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Validation of Design Methodology for Rainwater Harvesting for Tropical Climates

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Abstract: Promotion of sustainable development in the building sector with reduced embodied energy and life cycle costs has become a primary need for facing the emerging threats of global warming and depleting energy sources. In this context, the minimization of the dependence on reticulated water supply is of crucial importance due to the high level of operational energy and the cost associated with the reticulated water supply. For this purpose, rainwater harvesting (RWH) can offer an ideal solution where the harvested water can be easily used for flushing of toilets and gardening. Though design curves and parameters are available for design of the rainwater tanks for a significant water saving efficiency (WSE) in temperate climate regions, the validity and the applicability of these curves and parameters for tropical climate regions such as Sri Lanka, where rainfall patterns vary significantly across geographical and climatic boundaries, is still limited. It is also important to utilize a practical solution to develop multiple data, using short-term rainfall data, in order to compensate for the lack of available data for many geographical regions. In this research, a practical methodology was employed using short-term rainfall data and an experimental set up to validate design curves for WSE, obtained in temperate climate regions, to predict the WSE for tropical climate regions.

Key words: Rain water harvesting, sustainable development, water saving efficiency.

Introduction

The rapid growth of population and urbanisation around the world has led to increasing demand on water supply for both potable and non-potable usage. In this context, the dependency on reticulated water supply has become questionable due to the inefficiency in fulfilling the demand as well as the significant operational energy and the cost associated with it. On the other hand, the use of harvested rainwater that is captured and stored correctly has emerged as an economically viable and sustainable source of service water, specially for non-potable purposes such as flushing of toilets and gardening (for example: Boers and Ben-Asher, 1982; Handia et al., 2003; Kahinda et al., 2007).

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It is noted that, when rainwater harvesting is used for supplementing part of service water, its reliability is a main concern which will depend on the number of parameters such as climatic conditions, size of the roof catchment, rainfall patterns, the tank capacities, capture efficiencies and the size of first flush devices (Villarreal and Dixon, 2005; Basinger et al., 2010). However, the lack of knowledge on these parameters has constrained the optimum design of rainwater harvesting systems (RWHS), particularly in terms of the tank capacities, and therefore impeding the reliability and the feasibility in implementing rainwater harvesting systems.

A set of dimensionless design curves has been developed by Fewkes (1999b), relating the annual average demand for collected rainwater, storage capacity and annual average rainfall to predict the annual water saving efficiency for a given RWH system which would facilitate optimizing the collector tank capacity for a desirable water saving efficiency. However, the design curves developed by Fewkes (1999b) are based on rainfall data obtained in temperate climates, where the rainfall patterns differ significantly from that of tropical climates, thereby requiring validation of the curves for tropical climates for universal applicability. This paper describes outcomes of a comprehensive research project carried out with an experimental set up consisting of a complete rainwater harvesting system to investigate the validity of the applicability of the design curves to Sri Lanka, a country located between 5.8° and 9.7° latitude, representing the tropical region.

Objective

The objective of this study is to determine the validity and the applicability of design curves for WSE, developed for rainfall patterns of temperate climates, for tropical climates so that such curves can be used as a design tool to optimize tank capacities in RWH systems in tropical countries such as Sri Lanka.

Methodology

1. A survey has been used to find the details of domestic water usage patterns in typical houses.
2. Capture efficiencies of Roof Top Rain Water Harvesting Systems (RTRWHS) were determined experimentally for three different roofing materials namely concrete tiles, cement fibre and metal.
3. A prototype rainwater harvesting model was set up with a concrete tiled roof and a daily time series of rainfall and yields were recorded to calculate water saving efficiencies for a given demand.
4. A simple technique of forecasting and generating of extra series of data were employed to obtain more data points from a general set of data.
5. Data obtained were used to validate the WSE curves developed for temperate climate regions, determining their applicability to predict the water saving efficiencies for rainfall patterns in Sri Lanka.

The Models for Determining the Efficiencies

Fewkes and Butler (2000) reported the results of a preliminary mapping exercise conducted in the United Kingdom (U.K.) where the accuracy of behavioural models for the design of rainwater collection systems were evaluated using both different time intervals and reservoir operating algorithms applied to a comprehensive range of operational conditions.

