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Tackling rainwater shortages during dry seasons using a socio-technical operational strategy

Tulinave B. Mwamila, Mooyoung Y. Han, Tschung-il Kim and Preksedis M. Ndomba

ABSTRACT

The management of water resources during the dry season is a major challenge associated with rainwater harvesting (RWH) technology, but is necessary given the human suffering that follows from resulting conditions of water scarcity. In this study, the parameters for dry season assessment are defined in terms of 'no water days' (NWD) and rainwater usage ratio. A simple socio-technical operational strategy making use of a water level monitoring system is proposed for NWD reduction. This involves water level monitoring, whereby daily water demand varies with user cooperation, as based on the available water in a tank. The results of our study show that an NWD as low as 10 can be achieved as compared with the current value of 115 days, before considering investment on additional roof catchments and tank volume. These parameters are useful for analyzing any type of rooftop RWH system. Furthermore, this operational strategy can be made practical and simplified by incorporating an easily visible and understood guideline onto the RWH system. This strategy is replicable anywhere in the world, with consideration of site-specific conditions such as rainfall amounts, roof sizes, and population.

Key words | dry season strategies, no water days, rainwater harvesting system, rainwater usage ratio, water level gauge, water level monitoring

Tulinave B. Mwamila
Mooyoung Y. Han (corresponding author)
Department of Civil and Environmental Engineering
Seoul National University,
599 Gwanak –ro, Gwanak – gu,
Seoul 151-744,
South Korea
E-mail: *myhan@snu.ac.kr*

Tschung-il Kim
Integrated Research Institute of Construction and Environmental Engineering,
Seoul National University,
599 Gwanak –ro, Gwanak – gu,
Seoul 151-744,
South Korea

Preksedis M. Ndomba
University of Dar es Salaam,
P.O. Box 35131, Dar es Salaam,
Tanzania

BACKGROUND

To tackle the issues of water scarcity, rainwater harvesting (RWH) is being promoted as a sustainable alternative water source, especially in developing countries (Katambara 2013; Nguyen *et al.* 2013). It has also been proposed as a new water paradigm to address climate change (Kravčík *et al.* 2008). However, the rainwater quality maintenance and cost of RWH systems, as well as the effect of dry days, still pose major challenges.

For rainwater quality maintenance and improved portability, recommendations have been proposed for design measures, management techniques, and cheap treatment types such as solar disinfection (Worm & Hattum 2006; Amin & Han 2009; Lee *et al.* 2011, 2012).

For an increased use of RWH, especially in developing countries, the construction of cheaper alternative storage facilities has been initiated (Nega & Kimeu 2002; Thomas & Martinson 2007).

Despite these efforts, the major challenge affecting RWH technologies on a global basis is the occurrence of the dry season, leading to conditions of water scarcity. In light of this issue, the reliability of RWH systems has been assessed by a number of studies (Ndomba & Wambura 2010; Imteaz *et al.* 2012). The effect of increased inter-annual variability has also been acknowledged in previous research (Palla *et al.* 2012). The establishment of optimal tank sizes (Campisano & Modica 2012; Palla *et al.* 2012) and the strong impact of the antecedent dry weather period have also been considered. A reliance on dual water supplies has been suggested as a potential solution (Nguyen & Han 2013).

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Nevertheless, without the inclusion of a tangible guide, research feedback cannot be effectively put into practice, with the knowledge that most storage facilities are non-transparent. Moreover, when roof catchment sizes and water tank volumes are insufficient to handle daily usage, water shortages will inevitably occur.

This phenomenon was observed by the authors in a recent rooftop RWH demonstration project in a Tanzanian primary school (Mwamila & Han 2015). In that project, quality issues were dealt with by the incorporation of equipment such as a coarse screen, and a first flush and sedimentation tank. Any cost concerns were resolved as a corporate social responsibility (CSR) donation by Seoul National University Rainwater Research Center and Korean Society of Civil Engineers. Regardless, students were expected to be without water for at least 100 days.

