing the two models it is clear that at the optimum system performance condition of D = AR for a given AR, Three Tank model is outperforming the Two Tank model. Since this is a result of a higher fraction of the storage capacity distributed to upper floor levels, it can be deduced that at D = AR the overall WSE to increase with the number of feeder tanks.

In actual practice, due to collection inefficiencies, ESD% could marginally increase but will not pose an impact on the result. System losses and water retained in the piping network is not considered for the calculation due to its negligible scale.

REFERENCES

[1] Fewkes, A. (1999a), "Modeling the performance of rainwater collection systems towards a generalized approach", Urban Water, 1, 323-333.

[2] Fewkes, A. (1999b), "The use of rainwater for WC flushing: The field test of a collection system", Building & Environment, 34, 765-772.

[3] Hermann, T., Schmida, U. (1999),"Rainwater utilization in Germany: efficiency, dimensioning, hydraulic and environmental aspects", Urban water, 1, 307-316.

[4] Jenkins, D., Pearson, F., Moore, E., Sun, J.K., Valentine, R. (1978), "Feasibility of rainwater collection system in California", Contribution No. 173, Californian water resources center, University of California.

[5] Sendanayake, S., Miguntanna, N.P., Jayasinghe, M.T.R. (2014), "Validation of design methodology for rainwater harvesting for tropical climates", Asian Journal of Water, Environment & Pollution, vol. 11, no. 1, pp. 87-93.

[6] Sendanayake, S., Jayasinghe, M.T.R. (2016a), "Multi tank model for energy efficient rainwater harvesting", Ideal Journal of Engineering and Applied Sciences, Vol 2, No. 2, pp. 45-52, ISSN: 2067-7720.