An important parameter of this is Yield After Spillage (YAS). The YAS operating rule assigns the yield as either the volume of rainwater in storage from the preceding time interval or the demand in the current time interval whichever is smaller.

Fewkes (1999b) developed a generic set of curves using a YAS daily time interval model, for a range of storage and demand fractions for a rainwater harvesting system installed in a house in U.K. Different combinations of roof area, store capacity and demand were expressed in terms of two dimensionless ratios, namely the demand fraction and storage fraction. The demand fraction is given by D/AR, where D is the annual demand (in m^3), A is the roof area (in m^2), and R is the annual rainfall (in m). The storage fraction is given by S/AR, where S is the store capacity (in m^3).

The above fractions can be used to predict the performance of rainwater collectors within a particular geographical area. The performance of the rainwater collection system is described by its Water Saving Efficiency (WSE) as described by Dixon (1999).

Water saving efficiency is a measure of how much mains water has been conserved in comparison to the overall demand and is given by

$$WSE = \frac{\sum_{t=1}^{t=T} Y_t}{\sum_{t=1}^{t=T} D_t} \times 100 \qquad (1)$$

where Y_t is the yield from storage facility (m^3) during time interval, t, and D_t is the demand (m^3) during the time interval t. T is the total time under consideration.

Generic curves for system performance of a RWH system were developed based on the generic configuration of the rainwater collection system illustrated in Figure 1 and the YAS form of the reservoir operating algorithm used in the system simulation models.

The variation of average water saving efficiency of a rainwater collector at demand fractions of 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75 and 2.00 each with a storage fraction range of 0.005-0.40 obtained by Fewkes (1999b) is illustrated in Figure 2.

It is useful to validate these design curves for tropical climate regions such as Sri Lanka, to be used with monthly rainfall data, so that they could be used

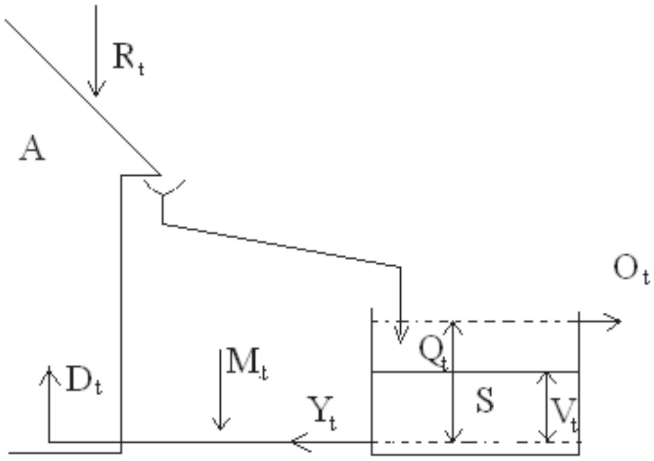

Figure 1: Generic configuration of the rainwater collection system.

with confidence when designing rainwater harvesting systems.

Validation with Experimental Data

For validation of design curves, it is necessary to find the daily water usage patterns and to examine the performance of a prototype RWHS under such usage patterns.

Survey on Water Usage

To ascertain the water usage pattern of a typical middle-income household in Sri Lanka, where potable water is being currently used for Water Closest (WC) flushing, household uses and garden watering, a detailed survey was carried out at five different houses in the intermediate climate zone of Sri Lanka where the annual average rainfall is in the range of 1000-1750 mm. Number of uses of WC, and the amount of water used for gardening were recorded on a daily basis. WCs were adjusted to discharge 10 litres per flush and in gardening, the user was advised to use a garden hose with the tap fully open. The rate at which water was discharged from a fully open tap was measured. The activity duration in minutes were recorded which allow the determination of discharge quantities with a reasonable accuracy when the output flow rate is known. Water requirement in litres could thus be calculated.

Once the overhead storage tank is full, it is utilized fully till the tank is empty. Number of fillings over a period was recorded in order to determine the daily usage. From the data collected, it could be concluded that service water usage per person in Sri Lanka in the intermediate zone has an average of about 200-220 L/day, which is found to be slightly higher than the generally used volumes in a temperate country, which is about 160-180 L/day (Villareal and Dixon, 2005). General absence of water saving devices such as self-closing taps etc., may also be contributing to high service water usage in addition to the higher ambient temperatures prevailing in the tropics. It should also be noted that four of the five houses used for the survey had gardens and cars; hence this average of 200–220 L/day may be due to high usage in gardens and washing of vehicles.

