A Mathematical Model for Rain Harvesting Systems to Optimise Storage Tank Volumes and Roof Areas to Achieve Uninterrupted Water Supplies Into Households

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ABSTRACT

The determination of the necessary storage volume of rainwater harvesting systems (RHS) for a reliable water supplies for households is not a trivial task. In most areas, rainfall is seasonal, intermittent and highly variable throughout the year and dry periods could linger for a few weeks or months. In contrast, household water demand is relatively constant over time and rainwater tank storage capacities need to be sufficient to supply water during dry spells. The harvested volume of rainwater is primarily dependent on the storage capacity of the RHS, connected roof catchment area, the rainfall intensity and duration and the rate at which the stored rainwater is consumed. Significant losses occur from the point of rain deposition on a roof to the final water outlet due to splash and spray loss, evaporation and spillage from the RHS. Consideration of all these processes are required to estimate the average proportion of household water demands that can be reliably supplied by the RHS. Mathematical modelling is valuable in being able to simulate these processes to help understand the behavior of rain harvesting systems and to help optimise the design of a RHS for each household, both in terms of effectiveness and cost.

Many RHS models have been developed and used around the world. In this paper, we describe a proposed modelling study involving adapting a daily time-step rainwater harvesting model developed in Queensland, Australia, to Sri Lankan conditions. The proposed study will measure and source information on household water use, climate data, roof catchment characteristics and the unique characteristics of the locally-built RHS already installed in ten households in Badulla

and Anuradhapura districts in Sri Lanka as part of a RHS pilot project. Significant processes not yet captured in the current model will be identified and incorporated, before testing the model using local data from different climatic regions in Sri Lanka. The outcome of this modelling work is anticipated to significantly benefit the Sri Lanka's rainwater harvesting system designs to achieve a safe, reliable and cost-effective potable water source.

Keywords: rain harvesting, mathematical model, simulation, supply reliability

INTRODUCTION

Sri Lanka has a long history of collecting and storing surface and sub-surface rainwater runoff in dams or lakes for irrigation purposes. In contrast, rainwater harvesting from roofs as a potable water source has not been commonly practiced due to the abundance of groundwater and stream water for domestic consumption. However, due to recent changes in land use and agricultural practices, groundwater water quality has been adversely impacted in some rural areas. There is now evidence that clearly shows that polluted groundwater can lead to serious health issues in many parts of Sri Lanka. A recent publication (Dissanayake et al. 2013) indicated a link between consuming water from shallow wells and chronic kidney disease (CKD). There is no quick solution for poor groundwater quality issues in Sri Lanka and so providing a safe drinking water source is essential for these rural communities. A pragmatic and economically viable option would be to use rainwater for direct human consumption. Such a practice is used in many parts of the world including rural Australia.

Pilot project: The perception of the high cost of rainwater harvesting systems (RHS), low water quality and the poor reliability of tank water supplies for households is a major impediment to harvesting rainwater for potable use in rural areas. A pilot project involving rainwater harvesting system for potable use is currently being conducted in Badulla and Anuradhapura districts. The main objective of this pilot project is to test and evaluate a *new* RHS design. This design addresses the water quality issues due to the ingress of organic (e.g. leaf and faecal) material into the rainwater tanks by including a leaf diverter and first flush mechanism. Growth of algae and other nuisance aquatic plant species is prevented by excluding light penetration into the tank. Infestation of the tank by mosquitoes and other insects is prevented by ensuring the tank is adequately sealed.

The use of reinforced Ferro-cement to construct the rainwater tanks allows evaporative cooling of the stored water. The shape of the rainwater tank allows any sludge build-up to accumulate at the centre bottom of the tank where a special built-in flush-out pipe allows for easy cleaning (Figure 1). Ten complete units have been installed in households selected to cover different climates and household sizes and these units will be used to derive data for the proposed modelling study.

Figure 1. (Left) A white leaf diverter to strain off bulky material connected to a first flush device which allows the contaminated first flow from the roof to be discarded. (Right) The unique design of locally-crafted tank.

