From drops to drums

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From drops to drums: Assessing rainwater storage's quality and quantity for addressing water demands in dry periods – A case study from Arusha Tanzania

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ABSTRACT

Sustainable Development Goal 6 highlight the importance of providing reliable, affordable, and safe source of clean drinking water and sanitation for all by 2030. In Tanzania there is a dire need of a water supply strategy due to high levels of natural fluoride contamination in ground water (upto 74 mg/L) and the challenge of meeting water demand during 5 months long dry period. This study assesses social and technical feasibility of implementing rainwater harvesting (RWH) along with treatment technologies that includes Denutritor® to remove ammonia/pesticides and ultrafiltration to eliminate carbon. This integrated technology known as "Mbinguni Maji" is aimed for the long-term water storage to supply drinking water throughout the dry season. The methodology involves i) Assessing the technical feasibility of RWH using database from QGIS and Water Productivity Open-access portal (WaPOR) from the Food and Agricultural Organization of the United Nations; ii) conducting pilot demonstration in 5 different locations in Tanzania; and iii) conducting socio-economic survey for social acceptance of the technology through detailed questionnaires administered to residential homes, medical facilities, schools, hotels, and water kiosk owner. The result indicates that, from technical perspective, there is ample rainfall (average of 1036 mm/year) to supply water throughout the dry season, primarily for drinking and cooking purpose only (upto a maximum of 10 lpcd). The pilot demonstration confirms that the Mbinguni Maji RWH technology produce water that meets WHO water quality standards. The produced water is free from nutrients like carbon and ammonia, ensuring the possibility of long-term storage without bacterial and algal growth. Furthermore, Lab scale demonstration of Denutritor® show promising result of removing nitrite, ammonia even at high elevated temperature (30 °C), which can be effectively applied in Tanzania. In terms of social acceptance, RWH technology is already widely practised in Tanzania during the rainy season. However, the initial investment costs and operation & maintenance (O&M) concerns hinder the usage of RWH technology. Therefore, to ensure the long-term sustainability of RWH technologies, there is a need of development of comprehensive business plan and community awareness campaign.

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1. Introduction

The Arusha region, located in the north-east of Tanzania along the Kenyan border within the East African Rift System [8], relies on agriculture, mining, and tourism as its primary economic activities. Agriculture in Arusha includes cultivation of coffee, cotton, grains, various vegetables, and papaya. Mining companies extract magnesite, sepiolite, mica, and salt throughout the ore bands that stretch across the area. Lastly, tourism for the Tarangire National Park, Lake Manyara, and Ngorongoro, Serengeti and Ngurdoto craters create a major economic influence, especially in Arusha.

Reliable, affordable and safe drinking water is a major challenge for rural and semi-urban areas in Tanzania, where groundwater and surface water are the main sources of drinking water [2]. However, the water sources suffer from pollution and contamination originated from industrial effluent, agriculture, pit latrines, septic tanks, open dumping, and sewage discharges [11]. Additionally, high fluoride levels due to volcanic activities are a major concern for water quality in the region [6,10].

Fluoride is a common element present in minerals such as fluorspar and fluorapatite, often leaches into groundwater from fluoride-rich minerals in aquifers and sediments. High fluoride concentrations (> 1.5 mg/L) can cause health issues such as fluorosis, while low concentrations (< 0.5 mg/L) may lead to dental caries. The World Health Organization (WHO) recommends a guideline value of maximum 1.5 mg/L of fluoride in drinking water [15]. Unfortunately, both groundwater and surface water sources in Arusha have naturally occurring fluoride concentrations well above this recommended level (> 35 mg/L), requiring robust treatment methods to bring the fluoride levels down to the desired concentration [1]. These contamination levels lead to the higher CAPEX and OPEX cost to produce the high-quality drinking water. Defluoridation technologies have been developed mainly rely on adsorption techniques using various materials, coagulation-flocculation-filtration and membrane filtration [9,12]. However, these techniques have limitations, such as high initial and operational cost, as well as the requirement of having high skilled operators, making these technologies to be unsustainable [9]. Consequently, having an alternative water source with a low concentration of fluoride is a way forward.

