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Performance evaluation of rainwater harvesting system and strategy for dry season challenge

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Abstract

The extensive application of rainwater harvesting (RWH) projects is inhibited by the challenge posed by the dry seasons. In a case study of Mnyundo Primary School, Tanzania, the performance of the RWH system was evaluated using a daily water balance model. The methodology is based on defined dry season parameters – no water days (NWDs), rainwater usage ratio (RUR), and water level in local water storages; while the system operational methods involve users adopting either fixed (constant) demand or variable demand (demand varying with respect to available water in the storage tank), throughout the system utilization. Additionally, the cost of installing an RWH system to achieve a substantial reduction of NWDs to zero was calculated. It was established that the existing system cannot achieve zero NWDs under consideration of both operational methods. However, the greater the number of tanks, the lower the NWD, and in the variable demand operational method, better RUR was achieved. For mitigating water shortages in the dry season, the school should adopt RWH in two buildings under the demand scenario ($300 \leq$ demand ≤ 900 L/d, for the respective water levels in the storage tanks), yielding 58% RUR. The performance of the system can be improved by monitoring water levels and adhering to demand guidelines. These are useful strategies for practitioners in water supply.

Key words: demand operational methods, dry season challenges, dry season parameters, performance evaluation, rainwater harvesting

BACKGROUND

Rainwater harvesting (RWH) is a potential and sustainable alternative water source to solve water shortage problems, in particular, in developing countries (Mayo & Mashauri 1991; Nguyen *et al.* 2013).

Rainwater (RW) is commonly valued for its purity, softness and nearly neutral pH. However, its quality may deteriorate depending on the type and conditions of collection, delivery, and storage facilities. Despite this, several techniques have been researched and are recommended to ensure that the end user is at little or no risk from contamination. These techniques include pre-filtration and settlement, e.g., using screens, first flush tanks, and/or sedimentation tanks, enhancing biological reactions using mechanisms like biofilms, considering measures for inhibiting contaminant introduction and suspension in system design, and applying low-cost post treatment mechanisms like solar disinfection (Han & Mun 2007; Thomas & Martinson 2007; Amin & Han 2011; Mendez *et al*. 2011; Lee *et al*. 2012; Amin *et al*. 2013; Coombes 2015). Further, the challenge of investment cost has been addressed through strategies for cost reduction, including tank shape optimization, workshop production, construction and material quality reduction, labor, and beneficiaries' contribution (Thomas & Martinson 2007; Kihila 2014).

Several researchers have developed/applied models for optimizing tank size and assessing storage tank performance (Ndomba & Wambura 2010; Campisano & Modica 2012; Imteaz *et al*. 2012; Mun & Han 2012; Katambara 2013). Most such analyses consider fixed demand through the year, regardless of the variable nature of rainfall. For low demand, system reliability (the proportion of time when demand is fully met) may be higher, but with low RW use resulting in large overflow losses. When high demand is maintained, there is less chance of saving water to meet dry season demand. Some computations by researchers and field practitioners have also relied on annual/monthly rainfall data input, but these have been shown not to capture rainfall variability during the year (Zaag 2000; Imteaz *et al*. 2011; Mwamila 2016).

Despite the research efforts to date, dry seasons still pose a challenge for this technology and daily water demand is hard to meet. This has limited the adoption and prioritization of the technology in developing countries.

Recently an RWH demonstration project was conducted at Mnyundo Primary School, Mtwara Region, southern Tanzania (Figure 1(a)). The project has shown good potential for sustainability after evaluation (Mwamila *et al*. 2016).