Designing a domestic RHS: Designing a domestic RHS, minimizing the cost of building the RHS, and achieving a high level of supply reliability, is not a trivial task. In certain areas, rainfall is seasonal, intermittent and highly variable throughout the year and dry periods could linger for a few weeks or months. In contrast, household water demand is relatively constant over time and storage capacities need to be sufficient to supply water during the dry spells. The harvested volume of rainwater is primarily dependent on the storage capacity of the RHS, connected roof catchment area, the rainfall intensity and duration and the rate at which the stored rainwater is consumed. Significant losses occur from the point of rain deposition on a roof to the final water outlet due to splash and spray loss, evaporation and spillage from the RHS. Consideration of all these processes are required to estimate the average proportion of household water demand that can be reliably supplied from RHSs.

Mathematical modelling is a valuable tool in simulating these processes to help better understand the behavior of rain harvesting systems and to help optimise the design of RHSs for households, both in terms of effectiveness and cost. Mathematical models have been developed for rainwater harvesting systems in many parts of the world (Coombes and Barry 2007, Mitchel 2007, Su et al. 2009, Jones and Hunt 2010, Fewkes 2000, Palla et al 2012) and have shown their effectiveness in system design and management. However, thus far, no reliable rainwater harvesting simulation model has been developed for Sri Lanka which has unique climatic conditions.

As part of a proposed pilot project conducted to evaluate RHS as a portable water source in the CKD impacted areas, we describe in this paper a proposed modelling study which adapts and outlines an existing RHS model for optimizing the design of the Sri Lankan RHS. The Rainwater TANK model developed in Queensland, Australia (Vieritz et al. 2007ab) was chosen because of its simplicity of inputs and accessibility of the programming algorithms for modification to Sri Lankan conditions. The model inputs will be modified to match available climatic data, roof characteristics, household water demand and the features of the storage tank where required. The requirement for periodic storage-tank washout will need to be considered. The model will be evaluated using the specially designed rain harvesting systems which have been installed in Badulla and Anuradhapura districts.

CLIMATE

Sri Lanka has a unique rainfall pattern and a long-term average annual rainfall that varies from less than 1000mm to 5000mm (Figure 2). The rainfall pattern is dominated by two monsoon periods from May-September and December-February and so follows typical bimodal pattern with four distinct rainfall seasons (http://www.statistics.gov.lk/Abstract2014/CHAP1/1.6.pdf).

1. The South-West monsoon period (May to September)
2. The Inter-monsoon period following the South-West monsoon (October to November)
3. The North-East monsoon period (December to February)
4. The Inter-monsoon period following the North-East monsoon (March to April)

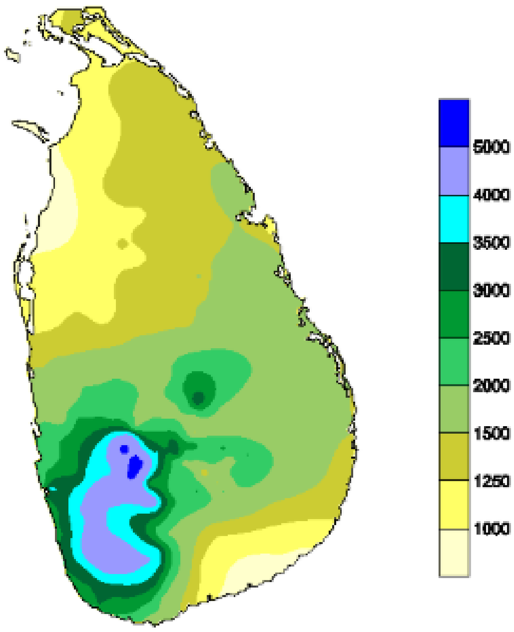

Figure 2. Map of Sri Lanka showing the variation in average annual rainfall (http://www.meteo.gov.lk).

The annual average rainfall varies from less than 1000mm over a small region in the arid parts of the North-West and South-East of Sri Lanka. An annual rainfall over 5000mm is received on parts of the western slopes of the central hills. During the South-West monsoon, annual rainfall may exceed 3000mm in some areas whilst during the North-East monsoon, the eastern half of the Island may receive from 200mm to >1200mm of rainfall. The annual distribution of rainfall of selected districts is shown in Figure 3.

