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Strategies for Household Water Supply Improvement with Rainwater Harvesting

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Abstract

There are significant household water supply challenges including quantity sufficiency and quality, which have economic and social implications. The challenges have remained despite the efforts of government establishing centralized or groundwater systems, and/or having individual crude systems. A Tanzanian rural household case study was considered by assessing the performance of a currently relied surface runoff collecting pond system for domestic purposes. A daily water balance model was applied with performance parameters, no water days (NWD) and rainwater usage (RUR). Rooftop runoff harvesting system was proposed as a water supply source in addition to the current one. Under such dual supply conditions, users can meet the drinking and non-drinking demand even in dry seasons at a minimum of 2 and 20 L/person/d, respectively. For rainwater harvesting adoption (considering selected regions), it was further established that amount and variation in rainfall impacts on quantity available for meeting demand. Increased catchment implies increased harvestable quantity, and with same storage higher reduction of number of NWD although with slight decrease of RUR. Also, increased storage is required for achieving higher RUR in case the same demand is maintained. But same storage can be maintained for increased demand relative to catchment size. However, rainwater catchment increase has greater impact on meeting a specified demand under given condition of rainfall quantity and variation. The RWH technology strategies presented in this study are replicable in other developing countries under site specific conditions.

Keywords

Dual Water Supply, Household Water Supply, Rainwater Harvesting Strategies, Rainwater Harvesting Technology, Tanzania

1. Introduction

A third of the Africa's population, is living in a water scarcity situation. To address this, the Africa Water Vision 2025 was established, which highlighted that underdevelopment and low water resources usage in Africa was due to poor financing and technology but not inadequacy of available water resources. Rainwater harvesting (RWH) has low cost and is capable of performing with low technology and in a decentralized manner.

Even though Tanzania, an eastern African country (**Figure 1**) is recognized with abundant annual renewable water resources of approximately 89 km^3 [1] and annual rainfall ranging from 400 to 2000 mm, the country still suffers water shortages. Low drinking water service coverage, which is 40% and 74% in rural and urban areas, respectively [2].

Efforts to address water supply problems and challenges in Tanzania have included centralized systems which have high operation and maintenance cost, and are limited to urban areas. Community based groundwater systems which include springs and wells, which also have problems including water point malfunctioning, limited supply chain and overexploitation of sources. Individual crude systems have challenges of low water quality, insufficient quantity as well as poor infrastructures.

Springs are the highest sought water supply source type, followed closely by shallow wells, and then boreholes, but rainwater harvesting (RWH) is one of the least sought [4]. In a GIS based RWH potential study, [5] established that harvestable rainwater for the medium rainfall (400 - 1200 mm), high population (>100 persons/km^2) rooftop domain ranges from 115.6 to 346.8 km^3 (which generally displays high ability to meet daily water demand), and occupies 38.3% of the country area.

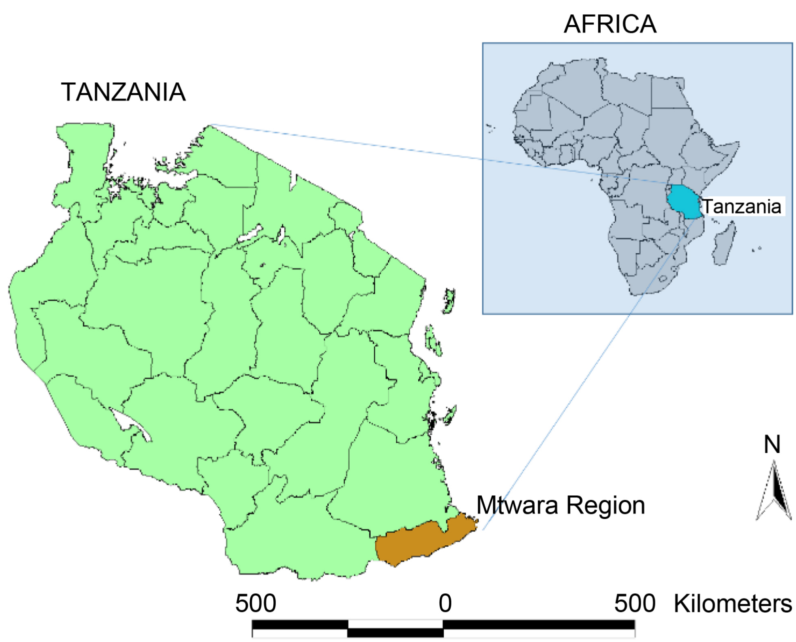


Figure 1. Location map of Tanzania and its regions (Modified from [3]).