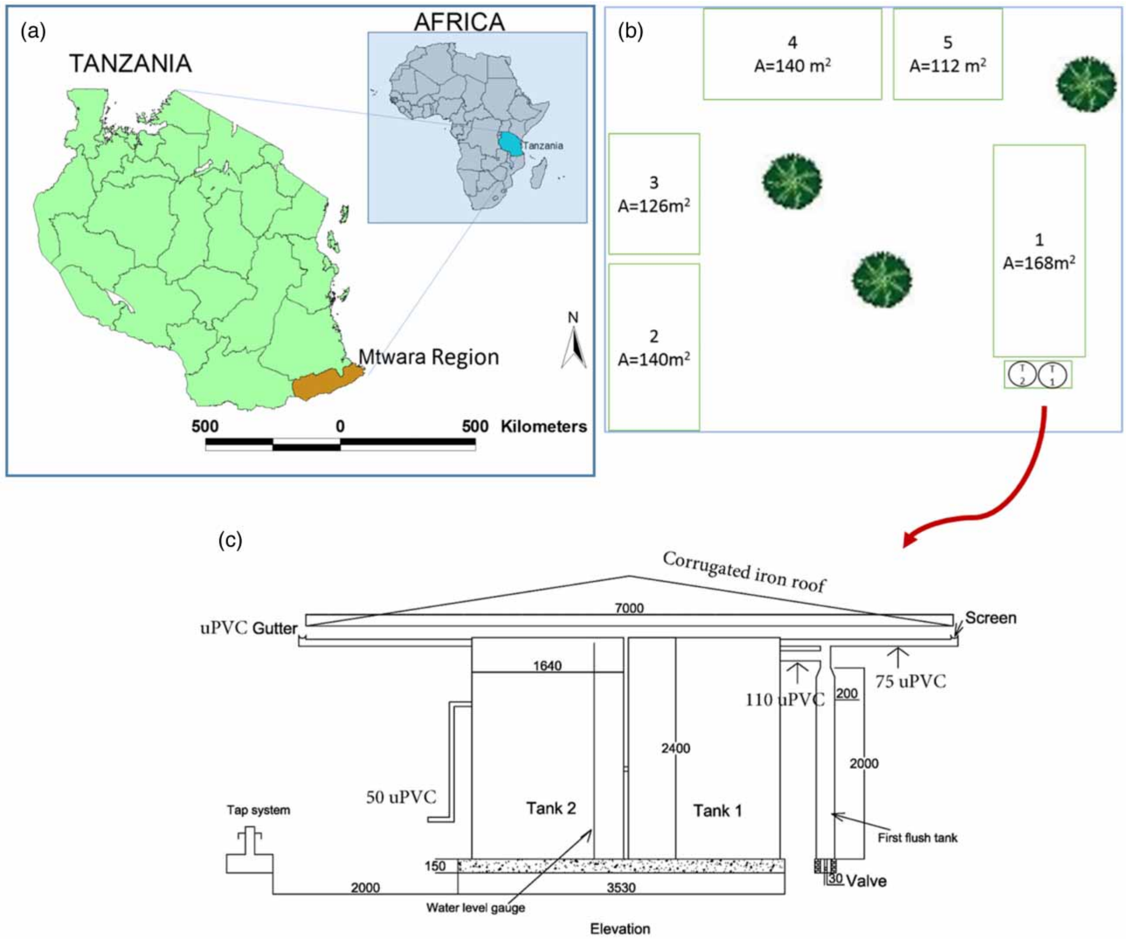

Figure 1 | (a) Mtwara Region, Tanzania (modified from PMORALG 2010), (b) Mnyundo Primary School layout, and (c) schematic of the RWH system.

The Mnyundo system incorporated technical components to ensure good harvested water quality, and a simple, functional, water-level monitoring system. Performance assessment parameters – no water days (NWDs), rainwater usage ratio (RUR), and water level in storage tank (WL) were defined and used. However, the system was inadequate because water users suffered for several days without water during the dry season. In an attempt to minimize NWDs using the existing system, a socio-technical strategy with variable demand application was introduced (Mwamila *et al.* 2015). Despite the strategy's potential for high NWD reduction in some demand scenarios, demand was still not fully met. Therefore, there was a need to consider extending the technology application by installing additional RWH systems in other buildings.

The objectives of this study are to: evaluate the performance of rooftop RWH technology due to increased number of rooftop RWH systems at the school; introduce a strategy to realize zero NWD through fixed and variable demand approaches, and; recommend a general methodology and strategy for RWH based on water level monitoring.