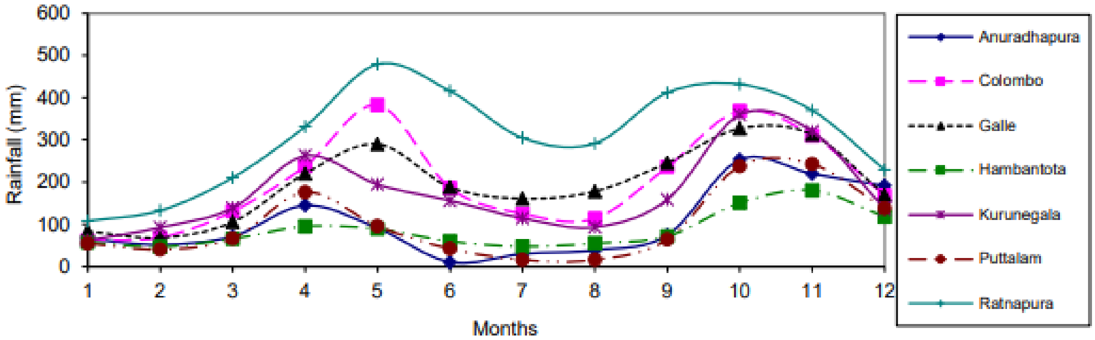

Figure3. Mean monthly rainfall for selected stations during 1961 to 1990.

This bimodal distribution pattern and the amounts received in these two peaks in May and October would be sufficient to fill the rainwater tank storage completely after emptying. This will allow the rainwater tanks to be washed out at the beginning of each monsoon period as part of the rainwater tank maintenance to reduce the microbiological growth risks and remove any sediments.

There may be limited availability of climate data (both rainfall data and pan evaporation data) for each district in Sri Lanka. Where daily data is not available, the possibility of disaggregating weekly or monthly data will be explored.

THE PROPOSED MODEL

The Rainwater TANK model (Vieritz et al. 2007ab) developed for urban households in Queensland, Australia, is available for use and modification for this proposed modelling study. In its current form, Rainwater TANK is a continuous simulation daily time-step model that calculates the water balance of the roof, rainwater tank, internal water use areas, and one external water use. The model incorporates a first flush device. The user of the model is required to enter in values for roof area, first flush device, tank storage capacity and management, household water use and climate data and the model provides a prediction of the likely average proportion of total water demand that would be met by the RHS, along with many other data such as spillage (tank overflow) losses over time. If the model indicates that spillage is excessive, the user can increase the capacity of the tank store and rerun the model, and so iteratively arrive at a suitable design.

The model can be described in three parts: the roof water balance, the rainwater tank water balance, and water demand. Areas that will need modification are discussed. A summary of the main algorithms used in the Rainwater TANK model, along with the symbol definitions and units is shown in Table 1.

Roof water balance

The physical components of the rainwater collection system are the roof area that is connected to the gutter system which collects the rainwater and channels it through to a leaf diverter (to remove large solids such as leaves) and first flush device (which removes the first volume of contaminated rainwater flowing from the roof, such as bird faeces) before finally piping it to a storage tank. In practice, not all the roof may be connected to the RHS and not all the rain that falls on the connected roof will reach the storage tank due to:

- Wetting up the roof surface. This initial loss is represented in the model as a simple "adhesion loss" (AL) in mm, the storage capacity of the roof to hold rainwater. Its value will depend on the roof material and the slope of the roof. Most of the rural housing in Sri Lanka use clay tiles, or metal or asbestos sheeting.
- Rainwater splashed, evaporated[1] or blown off from the roof and gutters. The water loss from the leaf diverter due to splashes when the water hits the angle wire mesh would also be included here. This direct roof "catch loss" (CL) is ongoing throughout the rainfall event and is represented as a proportion of total rainfall intercepted by the roof.
- Loss of the first flush volume (FFL) of rainwater from the roof due to the installation of a first flush device.