RWH is a potential and sustainable alternative water source to solve water shortage problems, in particular, in developing countries [6] [7]. With simple strategies rainwater can meet demand even during the dry season [8] [9]. Rainwater quality can meet Tanzania and WHO standards with simple techniques including those of particle load reduction, which may have resulted from the type and conditions of collection, delivery, and storage facilities [10]-[16]. Further, the challenge of investment cost has been addressed through strategies of promoting self-supply and funding initiatives including micro-financing [17] [18].

The objectives of this study are as follows: 1) establishing rooftop RWH potential to improve household water supply; 2) suggest strategies for better water supply practice with adoption of rooftop RWH in Tanzanian regions.

2. Methodology

The analysis was performed using a simple daily water 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) (3) and (4a)), defined by [9]. The authors considered all 365 days of the year, even though the site is a day school. Average daily rainfall data were used (**Figure 2**). Both fixed and variable demand conditions were considered. Variable demand was considered under water level monitoring strategy, Equation (4b) [8]. Equations (5) and (6) are the basic demand conditions.

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

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

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

$$\text{(a)} \quad WL_{t-1} = \frac{V_{t-1}}{S} \times 100; \quad \text{(b)} \quad D_t = f\left(WL_{t-1}\right); \quad WL_{t-1} = 0\%, \cdots, 100\% \tag{4}$$

D_t is a fixed value

For: $0 < V_t \le S; V_t > S$

$$Y_t = D_t;\ O_t \ge 0 \tag{5}$$

For: $V_t < 0; V_t = 0$

$$Y_t < D_t;\ Y_t = V_{t-1} + Q_t;\ O_t = 0 \tag{6}$$

where, Q_t is the rainwater harvested on the t^{th} day; V_{t-1} is the stored rainwater in the tank at the beginning of the t^{th} day; D_t is the daily rainwater demand on the t^{th} day; Y_t is the rainwater 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 a year; V_t is the cumulative water stored in the rainwater tank after the end of the t^{th} day; O_t is the overflow amount on the t^{th} day; WL_{t-1} is the water level percentage in the tank at the beginning of the t^{th} day; and S is the storage capacity.