STUDY AREA

The RWH project was conducted in February 2013 at Mnyundo Primary School, a typical rural public primary school with no water supply facility. One of five buildings was used (Figure 1(b)) and the system comprised six main parts (Figure 1(c)). Seoul National University Rainwater Research Center and the Korean Society of Civil Engineers (KSCE) financed the project with an investment of US$3,600 as part of their corporate social responsibility (CSR) endeavor.

METHODOLOGY

Data types and sources

The basic parameters adopted for performance evaluation of the RWH system, included a storage volume of 10 m^3, population of 300, and a corrugated iron roof with a surface area of 168 m^2 and a runoff coefficient of 0.8 (Thomas & Martinson 2007). The authors considered all 365 days of the year, even though this is a day school (accommodating extracurricular activities in holidays and at weekends). Daily rainfall data were used (Figure 2).

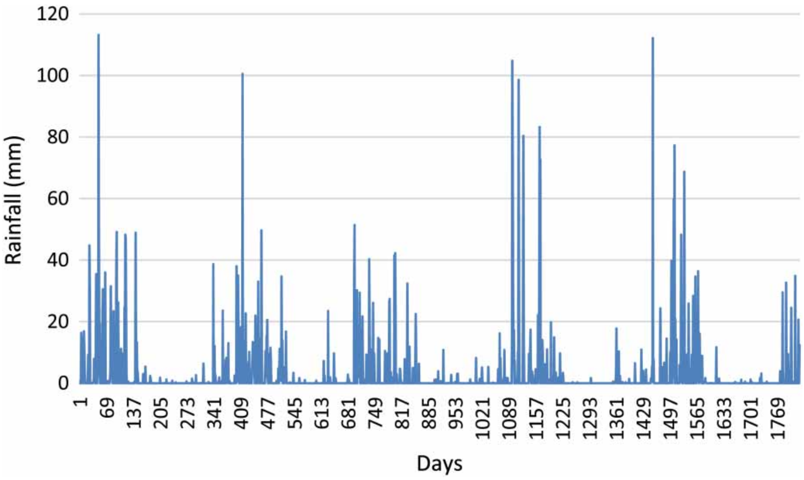

Figure 2 | Mtwara daily rainfall for the period January 2010 to December 2014 (source: Tanzania Meteorological Agency).

Data analysis

Analysis was performed using a simple daily water mass balance model with an overall cumulative water storage Equation (1). This incorporates the performance parameters for dry season quantification, NWD, RUR, and WL (Equations (2)–(5)).

$$\mathrm{V_t} = \mathrm{V_{t-1}} + \mathrm{Q_t} - Y_\mathrm{t} - \mathrm{O_t} \tag{1}$$

$$NWD = \frac{T - \sum_{t=1}^{T} WD}{T} \times 100 \tag{2}$$

$$RUR = \frac{\sum_{t=1}^{T} Y_t}{\sum_{t=1}^{T} Q_t} \times 100 \tag{3}$$

$$WL_{t-1} = \frac{V_{t-1}}{S} \times 100 \tag{4}$$

$$D_t = f(WL_{t-1});\ WL_{t-1} = 0 \ldots 100\% \tag{5}$$

where, Q_t is the RW harvested on the t^{th} day; V_{t-1} is the volume of RW stored in the tank at the beginning of the t^{th} day; D_t is the daily RW demand on the t^{th} day; Y_t is the RW supplied during the t^{th} day; WD is a day on which the demand is fully met; T is the total number of days in the year or years considered; V_t is the cumulative volume of water stored in the RW tank after the end of the t^{th} day; O_t is the overflow volume on the t^{th} day; WL_{t-1} is the water level in the tank at the beginning of the t^{th} day, measured as a percentage of the full level; and S is the total storage capacity. All volumes are measured in liters.

The analytical methods included fixed and variable daily demand scenarios (Table 1). Variable demand, based on the water level available in the tank at the beginning of the day (Equation (5)), is a novel approach devised by Mwamila *et al.* (2015) and involves water level monitoring. This approach entails making use of a water level gauge and a water use guideline taped to the storage

Table 1 | Fixed and variable daily demand scenarios for system operation

Daily demand scenarios				
Fixed		**Variable**		
ID	**Demand (L/d)**	**ID**	**Water Level (%)**	**Demand (L/d)**
F1	150	V1	>50	300
F2	300		≤50	150
F3	450	V2	>75	600
F4	600		≤75 and >50	450
			≤50 and >25	300
			≤25	150
		V3	>75	450
			≤75 and >50	300
			≤50 and >25	150
			≤25	75
		V4	>70	900
			≤70 and >30	600
			≤30	300

tank, and, in this case, a designated individual is required to check the water level gauge and refer to the guideline prior to collecting water for daily use.