The water balance for each day is:

$$Tank\ Inflow(m3) = Gross\ Rain\ Catch(m3) - AL(m3) - CL(m3) - FFL(m3)$$

… (1)

The Gross Rain Catch (GRC), the total volume of rainwater caught by the connected roof, is calculated by:

$$GRC(m3) = Rain(mm) \times RoofArea(m2) \times 0.001$$

….(2)

The Direct roof catch loss, the adhesion loss and first flush loss are calculated as follows:

$$CL(m3) = \left(1 - \frac{100 - \%CL}{100}\right) \times GRC(m3)$$

……(3)

The percentage catch loss (%CL) of a roof is a model input and depends on roof design, wind speed and direction, rainfall intensity. It could be determined by measuring of rainfall and roof water collection during rainfall events after the roof is wetted. The rainfall loss is then expressed as a percentage of GRC.

$$AL(m3) = AD(mm) \times RoofArea(m2) \times 0.001$$

……(4)

The depth of rainwater that is required to wet the roof before runoff occurs (AD) depends on the roof surface type and slope and could be determined by measuring rainfall and roof water collection from an initially dry roof over frequent time intervals during a light rainfall event.

[1]In contrast, the modelling approach described in Vieritz et al. (2015) explicitly models the roof evaporation by allowing the roof storage capacity to fill during a rain event but then subsequently evaporate according to the day's potential evaporation, with updating of the roof "stored water level" for the next day.

$$FFL(m3) = FFD(mm) \times Roof\text{Area(m2)} \times 0.001$$

…..(5)

The depth of water that flushes the roof area (FFD) is currently a model input and is determined from the volume of the first flush device, divided by the roof area. The first flush of rainwater from the roof is potentially contaminated with dust and organic matter and so the first flush device intercepts the first volume of rainwater from the roof, preventing it from entering the tank. The first flush device, once full, will allow all other flows to reach the tank. However, a small drainage hole at the base of the first flush pipe allows the collected water to slowly drain away so that it is empty for the next rainfall event. The first flush loss is applied to the rainfall that leaves the roof. The loss is applied only once on any rain day, since we assume that all the rain recorded for any day falls in one event (a limitation of a daily time-step model)[2].

Rainwater tank balance

The physical component of the rainwater storage tank is a handmade, completely opaque, Ferro-cement storage tank. The water intake into the house is drawn through the floating valve that has an inlet point around 10cm below the water surface. The top 10cm volume acts as a top dead storage and any floating debris (density less than 1.0 g/cm^3) are contained in this top dead storage. During tank overflow events, these floating impurities will be flushed out. The water intake is prevented from drawing water from below 20cm above the bottom of the tank. This bottom 20cm acts as the bottom dead storage and impurities with a density greater than 1.0 g/cm^3 will settle out in this bottom dead storage. The settled sludge will be periodically removed from the tank using the flush out valve installed at the very bottom of the tank.

Table 1. Main algorithms used in the Rainwater TANK model which are relevant to the pilot study. The algorithms defining the dead storage volume by depth have been replaced with the direct input of the top and bottom dead storage volumes. All user inputs are underlined.

Model Variable	Symbol	Unit	Algorithm
Gross roof rainfall catch	GRC	m3	<u>R</u>x<u>Ar</u>x0.001
Rainfall	<u>R</u>	mm	
Class A pan evaporation for the current day	<u>Pan</u>	mm	
Roof area	<u>Ar</u>	m2	

[2] A more comprehensive approach for modelling the first flush loss is described in Vieritz et al. (2015).

Tank inflow	TI	m3	GRC - CL - AL - FFL
Direct roof catch loss	CL	m3	%cl / 100 x GRC
Direct roof catch loss as %GRC	%cl	%	
Adhesion loss	AL	m3	AD x A x 0.001
Adhesion depth	AD	mm	
First flush Loss	FFL	m3	FFD x A x 0.001
First flush depth	FFD	mm	
Tank water volume	TW	m3	Yesterday's TW + TI - IWUt - EWUt
Tank volume	Vt	kL	
Top dead storage volume	$_T$RV	m3	
Bottom dead storage volume	$_B$RV	m3	
Reserve (dead storage) volume in tank	RV	m3	$RV_T + RV_B$
Tank overflow	TO	m3	Maximum(TW - MaxTW,0)
Tank water volume at the overflow outlet level	maxTW	m3	Vt - (AG x At)
Air gap - distance between tank top and maxTW	AG	m	
Internal household water use for each day	IWU	m3/hh/day	IWUp x n
Daily internal water use per person	IWUp	m3/per/day	
Number of persons in the household	n	per/hh	