Arusha residents have access to multiple sources of water, including surface water, groundwater, and rainwater [2]. The rainwater is clean and affordable resource, with an average annual precipitation of 1036 mm. However, during the five-month dry period in Tanzania, relying solely on rainwater harvesting becomes challenging. There exist several hydrological models that can predict the behaviour of rainfall and runoff but developed mainly for a large area (10^5–10^{10} m^2) as a centralized system. Recently, rainwater management systems (RWMSs) are designed on a decentralized basis, as the area of a rooftop is small (less than 2000 m^2) [7]. But the challenges stull exists during the dry period. Moreover, due to the ample rainfall during the rainy period, it is possible to collect and store excess water for utilization during the dry period. Moreover, the water collected through rainwater harvesting can also be impacted by local industries like mining, agriculture, and tourism, which can contaminate the water through dust and other pollutants settling on rooftops. The challenges in using rainwater harvesting exist; i) the potential for bacterial growth in the stored water due to the presence of organics, ammonia, and other air pollutants from the collection process; and ii) the ability to harvest enough rainwater from the roof to meet the water demands for different applications (drinking, cooking, cleaning & laundry, bathing, gardening, and livestock water).

To address these challenges, a new water treatment technology called "Mbinguni Maji - Water from Heaven" is proposed. This concept involves treating rainwater using a Denutritor® to remove ammonia, pesticides and an ultrafiltration membrane to eliminate bacteria and viruses, all without the need for chemical additives and energy (Fig. 1). The treated water is then stored and made available through taps within the residence or facility. The steps of treatment include; i) rainwater collection from roof through gutter system; ii) collection of rainwater into the tank; iii) treatment of rainwater using Mbinguni maji technology; iv) storage of treated water in the tank. Finally, by means of a pump followed by a polishing step, the water is then available in taps within the residence/facility.

The Denutritor® functions as a biological filter designed to extract nutrients from liquid streams. The elimination of ammonia and nitrite is particularly significant, as these substances serve as nutrients for bacteria. Over time, the presence of these bacteria in stored drinking water or rainwater can lead to waterborne diseases. Additionally, the removal of nutrients from water serves the purpose of preventing the development of biofilm due to growth of algae and bacteria in storage equipment and membrane modules. The Denutritor® also possesses the capability to eliminate small organic components such as pesticides. Furthermore, there remains uncertainty regarding the potential impact of the elevated temperatures in Tanzania on the Denutritor® 's performance, which requires further investigation.

This article explores the viability of rainwater harvesting and particularly Mbinguni Maji technology as a practical option to meet water demand during Arusha's dry period. The focus is on understanding the prevailing water usage practices, including water demand, available water sources, current usages, water costs, treatment expenses, and the community's willingness to pay for water-related services in Arusha, Tanzania. The investigation further encompasses the analysis of historical rainfall data, roof characteristics, and water demand patterns in Arusha to determine the potential amount of rainwater that can be harvested and stored. This assessment plays a pivotal role in understanding the reliability of rainwater harvesting as a sustainable water supply solution during the dry season.

The following aspects have been investigated and are described in this article:

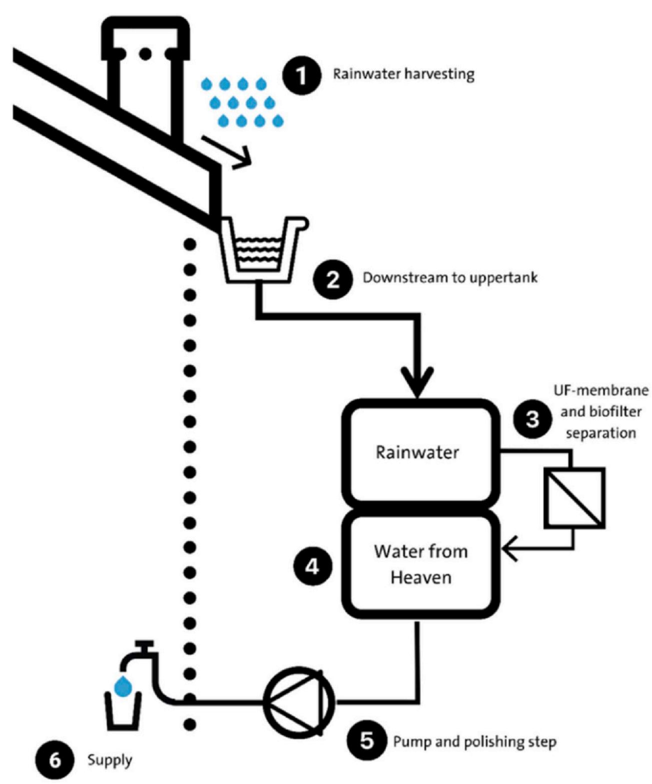

Fig. 1. Mbinguni Maji – Water from Heaven pilot phase project technology scheme.
(Source: Author).