Performance evaluation was based on dry season parameters, operational methods, and construction cost. It was carried out for both the existing system and the consideration of additional systems in the school. In all cases, the same construction costs were assumed (Table 2) regardless of roof size (which varies little). Using two, three, four, or five buildings will thus incur multiples of the same cost as that for the existing system.

Table 2 | RWH system construction cost considerations for Mnyundo Primary School

Number of buildings	Total roof size (m^2)	Total tank size (m^3)	Construction cost (US$)	Remarks
1	168	10	3,600	Existing case
2	308	20	7,200	Proposed cases
3	434	30	10,800	
4	574	40	14,400	
5	686	50	18,000	

RESULTS AND DISCUSSION

Performance evaluation of the existing RWH system

The existing system cannot achieve zero NWD under any of the daily demand scenarios (Figure 3). With demand fixed as F1 (150 L/d), the minimum NWD attainable is 25% with 29% RUR, implying significant overflow losses. For higher demand values – F2, F3, F4 – RUR and NWD increased accordingly. An optimal operational approach with reasonable values for both NWD and RUR, would be by adopting demand values in the range of F3 to F4, and resulting to RUR above 50%, and NWD in the range 51 to 59%. The resulting NWD are equivalent to more than two years of insufficient water. The optimal operational approach under variable demand was V3, with improved NWDs and RUR at 20 and 52%, respectively. This implies further reduction of overflow losses and over 50% reduction in NWDs compared to the fixed demand approach.

Performance evaluation of extending RWH technology at the school

A graphic representation of the expanded system was established, to determine the performance of different numbers of tanks relative to construction costs (Figures 4 and 5). Under fixed demand conditions, zero NWD can be achieved when:

- the system is installed in three buildings with RUR limited at 15% for F1;
- the system is installed in four buildings with RUR limited at 11% for F1; or,
- the system is installed in five buildings with RUR limited at 9 and 19% for F1 and F2, respectively.

When an attempt was made to reduce NWD and increase RUR, in scenario F4 with the system installed in five buildings, 20% NWD and 31% RUR were achieved. The implementation cost is four times that of the existing system, and over 50% of the harvested RW is lost as overflow.

On the other hand, under variable demand conditions, zero NWD can be achieved when:

- the system is installed in three buildings with RUR limited at 30% for V3;
- the system is installed in four buildings with RUR limited at 20 and 25% for V1 and V3, respectively; or,