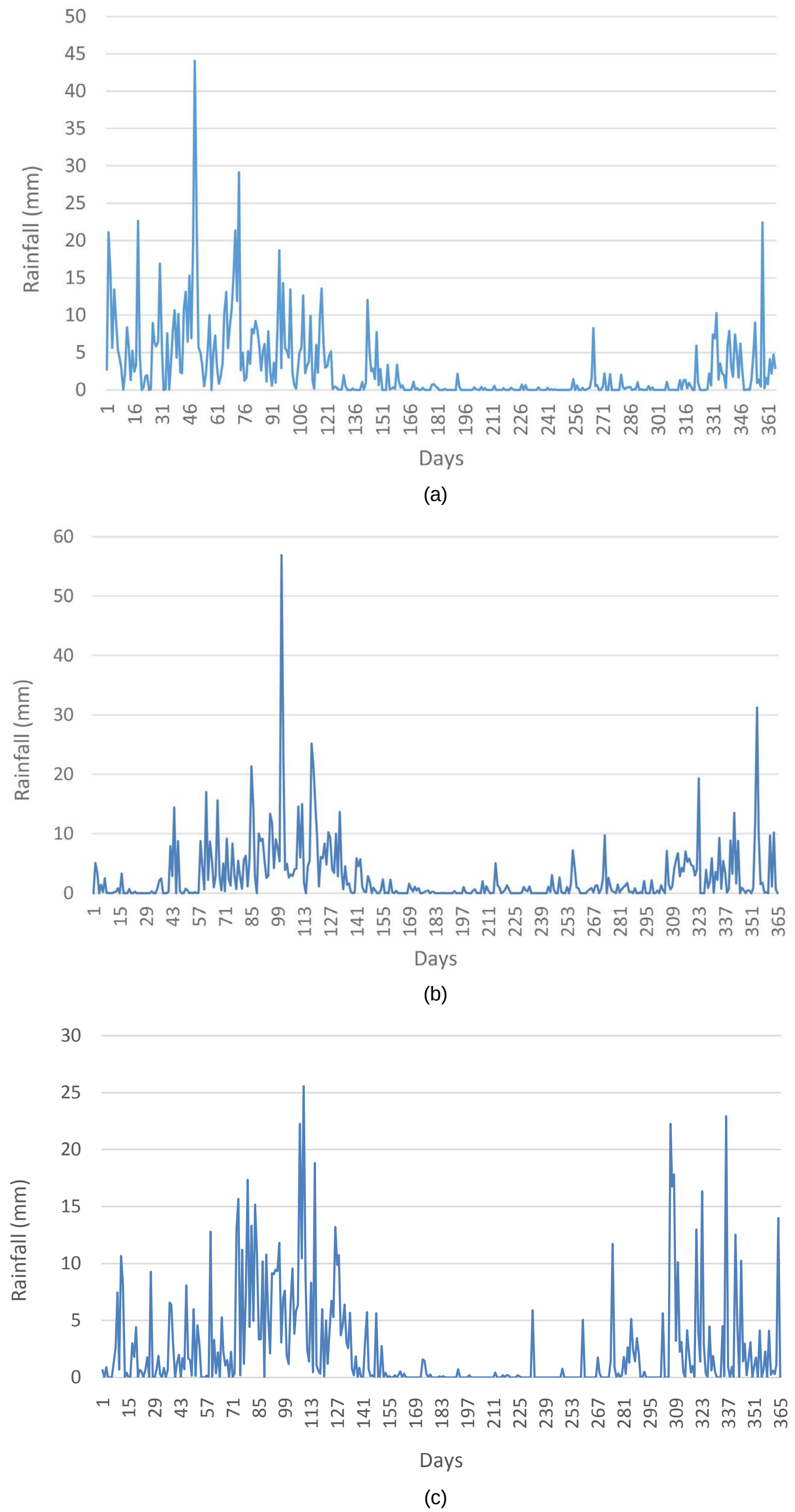


Figure 2. Average daily rainfall data for the period 2010-2014 for, (a) Mtwara, (b) Dar es Salaam, and (c) Arusha Regions (Source: Tanzania Meteorological Agency).

2.1. Rural Household Case Study

Mtiniko is a village within Mtiniko Ward, which is among 28 wards located within the Mtwara rural LGA in Mtwara Region. Thatched roofs accounts for 80% of roof types, whereas only 20% are iron. Individual efforts to address water supply challenges have led to a common practice of constructing open cemented ponds, which collect and store surface water runoff during the rainy season. The collected water is used mainly for domestic purposes.

2.2. Challenges of Current Water Supply Practice

Quantity and quality challenges of currently adopted practices affect the economy of the households, limiting opportunities for social empowerment of the village.

2.2.1. Water Quantity Sufficiency

Because the pond is open, precipitation falls directly into the pond during the rainy season. Depending on the size of the pond and quantity of rainfall, rainwater loss during the rainy season will be mainly due to overflow only, whereas during the dry season, in addition to daily consumption, losses from evaporation are significant. Annual evaporation in the country is estimated at 2000 mm [19], which if divided equally among the 117 dry days of an average year (**Figure 1(a)**), is approximately 17 mm. A low runoff coefficient of at most 50%, due to seepage into the catchment, further reduces quantity harvested from a given rainfall.

2.2.2. Basic Condition

The daily water balance model, with modifications incorporating evaporation losses in case of an open pond, was applied to assess the pond performance during the year under fixed demand conditions. The following were basic conditions: population, 5; catchment size, 150 m^2; pond area, 12.6 m^2; and volume, 20 m^3. Evaporation was considered significant for those days when rainfall ≤ 2 mm and the C is 0.5.

2.2.3. Analysis Feedback

Figure 3 illustrates the current pond performance. The lowest NWD is 70 NWD which is at a lower demand of 100 L/d and corresponds to 41% RUR.

2.2.4. Water Quality Concern

Algal growth was an obvious challenge at one site in Mtiniko village. This may have been promoted by the openness of the pond, exposing it to the sun and nutrients from the surroundings, which could easily find their way into the pond through wind effect and runoff from rainfall. Means of accessing water by users is through dipping bucket. The samples were collected and analyzed (within 2013 and 2014) for physical, chemical, and microbiological quality at the Mtwara Zonal and University of Dar es Salaam Water Quality Laboratory. Based on water quality results (**Table 1**), the pond at Mtiniko village failed the color test and had high total coliform counts, which were also measured in the samples from the other two villages.