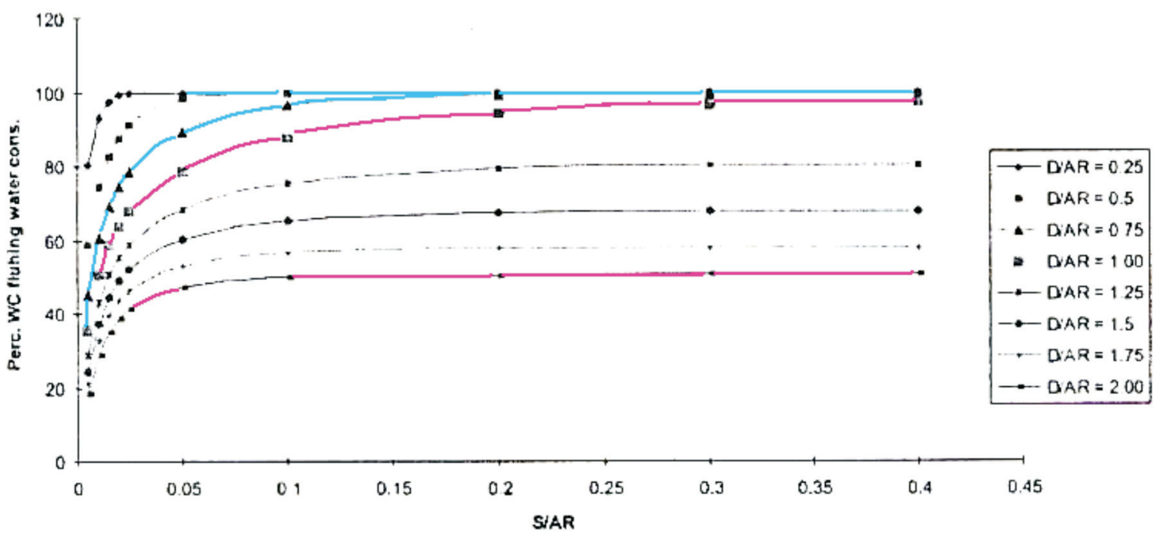

Figure 2: Generic curves for Water Saving Efficiency (WSE) (Fewkes, 1999b).

It is also noted that the per capita service water requirement for WC usage is between 40 and 50 L/day (i.e. 4-5 flushes per day). This shows that on an average, 25% of drinking quality water is being used for WC flushing. The fact that average per capita usage remained almost same for five houses with different people compositions validates the finding that the average per capita water usage is generally a constant and is habitual for a population in a given geographical region. For example, it is considered that the service water usage for WC flushing is about 20% for United Kingdom (Fewkes, 1999a) or 30% for Sweden (Villareal and Dixon, 2005). Thus, it may be reasonable to use a value of about 25% for Sri Lanka. For activities where high quality water is not required, it may be reasonable to consider that an average of about 25-30% of drinking quality water is used. This percentage may increase if garden activities are intense. This typical usage pattern should be viewed in the context of Sri Lanka having tropical climatic conditions and people getting into the habit of using water liberally when pipe-borne supply is available.

Experimental Study

In order to determine the actual values of design parameters and also to validate the applicability of the design curves obtained for temperate climate regions to tropical climate regions, a rainwater collector with a storage tank of 1500 litres having the ability to discharge varying quantities of water, was installed at Marawila in North Western Province, Sri Lanka, having intermediate climatic conditions. The performance of it has been monitored for a period of one year.

The system was installed in a house of single storey construction with a pitched roof covered with profiled, granular face concrete tiles. Rainwater was collected from a roof area of 25 m^2 and water was drawn-off the tank via the outlet. The quantity drawn off was based on various demands that needed to be simulated. An overflow was fitted to the storage tank which discharged into the household's surface water drain as shown in Figure 3.