The dry season refers to the period of time following the end of the rainy season, during which the available water storage is utilized without replenishment. In a situation where usage control is absent, water may be unavailable for basic uses at a moment's notice. This is because in most cases, people will likely maintain the same water usage habits as those prior to the onset of the dry season. This forces users to walk long distances to obtain water from alternative sources, which may be of questionable quality.

The purpose of this paper is to (1) define two parameters: NWD ('no water day') and RUR (rainwater usage ratio), to quantify the dry season and system efficiency, (2) recommend a socio-technical operational strategy using a simple water level monitoring system, and (3) evaluate NWD improvements for different operational scenarios.

METHODOLOGY

Site description

In February 2013, at Mnyundo Primary School in Mtwara, a region in southern Tanzania (Figure 1(a)), a 10 m^3 (two 5 m^3) RWH system (Figure 2) was constructed to serve a population of approximately 300 students, using one classroom roof with an area of 168 m^2.

Definition of parameters for dry season analysis

For the quantification of dry seasons and the realization of RWH system efficiency, the following parameters are defined.

(i) NWD: These are the days in a year when the storage tank contains insufficient water to meet usage demands.
(ii) RUR:

$$\text{RUR} = \frac{\text{water usage}}{\text{total amount of rainfall}} \times 100 \quad (1)$$

Dry season analysis of an existing rainwater harvesting system

The basic conditions adopted for analysis of the existing RWH system in Tanzania (Figure 2) included 10 m^3 of storage volume, 300 users, 168 m^2 of roof area, 0.8 as an assumed runoff coefficient (iron roof type), and a daily demand of 300 L/d (1 L/cap./d). Average daily rainfall

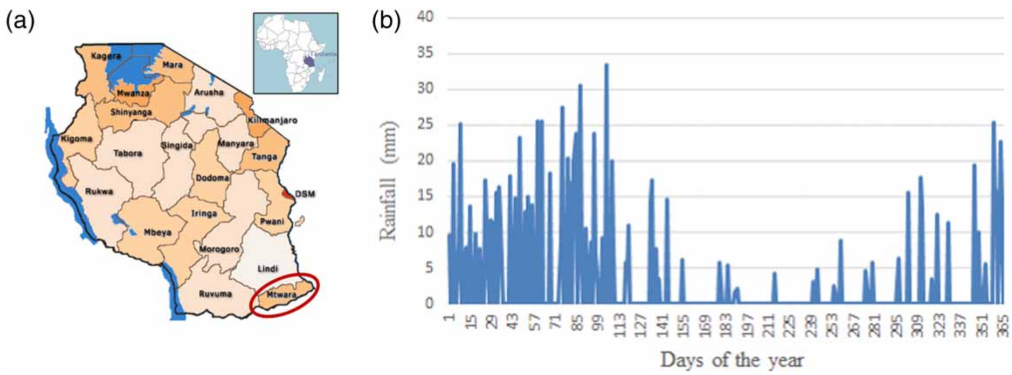

Figure 1 | (a) Location of the Mtwara region in Tanzania (modified from PMORALG (2010)). (b) Average daily rainfall distributions in the Mtwara region (modified from Tanzania Meteorological Agency).

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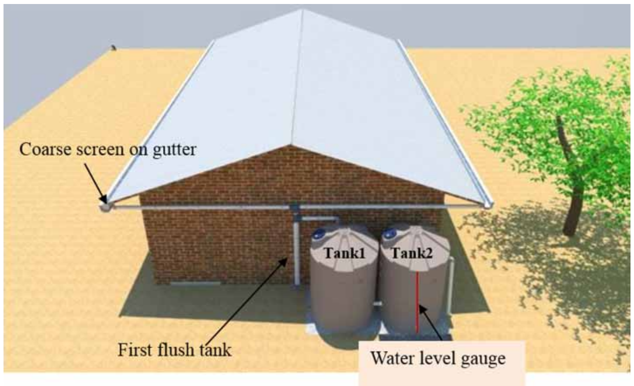

Figure 2 | Schematic representation of the rainwater harvesting system at Mnyundo Primary School, Mtwara, Tanzania.

data used were modified from monthly data for the years of 1990–2012, which were provided by the Tanzania meteorological agency (Figure 1(b)).