Table 1
Assumed collection parameters.
(Source: Field survey data, Author).

Variables	Unit	Value	Citation
Number of residents per household	capita	6	From residential questionnaire
Water demand	lpcd[a]	Variable*	Calculated
Roof pitch	-	1/3	Assumed [4]
Average area of roof	m^2	84	[5], Calculated (Field survey data)
Runoff coefficient	-	0.85	Assumed [3]

* The water demand variable values are 5, 10, 30 and 60 lpcd.
[a] Lpcd = liter per capita per day.

- Examine the practical viability of rainwater harvesting as a solution to fulfil water demands during dry periods.
- Evaluate the technical viability of the Mbinguni Maji technology (comprising Denutritor® and ultrafiltration systems) in achieving WHO water quality standards.
- Investigate the social, economic, and demographic factors influencing water usage patterns (including water demand, sources, utilization, water-related expenses, expenses linked to water treatment alternatives, willingness to financially contribute, and the level of community approval towards the technology).

2. Methodology

2.1. Case study

The study focused on the Arusha region (rural and semi-urban area), located along the north-eastern boarder of The United Republic of Tanzania. This location is the pilot demonstration area for the Mbinguni Maji - Water from Heaven project and was selected due to the dire water conditions of fluoride contamination in the water. Pilots demonstration projects were installed at 5 different location within Arusha (a school, a hospital, a kiosk, an education institute and a greenhouse).

2.2. Water usage practices

To understand the social, economic, and technical acceptability of rainwater harvesting in rural and semi-urban areas of Arusha, Tanzania, a quantitative and a qualitative research approach was used. The quantitative approach focused on data provided from the residents of Arusha representing from hospitals, schools, hotels/resorts and local water entrepreneurs as well as from the literature review. The respondent shared information about how much water they use for different activities in their daily life based on their daily routines and experiences. This included data based on their use of 10 L and 20 L gallon containers as reference points for their daily consumption. In general, gathering data based on experience of the respondents may have limitations in terms of precision and accuracy compared to real measurement, but it still provides valuable insights into daily water consumption patterns and contribute to a more holistic understanding of the water usage in the area.

The qualitative approach focuses on the ideas and experiences of the Arusha residents.

2.2.1. Sampling technique and sample size

For the population of Arusha, 200 questionnaires are the sample size necessary for questionnaires to have an 85 % confidence level and an error margin of 5% was calculated using Eq. (1). This level was selected due to the time and partnership availability during the study period.

$$n = \frac{z^2 * p'(1 - p')}{\varepsilon^2} \tag{1}$$

Where:

z = z score associated with the confidence level of the population; 1.44.

p′ = population proportion, which was assumed to be 50% urban and 50% rural residents.

ε = margin of error; 5 %.

2.2.2. Data collection and analysis

A set of questionnaires, consisting both open and close ended questions, were drafted and then distributed to a total of 200 responded within rural and semi-urban regions of Arusha. Among these, 150 questionnaires were collected from rural and semi-urban residents, 20 for medical facilities, 10 for educational institutions, 10 for hotels/resorts, and 10 for local water entrepreneurs operating water kiosks. The questionnaire developed is attached in the Annex 1.

The collected qualitative data was then analysed and converted into quantitative data. The numerical data was then used to analyse patterns between the variables of household demographics, water demands, water sources utilized, and additional variables.

2.3. Analysis of rain water quantity and storage capacity

2.3.1. Historical rainfall data analysis

Historical rainfall data (2009–2019) for the city of Arusha was extracted from WaPOR platform from the Food and Agriculture Organization of the United Nations (https://wapor.apps.fao.org/home/WAPOR_2/1). WaPOR utilises satellite imagery in combination with local organizations to produce a variety of data throughout Africa. Rainfall concentrations, both daily and monthly were extracted from this program and calculated the average and minimum values.

2.3.2. Storage capacity calculations

The storage capacity of the harvested rainwater was calculated considering the factors such as; rainfall concentrations, residents per household, water demand, average roof area, roof pitch, runoff coefficient, the first flush and the amount of water needed for the dry period. All the required data for this analysis were collected through questionnaires with local residents and some data from literature (Table 1).