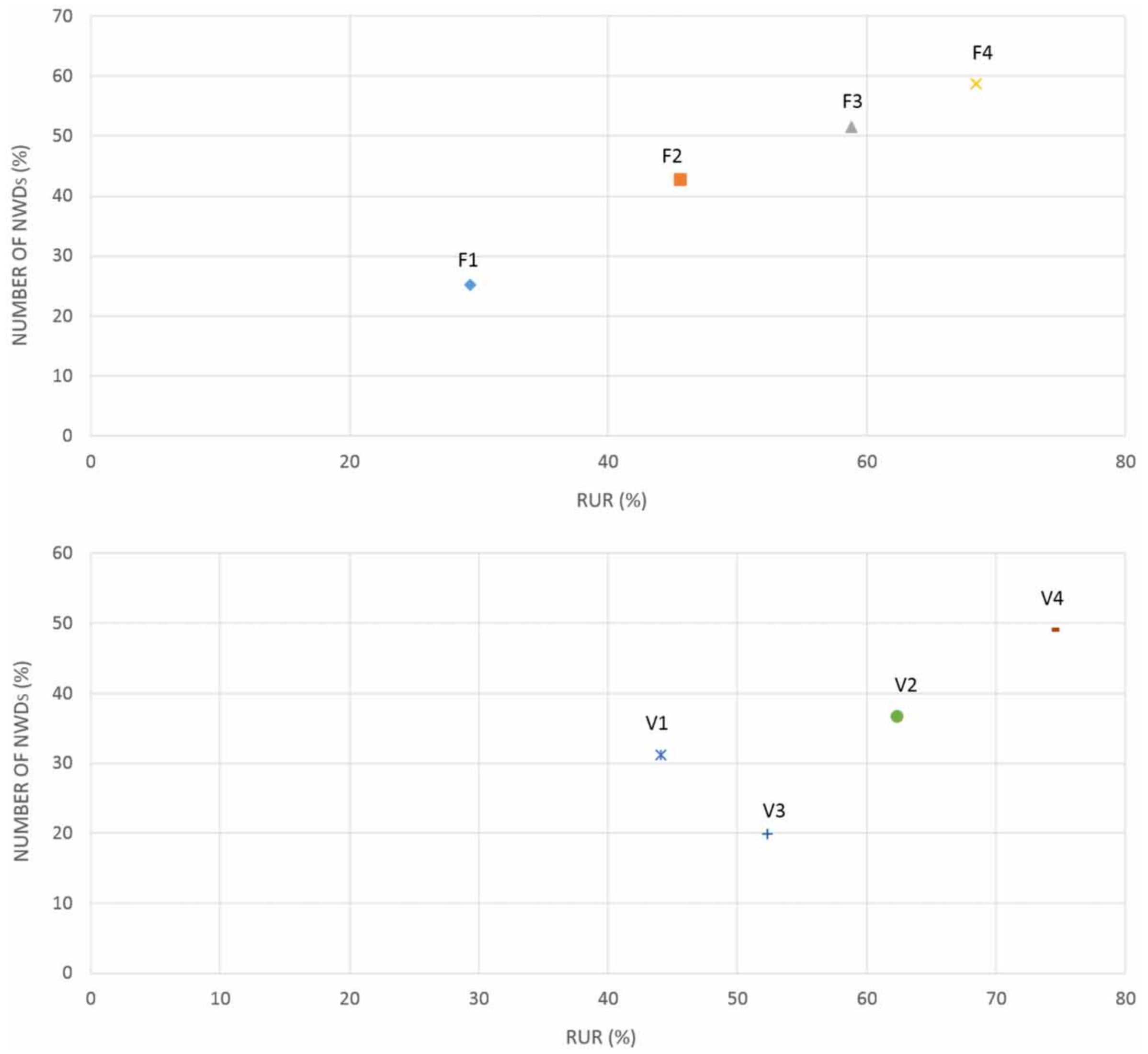

Figure 3 | Performance of the existing RWH system under fixed and variable demand conditions.

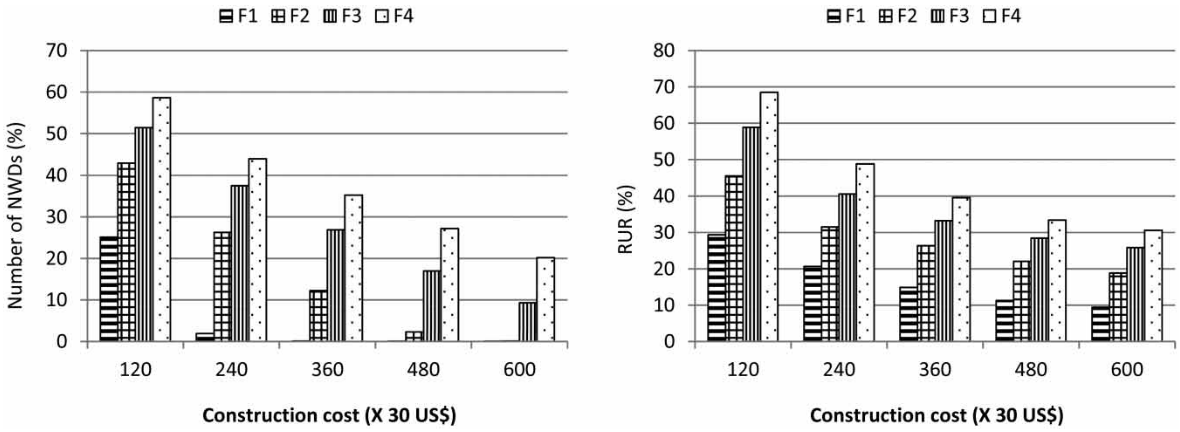

Figure 4 | Performance of RWH systems under fixed demand conditions and cost implications.