The analysis was performed using a simple daily water mass balance model (Mun & Han 2012) to determine daily consumption. The following overall cumulative water storage Equation (2) was utilized:

$$V_t = V_{t-1} + Q_t - Y_t - O_t \quad (2)$$

Current water use approaches

Fixed daily demand approach

It is a common practice for people to maintain consistent water consumption habits. Considering different fixed demand values, the impact of these habits on NWD, when applied to the school's RWH system, was analyzed. For this dry season analysis, demand values were considered from as low as 75 L/d (0.25 L/cap./d) to 900 L/d (3 L/cap./d). The following Equations (3) and (4) were utilized.

D_t is a fixed value

$$\text{For: } 0 < V_t \le S;\ V_t > S \quad Y_t = D_t;\ O_t \ge 0 \quad (3)$$

$$\text{For: } V_t < 0;\ V_t = 0 \quad Y_t < D_t;\ Y_t = V_{t-1} + Q_t;\ O_t = 0 \quad (4)$$

Daily demand restriction approach

In addition, daily demand restrictions were considered as based on rainfall variance (Nguyen & Han 2013). In this case, daily demand was varied in such a way that it could not be lower or higher than the defined minimum and maximum demand values, respectively, yet could be high enough to prevent the storage tank from overflowing (Equations (5)–(7)).

$$\text{For: } V_t > S,\ V_t = S \quad D_t = Q_t + V_{t-1} - S;\ Y_t = D_t; \quad (5)$$

$$\text{For: } 0 < V_t \le S \quad D_t = D_{\min};\ Y_t = D_{\min}; \quad (6)$$

$$\text{For: } V_t \le 0,\ V_t = 0 \quad Y_t < D_{\min};\ Y_t = V_{t-1} + Q_t \quad (7)$$

Proposed socio-technical operational strategy

The dry season strategy that is being introduced by this study involves water level monitoring. With this proposed strategy, the daily demand should be varied based on the available water level in the tank at the start of the day (Equation (8)). Water level scenarios (Table 1) were identified based on typicality, and were analyzed using the defined dry season parameters NWD and RUR. The above Equations (3) and (4) were also utilized.

$$D_t = f(W.L._{t-1});\ W.L._{t-1} = 0 \ldots 100\% \quad (8)$$

e.g., Scenario 1: if $W.L._{t-1} > 50\%$ then $D_t = 300$ L/d, else $D_t = 150$ L/d

In the above equations, V_t is the cumulative water stored in the rainwater tank (L) after the end of the tth day, Q_t is the harvested rainwater (L) on the tth day, O_t is the overflow amount (L) on the tth day, V_{t-1} is the storage in the tank (L) at the beginning of tth day, D_t is the daily rainwater demand (L) on the tth day, $D_{\min}$ is the minimum allowable daily demand (L), S is the capacity of the rainwater tank (L), Y_t is the water supplied (L) during the tth day, and $W.L_{t-1}$ is

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Table 1 | Current and proposed water level strategy scenarios, including their determined no water days (NWD) and rainwater usage ratio (RUR) values

Description	Scenarios	Water level (%)	Demand (L/d)	NWD (d)	RUR (%)
Current scenario		0–100	300	115	55
Proposed scenarios	1	>50	300	60	52
		<50	150		
	2	<75	600	84	74
		<75 and >50	450		
		<50 and >25	300		
		<25	150		
	3	>75	450	10	62
		<75 and >50	300		
		<50 and >25	150		
		<25	75		
	4	>70	600	77	73
		<70 and >30	300		
		<30	150		

the water level percentage in the tank at the beginning of the tth day. In this case, D_{min} was 300 L, D_{max} was 6,000 L, and S was 10,000 L.