Details of the System

The following are the main characteristics of the prototype:

1. Effective roof area = 25 m^2
2. The conveying system = 100 mm diameter PVC down pipe.
3. A first flush device was installed with a capacity of 13 litres. It consists of a down pipe identified as 'A' in Figure 3. The capacity of the first flush device is determined to have a rainfall depth of 0.5 mm to be removed so that it can wash and clean the roof prior to the collection of water. A depth of 0.5 mm is sufficient for areas with low levels of air pollution as described by Zobrist (2000). Luxmore (2005) also used a depth of 0.5 mm for three display homes constructed in Australia for promoting the use of sustainable development principles by demonstrating actual examples.
4. Storage facility consisted of a galvanized steel tank of net capacity 1500 litres with an outlet at the bottom and an overflow at the top. This means that for determining the ratios that works out to be S = 1.5 m^3.

Figure 3: Prototype RTRWHS.

Calculation of Roof Run-off Coefficient (C_f)

The roof run-off coefficient is an important parameter that determines the actual quantity of rainwater that can be collected from a typical roof after allowing for absorption.

The roof run-off coefficient was measured using the simplified equation,

$$C_f = Q_t / R_t A \quad (2)$$

where Q_t is rainwater collected at storage for a rain event in time t, A is the roof area and R_t is the rainfall in time t.

For measuring the roof run-off coefficient the first flush device was sealed off with its discharge orifice closed and then the quantity of water collected was monitored during rain events. It is observed that C_f remains steady for the prototype roof at about 0.85. The average value for C_f is within the specified range accepted for the accurate performance of generic curves introduced by Fewkes (1999b) and hence the prototype can be used to determine water saving efficiency performances in tropical climate regions.

Rainfall Data

Daily rainfall data was recorded using an on-site rain gauge to ascertain whether actual rainfall confirm to figures given by the Meteorological Department for the North Western Province (NWP) of Sri Lanka in the intermediate climate zone. Figure 4 shows the monthly rainfall data obtained from the Meteorological Department of Sri Lanka shown as Series 1 against test site rain gauge readings shown as Series 2. The Figure 4 indicates that the test site readings obtained are reasonably confirming to official data.

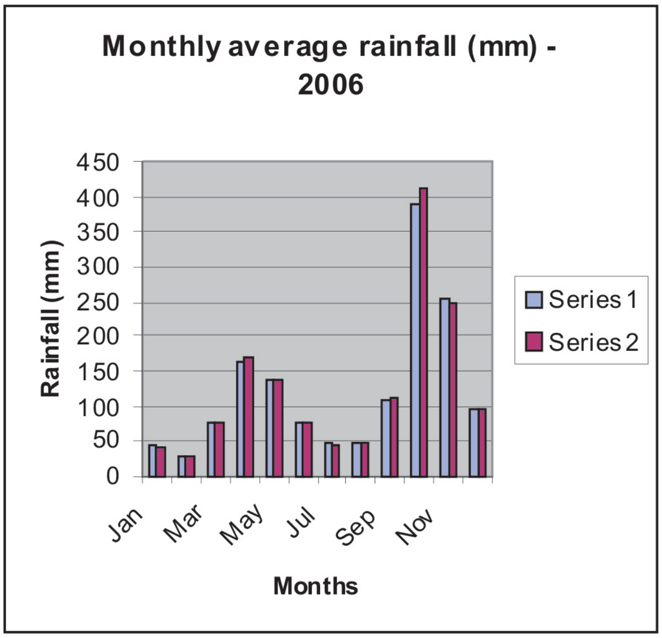

Figure 4: Comparison of monthly rainfall, Met. Dept. values against test site rain gauge readings.

The Data Collected

The following data were collected on daily basis.

(a) For a given demand D, the yield from store S and the rainfall was recorded on a daily time series.

(b) For a given demand D, Water Saving Efficiency (WSE) was calculated taking 30 consecutive days as a month.