The top dead storage will only impact on water availability when the tank water level reaches 30 cm above the tank base. At this point, the top and bottom dead storages collide, and no further water can be withdrawn. The Rainwater TANK model does allow a dead storage volume (and a top air gap if required) to be defined. However, the volume is defined according to depth, *assuming a tank with vertical sides.* This will need to be altered so that dead storage volumes are specified instead. The effective storage of the tank for water use then becomes:

$$EffectiveTank\ StorageVolume(m3) = TankVolume(m3) - TopDeadStorage(m3) - BottomDeadStorage(m3) \quad \ldots(6)$$

The Rainwater TANK model considers the tank to be closed with no evaporation losses or the rainfall gain into the storage tank (other than from the inflow pipe). The water balance for each day is:

$$TankWaterVolume(m3) = Yesterday's\ TankWaterVolume(m3) + TankInflow(m3) - Overflow(m3) - InternalWaterUse(m3)$$

….(7)

The Tank Inflow is determined by the roof water balance, previously described.

The daily internal water usage (IWU) is simply modelled as a function of the number of household occupants (n) and their daily water consumption demand (IWU_p).

$$IWU = IWU_p \times n$$

….(8)

For the overflow calculation, consideration must be given to the order in which tank inflow, removal of water for use (yield) and overflow (spillage) is calculated within each time step. In reality, tank inflow, yield and spillage can occur in any order or can occur simultaneously. They can also occur multiple times within a given time-step. For the sake of a daily time step model where each calculation must be performed once in a set order, two calculation order options are provided:

1. YAS (Yield after Spillage): This means that the order of calculation is:
   - Subtract any internal water use for the current day.
   - Add any rainfall received on the current day to the tank.
   - If the additions and subtractions have left the tank water volume exceeding the maximum volume, subtract the overflow for the current day, to reduce the tank water volume to the maximum volume.
2. YBS (Yield before Spillage): This means that the order of calculation is
   - Add any rainfall received on the current day to the tank.
   - Subtract any internal water use for the current day.
   - If the additions and subtractions have left the tank water volume exceeding the maximum volume, subtract the overflow for the current day, to reduce the tank water volume to the maximum volume.

The YAS calculation will remove the water used before any rainfall is added. This will reduce the water available for use, maximise the storage of rainwater and spillage. The YBS calculation will add the rain first, before removing the water used. This will maximise the water available for use and leave less for spillage. For conservative modelling of the yield, the YAS calculation is often used.

For each option, overflow is calculated as:

$$Overflow(m3) = \text{Maximum}\,[0, TankWaterVolume(m3) - MaxTankWaterVolume(m3)] \quad \ldots.(9)$$

Cooling and water evaporation from tank surface:

The assumption that no evaporation will take place from the tank may not be true for the cement tanks used in the pilot study and the model may require modification to allow an extra term in the water mass balance for the tank.

$$TankWaterVolume(m3) = Yesterday's\ TankWaterVolume(m3) + TankInflow(m3) - Overflow(m3) - InternalWaterUse(m3) - Evaporation(m3) \quad \ldots.(10)$$

The rainwater storage tank is made by molding cement (Ferro-cement) over wire reinforcing which is shaped to define the contours of the tank wall. The tank wall allows water to permeate to the exterior tank surface where it evaporates. This process cools the storage tank and helps to keep the stored water palatable, especially where, in some areas of Sri Lanka, the daytime temperature can rise to more than 40^0C. The impact of this evaporative loss on the tank water balance could be investigated by monitoring the water level of sealed tanks with different initial depths of water. Should evaporation be found to be a significant loss mechanism, modelling approaches (e.g. Leroux et al. 2015) would be considered as the basis for developing an algorithm for estimating Evaporation term for the Pilot study tanks.