RESULTS AND DISCUSSION

Analysis of the existing rainwater harvesting system

Under the basic conditions of the existing RWH system in Tanzania (Figure 2), at a daily demand of 300 L/d (1 L/cap./d), students were expected to suffer from water shortages for approximately 115 days.

Current water use approaches

Fixed demand approach

Considering various fixed daily demands (Figure 3), we observed that at higher usage values (e.g., 900 L/d), 95% RUR was achieved, but with values of up to 239 NWD and 1% overflow (percentage of harvested rainfall). Zero NWD could be achieved at usage values as low as 75 L/d, but with an RUR of only 20%. Thus, this strategy may not provide a practical solution for water scarcity during the dry season. It exhibits either a very high NWD due to low water savings, or extremely low RUR, since most of the water will overflow during the rainy season.

Daily demand restriction approach

During most of the days within the rainy months of February, March, and April, they could consume more than the minimum demand of 300 L/d (Figure 4): a maximum of 4,180 L/d could be consumed during certain days. Therefore, no overflow will occur, resulting in a high rainwater usage and 93.1% RUR, and the remaining 6.9% will be stored in the tank at the end of the year. However, with the current tank capacity, NWD was held constant at a

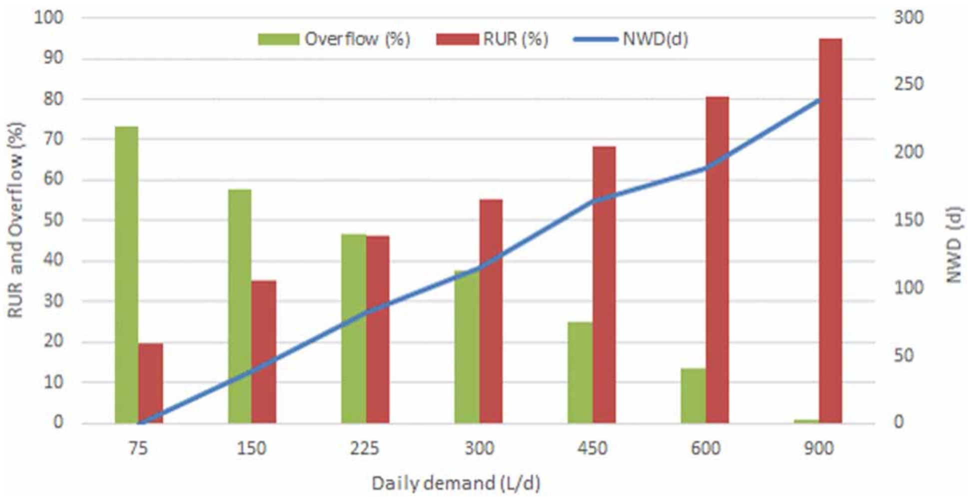

Figure 3 | Fixed daily demand approach analyzed for the number of no water days (NWD) and rainwater usage ratios (RUR).