(c) WSE figures obtained for a given demand and storage fraction were plotted against generic curves for WSE to ascertain whether the above figures confirm to the curves. The points obtained matched the generic curves reasonably well as shown in Figure 5. In calculating the demand and storage fractions for a given demand and storage capacity the variable is the annual rainfall. This is calculated by taking the annual rainfall based on rainfall received for the corresponding time period of 30 consecutive days. This way, a number of data points can be generated by using a limited set of data obtained over a short period of time as explained here subsequently. Since rainfall can directly influence S/AR and D/AR, many points can be obtained that cover the critical region of

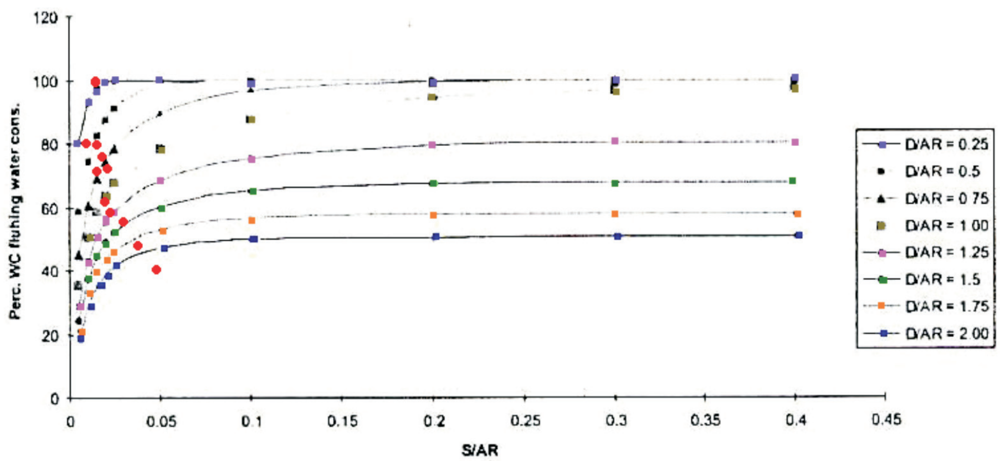

Figure 5: Water Saving Efficiency (WSE) curves validated for Sri Lanka.

Figure 5 which can be considered as where S/AR is less than 0.05.

Results

Capture Efficiencies

The rainwater capture efficiencies for cement fibre and metal roofs were found to be 88% while that for tile roofs are 83% allowing an average 85% capture efficiency to be taken as valid to Sri Lankan scenario.

The Demands Used for Experiments

The usage surveys have indicated that the water usage for bathroom flushing and gardening can be about 25-30% of the total water demand. Thus, for validation, water demand values of 100 L/day and 150 L/day were used. This can correspond to a house occupied with two persons and about three persons respectively where some water conservation measures have also been promoted. A usage higher than this will need a larger roof area and larger tank capacities. The roof areas can be 50-75 m^2 depending on the demand.

Creation of Additional Data

The rainfall recorded over a period of 12 months could yield only about 12 points for validation. In order to generate extra data points a moving average method was used where a consecutive thirty-day period from the daily rainfall data series was considered as one month. This means, for a set of readings taken over a period of 45 days with a given demand, it was possible to create 15 reading points with different monthly rainfalls. This way, it was possible to create sufficient number of points for validation by taking readings over a limited period of just over one year.

Validation of RTRWH System Performance Curves for Sri Lanka

The intermediate climate zone of Sri Lanka receives annual rainfall of 1000 to 1750 mm (Meteorological Department of Sri Lanka) with average annual rainfall being 1300 mm. This is well within the range covered in generic curves presented by Fewkes (1999b) for determining the Water Saving Efficiency (WSE).

It is also observed that the demand for WC flushing water remains a close constant at 25-30% of the service water requirement in both households with the average usage of about 200 litre per day per person. Therefore, in the absence of system performance curves for rainwater collection developed for Sri Lanka, the generic curves developed by Fewkes (1999b) can be employed as a standard design tool for roof types having a run-off coefficient of 0.80 to 1.0, in the wet and intermediate zones of Sri Lanka. The dry zone of Sri Lanka receiving less than 1000 mm of annual rainfall is omitted from the consideration as the region is characteristic of desert climate and is sparsely populated.

Conclusions

The generic curves for water saving efficiency developed using behavioural models with simulated time series of rainfall and yield patterns for temperate climate regions, once validated, can become a useful design tool in determining the optimum storage sizing in potential rainwater harvesting systems in tropical climate regions. Validation can be effectively and successfully carried out if multiple data points can be developed within the specified parameters, mainly the minimum annual average rainfall and constant demand values.