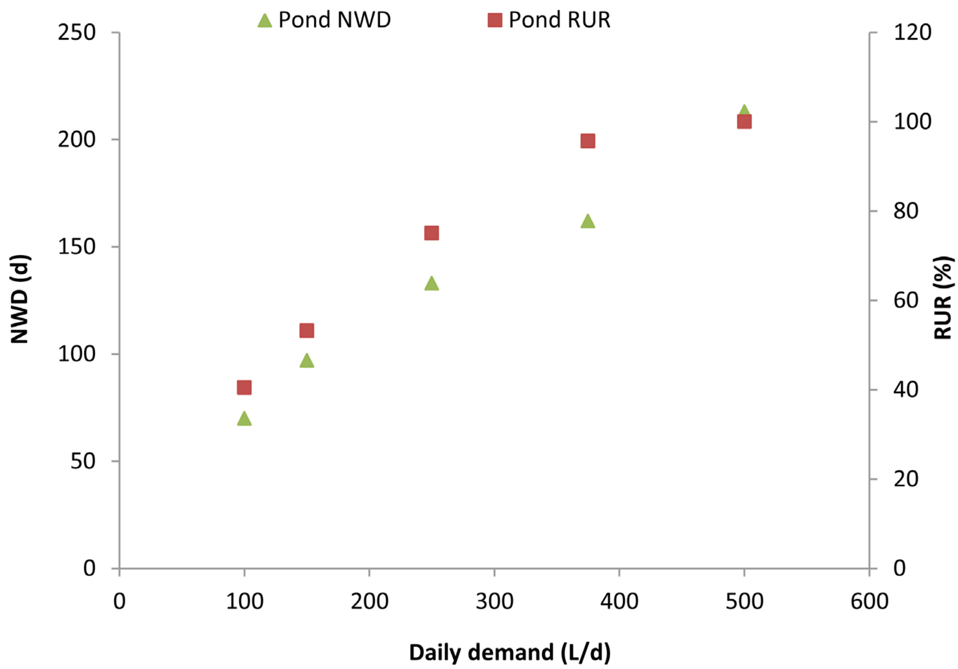


Figure 3. Performance of an open pond under fixed demand conditions.

Table 1. Water quality test results for samples from relied water sources within Mtwara District.

S/N	Parameter	Sampling Villages (source type)			Standards	
		Mtiniko (Pond)	Dinyecha (RWH tank)	Nanguruwe (Pond)	TZ	WHO
1	pH	6.56	8.5	5.75	6.50 - 8.50	6.5 - 8.5
2	Total Dissolved Solids (mg/l)	90	75.7	72.6	1000	1000
3	Colour (Pt.Co)	24	0	7	15	15
4	Total Hardness (mg/l) as $CaCO_3$	30	8.1	5.6	500	200
5	Sulphate (mg/l)	13	1	24	400	500
6	Chloride (mg/l)	5.0	2.72	25.45	250	200 - 300
7	Sodium (mg/l)	2.6	0	1.2	200	200
8	Faecal coliform (No./100 mls)	Not tested	11	37	Nil	Nil
9	Total Coliform (No./100 mls)	165	27	270	Nil	Nil

2.2.5. Strategies for Improving Water Supply Practice

For ensuring sufficient demand satisfaction, not only is pond covering recommended but having a simple rooftop RWH system is as well. These can be relied on in a dual manner, with drinking water taken from the RWH system and pond water used for nonpotable purposes to address quality concerns (Figure 4). RWH systems are a possibility as most households in this village had at least one building with an iron roof, even

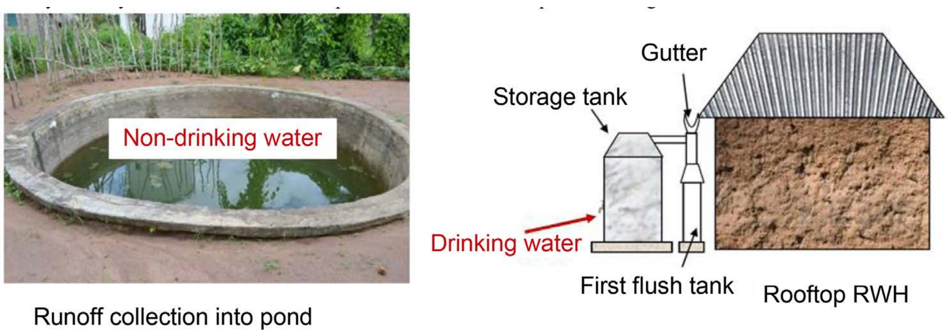


Figure 4. Proposed reliance on both surface and rooftop rainwater runoff collection.

if the walls were made of clay. Locally available materials such palm tree can be used in pond covering.