- the system is installed in five buildings with RUR limited at 18, 28, 22% for V1, V2, and V3, respectively.

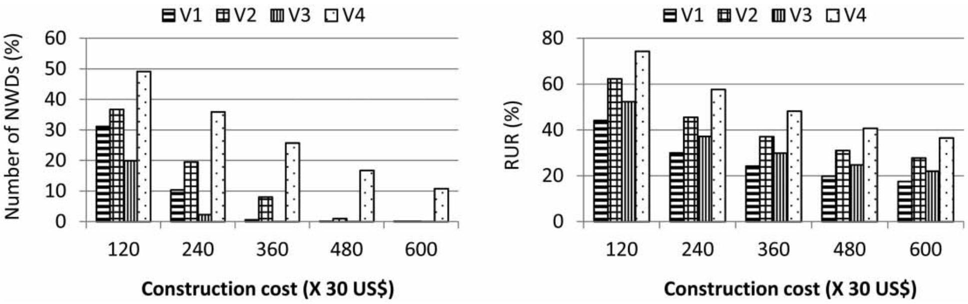

Figure 5 | Performance of RWH systems under variable demand conditions and cost implications.

For the two building case, in scenario V4, a reduced NWD of 36% and increased RUR of 58% are achieved. This is better, considering the performance parameters, and the implementation cost (an additional US$3,600) is comparatively lower than that for the scenario involving system installation in five buildings.

Proposed strategies for mitigating water shortages in the dry season

Increasing the number of RWH systems reduces the number of NWDs. However, with fixed demand, even at high demand values, the RUR is lower than that achieved with the variable demand operational approach. The latter offers useful solutions, however, considering the need to both reduce NWDs and increase RUR, because it takes the variable nature of rainfall into account. In addition, from the viewpoint of reducing construction costs, several suggestions are proposed for Mnyundo School to address the water shortage challenge during the dry season:

- For zero NWD, scenario V3 with three buildings is most favorable, at 30% RUR.
- For lowering NWD and simultaneously increasing RUR, scenario V4 is preferable, using two buildings to achieve 36% NWD and 58% RUR.

To make an additional RWH system affordable and improve sustainability, a recently proposed socio-economic model (Mwamila 2016) can be adopted. This promotes full, economic involvement of the private sector and community. Considering the social aspects of the project, complete engagement of the public and private sectors, and the community is recommended. The economic benefits of this are expected to include achievement of CSR, strong sense of ownership, and new synergistic business opportunities. The social benefits include active participation of community members, increased technical know-how, better maintenance and system monitoring, and better access to local working data and incentives.

CONCLUDING REMARKS

The case study at Mnyundo Primary School, Tanzania, has proven that RW can become a drinking water resource if managed properly. However, the number of NWDs during dry seasons form a bottleneck. Performance of an RWH system can be evaluated on the basis of NWD and RUR. For improved performance, high RUR and low NWD must be achieved.

The RWH system costs associated with meeting a requirement for zero NWDs were determined for different daily water demand and operational method scenarios. It was established for this school that the existing system cannot achieve zero NWD under either fixed or variable demand approaches. However, the greater the number of tanks the lower the NWD, and, in the variable demand approach, better RUR is realized.

As a strategy to mitigate water shortage during dry seasons, the school should adopt RWH in two buildings under the V4 demand scenario. This will achieve 58% RUR and 36% NWD, at an additional cost of US$3,600. The success of the strategy relies on all users, as they can affect directly whether NWD and RUR are reduced and increased respectively, through their flexibility in water use.

The defined dry season parameters can be used to evaluate the performance of any RWH system. Through cooperation in water level monitoring and by adhering to the demand guidelines, performance can be improved. These are useful approaches for practitioners in the field of water supply, and can be replicated elsewhere under site-specific conditions of rainfall amount, catchment and storage volumes, and costs.

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