It is found through a field survey that the average domestic per capita consumption of water in Sri Lanka is steady, at about 200-210 L/day. Although this is higher than the average water usage in many countries, which is about 160-180 L/day, it indicates the potential to reduce water consumption by utilizing water saving devices. However, importantly, the findings of the survey confirm that per capita water usage can generally be considered a constant, hence supporting the validity of system algorithm irrespective of the geographical and climatic boundaries. It is also found that the amount of water used for WC flushing and gardening was about steady 25-30% of the total water usage implying that an effective RWH system can be designed solely for such uses where treatment of collected rainwater is not necessary. Research also concludes that the roof run-off coefficient can be about 0.85 for generally used roof materials in Sri Lanka.

The multiple data generated, from a limited number of readings spanning a relatively short duration of one year, employing a moving average method has proved very effective, and enabling the generation of sufficient number of points to validate the generic curves for Sri Lanka based on monthly rainfall values. This is very useful since monthly rainfall data are readily available for most parts of Sri Lanka. This study has thus introduced a tool and a methodology that can be used confidently in Sri Lanka and in other tropical countries where similar climatic conditions prevail, for sizing rain water harvesting systems. Importantly, the curves can be used for different roof areas and demands in the absence of data collected over a long period of time. The research can be considered as an important step in taking the building sector of tropical countries to adopt sustainable development principles with respect to self sufficiency in water where the optimum system capacity can be determined for a given demand scenario at the design stage itself. The wider adoption of rainwater harvesting will also assist in reducing the incidence of flash floods since the amount of run-off from impermeable roofs could be reduced. It can also assist in minimizing the impact of a new development on surface water patterns and ground water condition in a given area.

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References

Basinger, M., Montalto, F. and U. Lall (2010). A rainwater harvesting system reliability model based on nonparametric stochastic rainfall generator. *Journal of Hydrology*, **392(3-4):** 105-118.

Boers, Th.M. and J. Ben-Asher (1982). A Review of Rainwater Harvesting. *Agricultural Water Management*, **5(2):** 145-158.

Dixon, A., Butler, D. and A. Fewkes (1999). Computer simulation of domestic water reuse systems: Investigating grey water and rainwater in combination. *Water Science Technology*, **38(4):** 25-32.

Fewkes, A. (1999a). The use of rainwater for WC flushing: The field-testing of a collection system. *Building and Environment*, **34:** 765-772.

Fewkes, A. (1999b). Modelling the performance of rainwater collection systems: Towards a generalized approach. *Urban Water*, **1:** 323-333.

Fewkes, A. and D. Butler (2000). Simulating the performance of rainwater collection systems using behavioural models. *Building Services, Engineering Research and Technology*, **21(2):** 99-106.

Handia, L., Madalitso, T. and C. Mwiindwa (2003). Potential of rainwater harvesting in urban Zambia. *Physics and Chemistry of Earth*, **28(20-27):** 893-896.

Hermann, T. and U. Schmida (1999). Rainwater utilization in Germany: Efficiency, dimensioning, hydraulic and environmental aspects. *Urban Water*, **1:** 307-316.

Kahinda, J.M., Taigbenu, A.E. and J.R. Boroto (2007). Domestic rainwater harvesting to improve water supply in rural South Africa. *Physics and Chemistry of the Earth*, Parts A/B/C, **32(15-18):** 1050-1057.

Luxmore, D.A., Jayasinghe, M.T.R. and M. Mahendran (2005). Mitigating temperature increase in high lot density sub tropical residential developments. *Energy and Buildings*, **37:** 1212-1224.

Villareal, E.L. and A. Dixon (2005). Analysis of a rainwater collection system for domestic water supply in Ringdansen, Norrkoping, Sweden. *Building and Environment*, **40(9):** 1174-1184.

Zobrist, J., Muller, S.R., Amman, A., Bucheli, T.A., Mottier, V., Ochs, M., Shoenenberger, R., Engster, J. and M. Boller (2000). Quality of roof run-off for groundwater infiltration. *Water Resources*, **34(5):** 1455-1462.