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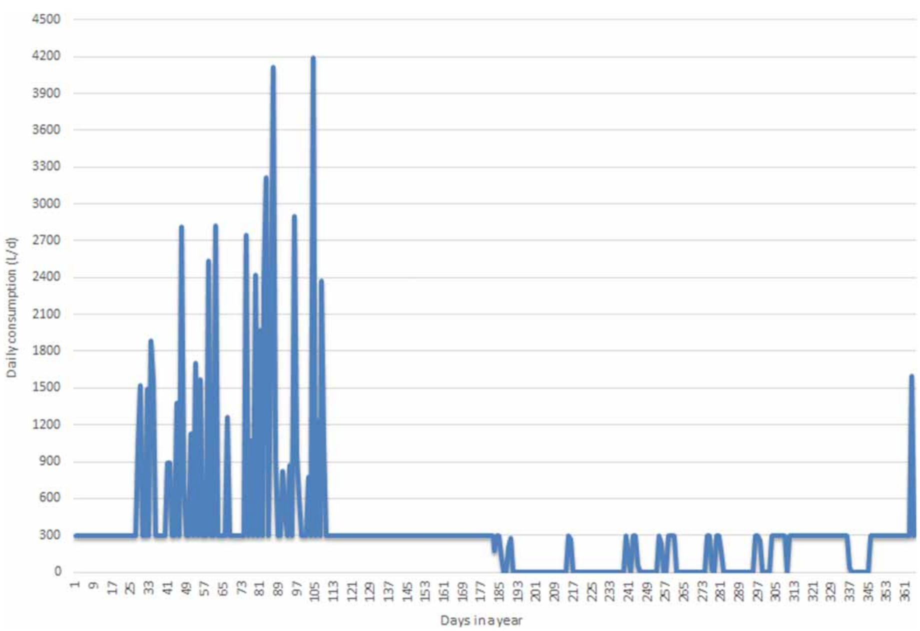

Figure 4 | Expected daily consumption upon the application of a daily demand restriction approach.

high value of 115 days. As well, this approach may not be very practical. It presents difficulties to children using this system, since it entails daily variations in consumption without specific physical guidance (Figure 4).

NWD are bound to occur in this experimental case, due to an insufficient storage capacity with respect to population size. The only solution in this case is to increase roof area by utilizing the remaining roofs, increase the storage size, or implement a water truck delivery system for use during the dry season. However, these costly options are currently unaffordable.

Nevertheless, the NWD can be adequately reduced in the meantime through water level monitoring, and the implementation of water use guidelines. These have been modeled by a modified water mass balance, incorporating various water level scenarios for the existing RWH system at Mnyundo School, and this approach was shown to be successful.

Proposed socio-technical operational strategy

In the absence of usage strategies, people tend to use water without regard to caution or planning, and maintain constant usage habits even during the dry season. The recommended water level monitoring strategy could be applied to new and existing RWH system designs for ensuring the elimination, or reduction, of NWD within a year. Dry season parameters, NWD and RUR, were determined for the proposed water level scenarios (Table 1).

The analytical results indicated that, scenario 3 was the most favorable for NWD reduction, due to its lowest exhibited value of NWD that, resulted in a reduction from 115 to 10 days out of the year. The other scenarios exhibited the following trend of decreasing favorability: scenario 3 → scenario 1 → scenario 4 → scenario 2 → current scenario (Table 1).

Furthermore, as indicated by the graphic representation of data derived from scenario 3 (Figure 5), although the water level at the start of day 296 was 0%, a demand of 75 L/d could still be accommodated. This is because of the occurrence of rainfall on that day, with the excess of the recommended demand as based on the water level being stored and distributed during the following days. In addition, there was an absence of water from days 231 to 239, which were dry days on which previous rainfall savings were already depleted. These can be considered as typical cases.

A designated individual is required to check the water level gauge prior to collecting water for daily use, and to translate it to the recommended consumption value. This water level monitoring strategy can be made practical by making use of a transparent water level gauge taped to