Further analysis was performed to establish a good application strategy. Basic conditions for rooftop case included, roof size of 18 m^2 with a runoff coefficient of 0.8. The storage capacities assessed were 0.5, 1, 1.5, 2.2, and 3.2 m^3 for a population of 5. Variable daily demand scenarios considered are shown in **Table 2**.

Scenario 1 offers better covered pond performance with NWD, and RUR values of zero d, and 58%, respectively (**Figure 5(a)**). For rooftop harvesting, Scenario 3 showed better performance with RUR above 50%. Considering increased storage size results in increased construction cost regardless of the type of material used, therefore, 2.2 m^3 is the optimal solution. This storage capacity results in zero NWD and a RUR of 54% under Scenario 3 (**Figure 5(b)**).

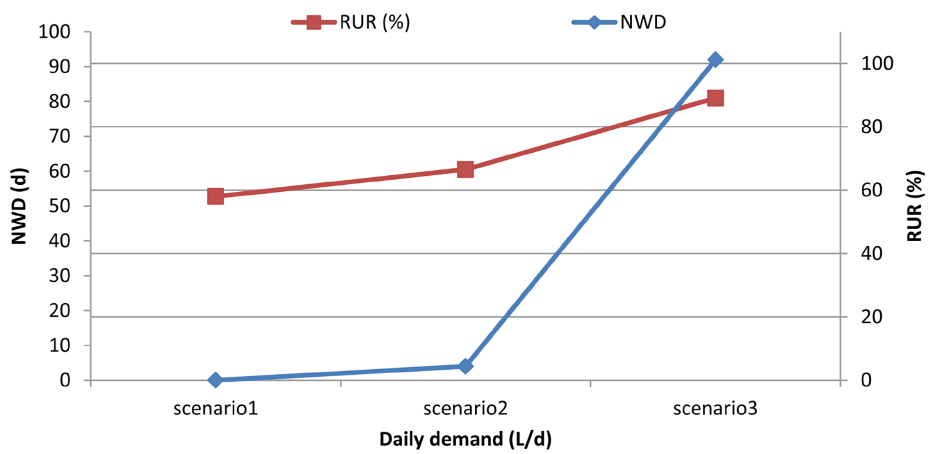
For total demand satisfaction throughout the year, both harvesting techniques can be adopted to work as a dual water supply. **Figure 6(a)** shows that during the rainy season the locals can rely on rooftop water for both drinking and cooking with up to 37.5 L/d, whereas during the dry season, it would only be used for drinking purposes at 10 L/d. During the rainy season, the pond (**Figure 6(b)**) can source up to 150 L/d of water for meeting household demands other than drinking, but during the dry season the usage would be limited to 100 L/d. This combination strategy assure the locals that even on dry days there should be at least 2 and 20 L/person/d for drinking and nondrinking purposes, respectively.