Tank cleaning

Tank cleaning is not modelled by Rainwater TANK but the need to flush out the tank at the start of each monsoon period could have a significant impact on the overall reliability of the supply of domestic water. The model would need to identify (from the rainfall data) when each monsoon period commences and then trigger a tank cleaning event where the tank water volume is reset to zero.

CONCLUSION

In this paper, we outline a proposed modelling study to support a pilot project aimed at providing a safe source of potable water supply for families in rural Sri Lanka where groundwater in some locations is no longer safe to drink. The pilot study proposed will show how the innovative approach of using water tank surface evaporation for stored water-cooling impacts on promoting harvested rainwater for drinking purposes in Sri Lanka.

The modelling approach described will build on an existing model, to take into account this unique RHS designed and used in the pilot project. Data generated from the pilot project will be used to inform the modelling tool. We anticipate that the model will then be used to further optimise the RHS design for different climatic regions and sizes of households in Sri Lanka.

The model is also expected to reduce construction cost of the domestic RHS through avoidance of installing over-sized tanks in relation to the available connected roof area etc. In rural Sri Lanka, the cost is one of the main constraints in adopting rainwater harvesting systems.

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References:

Campisano, A, and Modica, C. (2012) Optimal sizing of storage tanks for domestic rainwater harvesting in Sicily. *Resources, Conservation and Recycling* 63 (2012) 9– 16.

Coombes, P., and Barry, M. (2007) The effect of selection of time steps and average assumptions on the continuous simulation of rainwater harvesting strategies. *Water Science and Technology*, 55(4), 125-133.

Dissanayake, D.M., Jayasekera, J. M. K. B., Adhikari, S.B, and Bandara, P. (2013) Geographical distribution of chronic kidney disease of unknown origin in Sri Lanka. *Ceylon Medical Journal,* 58: 6-10.

Fewkes, A. (1999) Modelling the performance of rainwater collection systems: towards a generalised approach. *Urban Wate*r 1 323 – 333.

Jones, M. P. and Hunt, W. F. (2010) Performances of rainwater harvesting systems in the southern-east United State. *Resources, Conservation and Recycling* 54(10), 623-631.

Leroux, G., Mendes, N., Stephan, L., Le Pierrès, N. and Wurtz, E. (2015) An innovative cooling system based on evaporation from a porous tank. *Proceedings of 14th Conference of International Building Performance Simulation* Association, Hyderabad, India, Dec. 7-9, 2015.

Meteorological department of Sri Lanka
http://www.statistics.gov.lk/Abstract2014/CHAP1/1.6.pdf

Mitchell, V.G. (2007), How important is the selection of computational analysis method to the accuracy of rainwater tank behavior modelling. *Hydrological Processes*, 21(21) – 2850-2861.

Palla, A., Gnecco, I., Lanza, L.G., La Barbera, P. (2012) Performance analysis of domestic rainwater harvesting systems under various European climate zones. Resources, *Conservation and Recycling* 62, 71– 80.

Su, M. D., Lin, C. H., Chang, L. F., Kang, J. L., and Lim, M. C. (2009) A probabilistic approach to rainwater harvesting system design and evaluation. *Resources, Conservation and Recycling* 53(7), 393-399.

Vieritz A, Gardner T, Baisden J (2007a) Rainwater TANK Manual. Natural Resource Sciences. Department of Natural Resources and Water. Distributed with the software model.

Vieritz A., Gardner, T. and Baisden, J. (2007b) Rainwater tank model designed for use by urban planners. Ozwater Convention & Exhibition (2007: Sydney, New South Wales) & Australian Water Association 2007, Proceedings: Ozwater Convention & Exhibition, 4 to 8 March 2007, Sydney, Australian Water Association, [Artarmon, N.S.W.]

Vieritz A.M., Neumann L.E. and Cook S. (2015) Chapter 2. Rainwater tank modelling. *In* Sharma, A.K. Begbie, D., and Gardner, T. (Eds). Rainwater Tank Systems for Urban Water Supply: Design, Yield, Energy, Health Risks, Economics and Social Perceptions. IWA Publication, Alliance House, London SW1H oQS UK, ISBN 9781780405353.