The value for the average roof area was assumed to be 80 m^2 for a single-family dwelling. The roof pitch is assumed to 1/3, which indicates a low slope to the roof. Therefore, the supply of rainwater that can be collected depends on rainfall amounts (R), the area of the catchment surface (A_C), and the runoff coefficient (C). The mean annual runoff for a catchment was calculated using Eq. (2) [13].

$$S = R * A_C * C \tag{2}$$

Roof pitch determination was calculated using Eq. (3) [4]. The values for the rise and run as shown in Fig. 2.

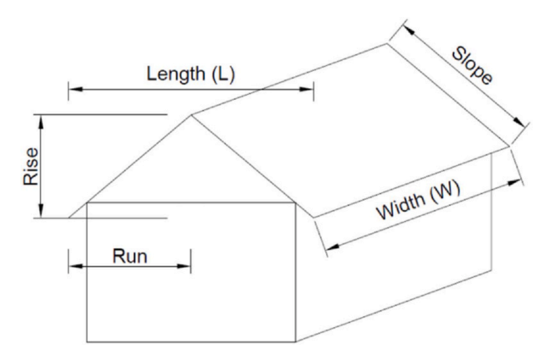

Fig. 2. Roof pitch and catchment surface area calculation.

Fig. 3. Laboratory scale Denutritor® columns.
(Source: Author).

$$RP = \sqrt{\left(\frac{\left(\frac{Rise}{Run}\right)}{12}\right)^2 + 1} \quad (3)$$

The area of the catchment surface (A_C) was calculated by multiplying the length of the house (L) by the width of the guttered area (W) by the roof pitch (RP), as shown in Eq. (4) [13] and Fig. 2.

$$A_C = L*W*RP \quad (4)$$

Therefore, for subsequent calculations, we utilized a roof area (Ac) of 84 m^2, as determined by the field survey measurement. Additionally, we used runoff coefficient of 0.85 for a metal roof, as cited in [3]. In the calculation, the amount of first flush was also considered, which is discharged to the drain.

2.3.3. Sizing of tanks

The sizing of the tanks was dependant on the cumulative rainfall harvested (V_H), first flush removal (V_f), the volume left in the tank (V_{T-1}), and the cumulative water demand for each demand scenario, as shown in Eq. (5) [13]. The difference between the two is the approximate tank size needed to provide the water throughout the dry season. Therefore, tank size was estimated, and the percentage of the tank filled at the end of the month should never be below zero.

$$V_T = (V_H - V_f) - V_D + V_{T-1} \quad (5)$$

Where:

V_T = Volume of water in the tank in time period t.
V_H = Volume of rainwater harvested in time period t.
V_f = Volume of the first flush removed in time period t.
V_D = Water demand for time period t.
V_{T-1} = Volume left in the tank from previous time period t.
t = one month for this study.

2.4. Demonstration of RWH treatment technology (Mbinguni Maji)

The demonstration of technology was performed in two phases; i) Initial testing of Denutritor® 's efficiency for ammonia removal at elevated temperature ii) Subsequently, the Mbinguni Maji technology was installed at five different locations in Tanzania, and monitored the water quality over time.

2.4.1. Optimization of Denutritor®

Five plug flow columns were used as shown in Fig. 3. The columns were filled (stacked) with precisely fitting round (cylinder) discs of polymeric foam material (Denutritor®). The diameter of the foam cells was 0.564 mm, the estimated specific surface was 3290 m^2/m^3 and the measured specific gravity was 33 g/L. The column length was 1.7 m including free board below and above the fill. The height of the fill was 1.5 m. The internal diameter of the columns was 67.8 mm and the volume of the fill was 5.4 L. The water flow rate was 1.08 L/min and the residence time of the water in the fill was 5 min. Sample ports were placed at intervals to sample water with 1, 2, 3, 4- and 5-min residence time.

Columns fed with water of different temperature were started simultaneously and studied side by side. The temperatures studied were 10 °C, 20 °C, 30 °C and 40 °C and were achieved by passing the water through five thermostatic baths set to these temperatures. All temperatures in the columns were performed in single copies, except those at 20 °C: these were performed in duplicate (i.e. two identical columns; to demonstrate reproducibility): A and B. The columns were fed from a 1 m^3 cubic vessel with tap water. The tap water contained enough elements and carbonate to build up the bacterial mass. The pH was also favourable but Ammonia was added as NH_4Cl. The columns were started with commercially available suspension of nitrifying bacteria (BactoPlus). In the glucose addition experiment, an additional inoculation was carried out with an aqueous extract of forest soil.