3. Strategies for Water Supply Practice with RWH in Tanzanian Regions

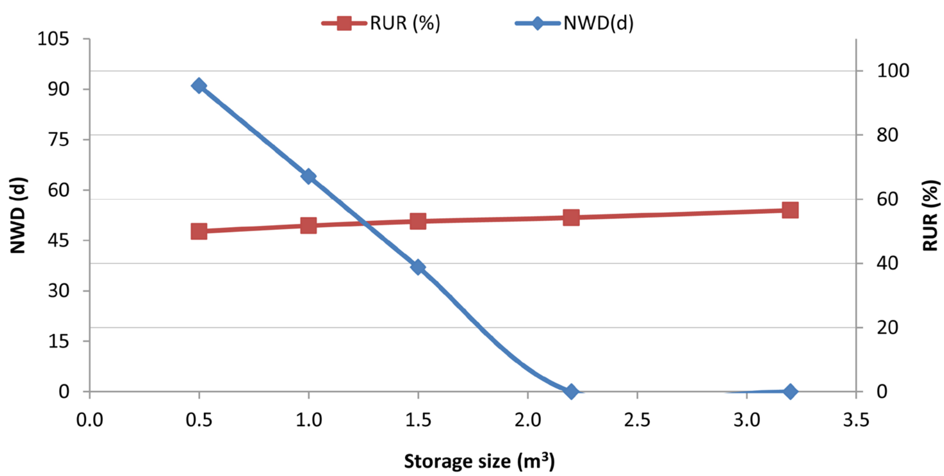
The national water sector development strategy [20] on the service level has aims to provide a minimum of 70 L/person/d for consumers with household connections to a water supply system. Analysis considered household cases in three regions, Mtwara, Arusha and Dar es Salaam (DSM). Arusha and DSM regions are located in the northern and southeastern part of the country, respectively (**Figure 1**). Basic conditions included, population, 5 (average country household size); rooftop size, 60 and 100 m^2; runoff coefficient, 0.8; storage size, 5 and 10 m^3; and fixed demand, 70 and 100 L/person/d. Supplement displays percent of annual water demand that would not be met

Table 2. Variable daily demand scenarios for the pond and rooftop cases.

Scenarios	Pond		Roof	
	Water level (%)	Demand (L/d)	Water level (%)	Demand (L/d)
1	>50	150	>50	15
	≤50	100	≤50	10
2	>50	200	>70	25
	≤50	100	≤70 and >30	15
			≤30	10
3	>70	375	>75	37.5
	≤70 and >30	250	≤75 and >50	25
	≤30	150	≤50 and >25	15
			≤25	10



(a)



(b)

Figure 5. Performance of (a) covered pond, and (b) rooftop harvesting, systems in variable demand.