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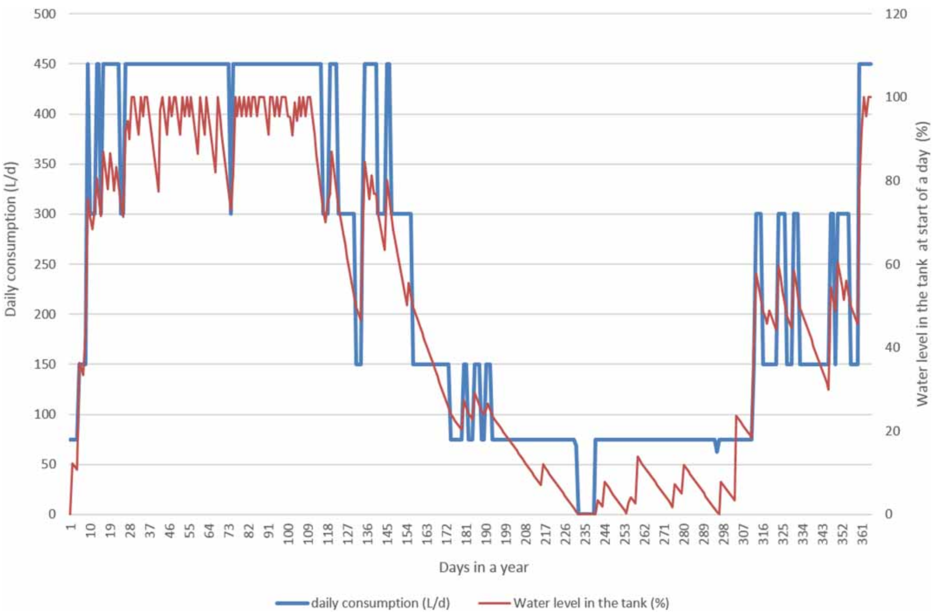
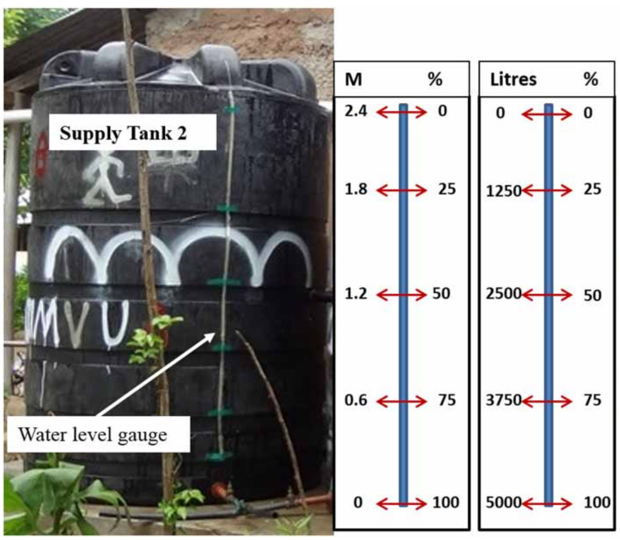


Figure 5 | Scenario 3, expected daily consumption with respect to the water level in the tank at the start of the day.



Scenario 3	
Water level (%)	Consumption (L/d)
100 → 75	450
75 → 50	300
50 → 25	150
25 → 0	75

Figure 6 | Application of the water level monitoring strategy.

the storage tank, and also providing a printed guideline attached to the storage tank close to the water level gauge (Figure 6). The simplification of these guidelines will encourage the cooperation and adherence of users during the dry season. The success of this strategy relies on the involvement of all users, whether skilled or unskilled. Users are thus placed in charge, should they desire NWD to be reduced. They should, therefore, be flexible in their water use, at times limiting it to more basic needs such as drinking.

CONCLUSION AND RECOMMENDATIONS

Rooftop RWH is an ideal option for developing countries, in terms of water quality, quantity, and accessibility. A major

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challenge to this strategy, however, is the occurrence of the dry season, which leads to prolonged water shortages.

In this study, the parameters for dry season assessment are defined as the number of NWD and RUR.

A simple socio-technical operational strategy that makes use of a water level monitoring system is being proposed for NWD reduction. This system of water level monitoring involves the variance of daily demand with user cooperation, based on the available water in the tank.

As a result, for the Mnyundo School in Tanzania, NWD as low as 10 days could be achieved, as compared with a previous value of 115 days, before additional investment is required for increased roof catchment areas and tank volumes.

These parameters are useful for analyzing all types of rooftop RWH systems. This operational strategy can be simplified, and made practical by incorporating a highly visible and easily understood guideline onto the RWH system. This strategy is replicable anywhere in the world by making use of site-specific conditions of rainfall quantities, population, storage, and roof sizes.

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