The effect of temperature on start-up and performance of Denutritor® columns was studied using the five columns fed with ammonia-containing water (0.54 mg NH_4/L) for 22 weeks. Concentrations of nitrate, nitrite and ammonia were measured.

The effect of higher ammonia concentration and peaks were studied in one column (20 °C). The effect of a sudden peak could be observed by suddenly applying a higher ammonia concentration and taking samples immediately. By applying this higher concentration for a longer period of time, the long-term adaptation could be studied as well. First, 1 mg NH_4/L was tested, for one week and then 2 mg/L for another week. The effect of the presence of readily assimilable carbon compound was studied by adding 3 mg/L of glucose in one column and in another column without addition of glucose.

2.4.2. Pilot demonstration

Pilots were installed in various locations: a school, a hospital, a kiosk, an education institute and a greenhouse (Fig. 4). Water quality analysis measuring for *Escherichia coli (E. coli)* and chemical parameters (ammonia, nitrate, nitrite, pesticides, heavy metals) were carried out for samples collected from the inlet and outlet of the RWH technology.

2.4.3. Water quality analysis

The feed and outlet from each pilot location were tested for heavy metals such as nickel, copper, zinc and lead using the test method "TZS 861(Part 7):2006 - Flame Atomic Absorption Spectrometry" at the facility of African Assay Laboratories (Tanzania) Ltd, SGS Tanzania Superintendence Co. Ltd. The limit of detection for each were 0.5 mg/L, 2 mg/L, 5 mg/L and 0.1 mg/L, respectively for nickel, copper, zinc and lead. Likewise, SGS also measured ammonia, nitrate and nitrate and e-coli concentration in both samples.

3. Results and discussion

3.1. Water source availability

Fig. 5 displays the nine water sources available to the region of Arusha (water utility, public standpipe, water kiosk, bottled water, private well, swamp, river, rain, and other sources) and how the water sources chosen by households vary from the wet and dry season. The most utilized domestic water sources are the water utility (100 households), rainwater (85 households), private well (40 households), and river water (20 households). Due to the inability to store rainwater throughout the dry period, RWH is more predominant during the wet season due to the availability of rain.

Of the 149 respondents, 70 utilise more than one type of source

Fig. 4. Pilot demonstration of RWH in Arusha.
(Source: Author).

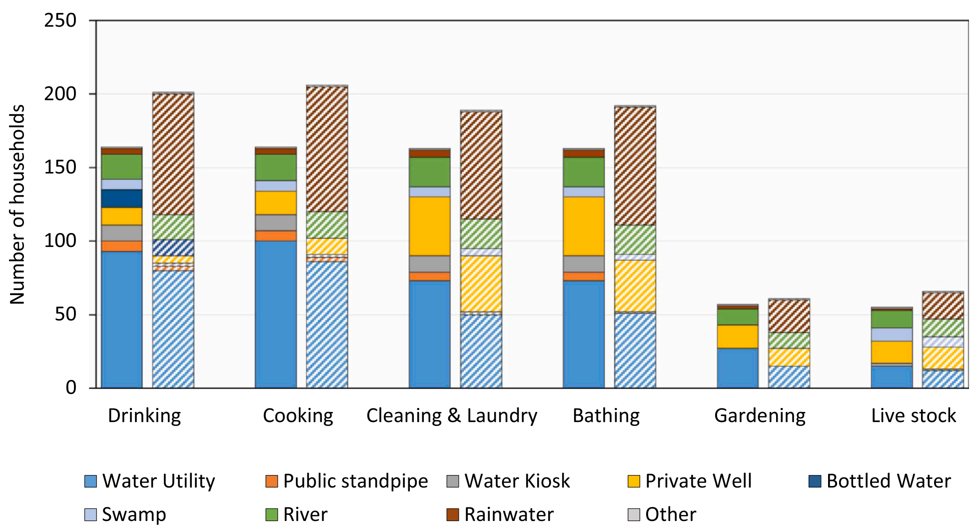

Fig. 5. Utilized water sources per season. The bars with without patterns indicate the usage in dry season and the bars with patterns indicate the usage in wet season.