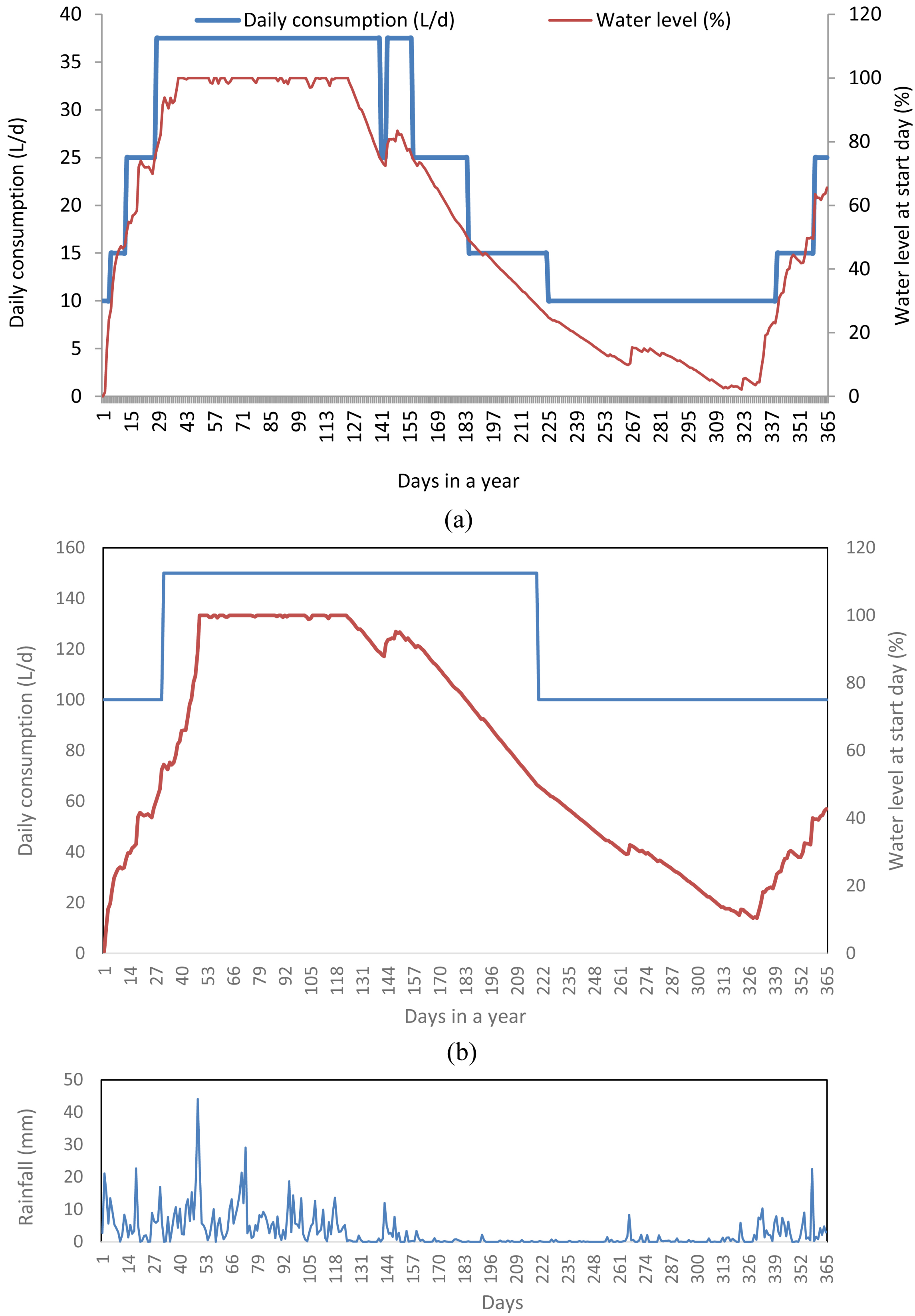


Figure 6. Recommended daily consumption in combined rooftop (a) and surface (b) runoff harvesting.

through RWH, hence demanding alternative sources.

Amount and variation in rainfall impacts on quantity available for meeting demand (Table 3). Mtwara (even though under unimodal rainfall regime), having highest average annual rainfall has lowest NWD and supplement requirement. Further, at limited catchment, increased storage may have no impact on NWD or RUR e.g., 60 m^2.

Moreover, increased catchment implies increased harvestable quantity (Table 3). With same storage, higher reduction of NWD although with slight decrease of RUR e.g., DSM at 5 m^3 where number of NWD reduction is equivalent to 2 months. As well, increased storage is required for achieving higher RUR in case the same demand is maintained, e.g., at DSM there is 6% increase in RUR with 10 m^3 at 70 L/person/d. But same storage can be maintained for increased demand relative to catchment size e.g., DSM there is a difference of 1% RUR between the two catchment sizes at 10 m^3. Generally, with 60 m^2 over 23% of annual demand can be met (at least 1.2 months are fully served), and in 100 m^2 over 38% of annual demand can be met (at least 3.5 months are fully served).

Rainwater catchment increase has greater impact on meeting a specified demand under given condition of rainfall quantity and variation (Figure 7). RWH is capable of reducing the stress of water shortage in both urban and rural areas. Additional sources can supplement rainwater especially in dry season to maintain the desired demand, hence dual system.

Self-financing initiatives should be introduced and promoted including microfinancing, to empower citizens to address own water challenges with RWH. Government should offer incentives, subsidies for those taking responsibility in addressing own water challenges. Increased training on alternative water supply sources e.g., RWH,

Table 3. Performance variation of rainwater harvesting system in the selected regions of Tanzania.

Demand (L/d)	Storage (m^3)	Regions	Roof area-60 m^2			Roof area-100 m^2		
			NWD (d)	RUR (%)	Supplement (%)	NWD (d)	RUR (%)	Supplement (%)
70	5	DSM	273	100	63	208	81	50
		Mtwara	250	100	60	192	78	48
		Arusha	280	100	67	214	87	52
	10	DSM	273	100	63	193	87	46
		Mtwara	250	100	60	175	84	44
		Arusha	280	100	67	199	94	48
100	5	DSM	325	100	74	260	93	60
		Mtwara	319	100	72	229	94	56
		Arusha	328	100	77	259	98	62
	10	DSM	325	100	74	249	99	57
		Mtwara	319	100	72	219	100	54
		Arusha	328	100	77	255	100	61

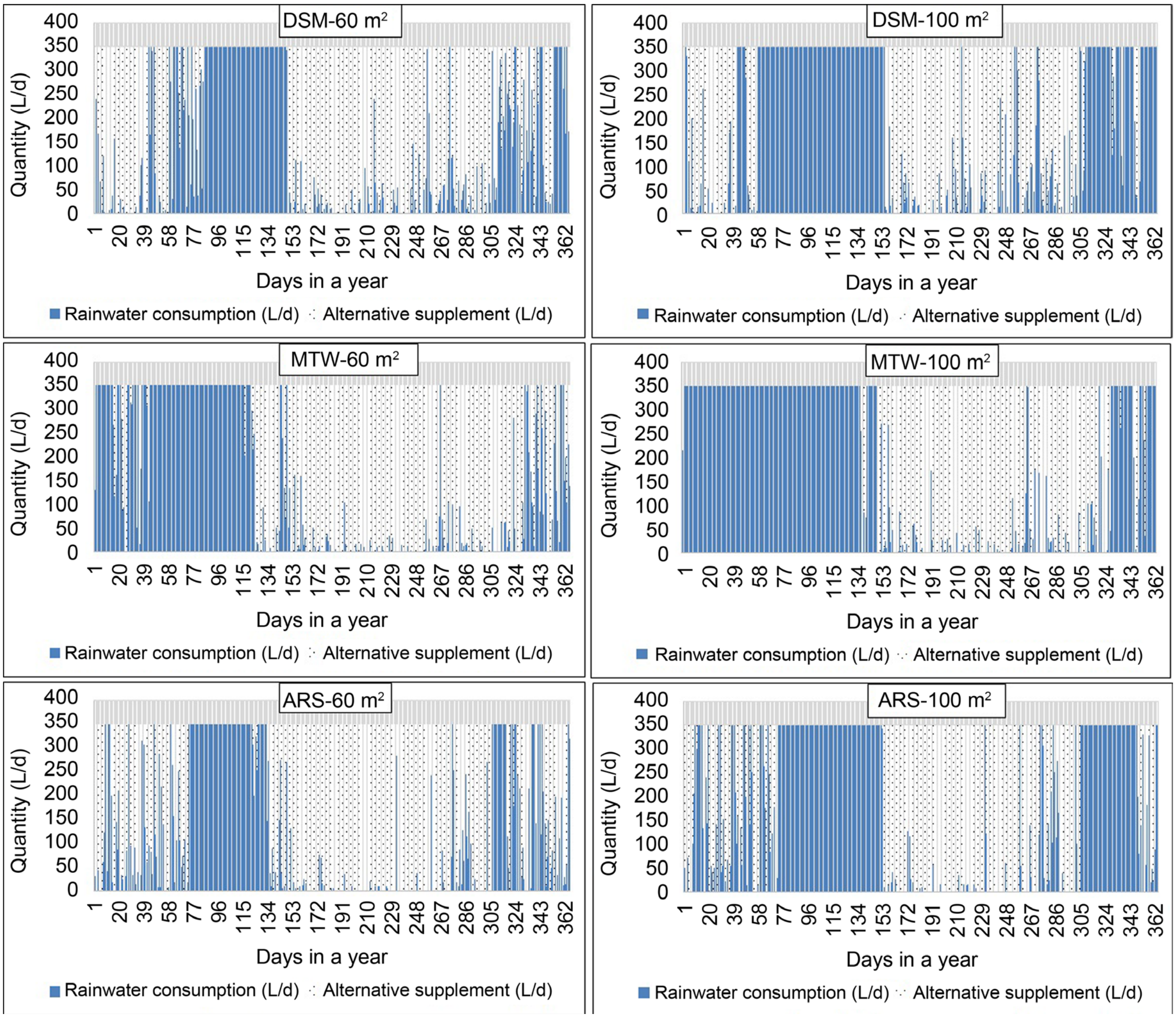


Figure 7. Rainwater consumption and supplement required at different catchment size in the selected regions at 70 L/person/d with 5 m^3.

through demo projects, media, village meetings, and with national guidelines established for consistency in application [21].

4. Conclusions

Rainwater may not necessarily serve as the sole water source, but it can be useful under dual supply conditions, with other water supplies including surface and GW sources. Having multiple convenient water sources boosts the household water supply self-sufficiency, as was established for the case of Mtiniko village with rooftop RWH. Rainwater catchment increase has greater impact on meeting a specified demand under given condition of rainfall quantity and variation. In terms of quality, rainwater can be prioritized as a drinking water source under dual supply conditions.

In developing countries, available indigenous water supply approaches can be studied, evaluated and improved upon to ensure sufficient and good quality water. These would include crude water harvesting practices. RWH is recommended as a sustainable water supply technology, and governments should invest in empowering individuals to address their own water supply challenges with this technology through increased awareness, incentives, and technical and financial support strategies.

This study has offered replicable strategies in addressing household water supply challenges with respect to local conditions of any given developing country.

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