Table 2
Number of respondents that use multiple water sources.

	Number of Sources used per household			
	3 sources	2 sources	1 source	0 sources
Drinking	0	52	97	0
Cooking	3	51	95	0
Cleaning & laundry	1	38	110	0
Bathing	1	41	107	0
Gardening	0	4	53	92
Livestock	0	11	42	96

water in their homes per day. Table 2 displays the number of households that use multiple sources per demand category. Based on the result, 92participants did not practice gardening and 96 participants did not practice animal husbandry.

The preference for harvested rainwater is seen during the rainy season and coincides with a decreased usage in water utility and private well (especially in the drinking water category). Due to the inability to store rainwater throughout the dry season residents are forced to utilise other water sources of lower quality (groundwater and surface water contaminated with fluoride). The clear preference for rainwater shows high levels of social acceptance already in the Arusha region.

It is essential also to recognize that the community is using both paid and free sources. Paid water sources include water utility, public standpipe, water kiosk, bottled water, and the private well. A private well is included in the paid sources because 28 respondents out of 41 claims to have a cost of more than €5 a month on pump fuel. The free sources are defined as swamp water, river water, rainwater, and other water sources.

During the wet season, the domestic water demand is split by approximately 50 % using paid and free water sources. The water sources used changes upon the availability of the source and the intended use. Perceived water quality also plays a significant role in usage percentage. Sources such as rainwater are readily available and can be collected in buckets or through a harvester. During the dry season, approximately 80% of household respondents use a paid water source, and less than 20% of respondents use free sources to meet the domestic water demand. Less free water sources are readily available during the dry season as swamps, rivers, and rainfall dry out [13].

Table 3
Percentage of household using paid or free water sources.

	Paid water source		Free water source	
	Dry season (%)	Wet season (%)	Dry season (%)	Wet season (%)
Drinking	82	50	18	50
Cooking	82	54	18	46
Cleaning & Laundry	80	48	20	52
Bathing	82	45	18	55
Gardening	75	44	25	56
Livestock	58	42	42	58

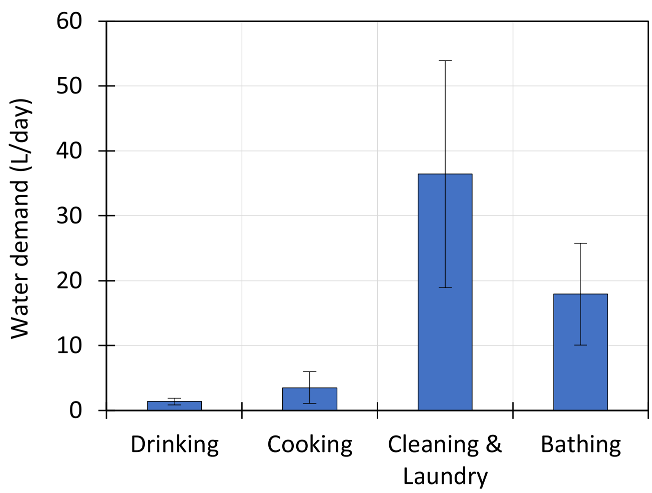

Fig. 6. Domestic water demand (n = 149).

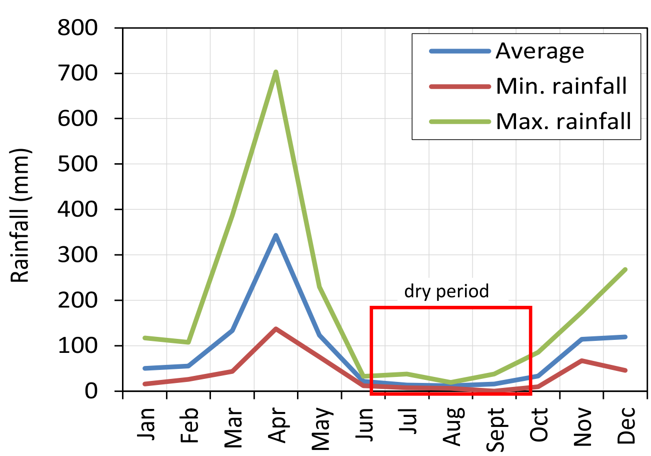

Fig. 7. Monthly rainfall in Arusha, Tanzania (2009–2019).

3.1.1. Water demand analysis

The domestic water demand, Fig. 6, is met through a combination of the nine sources of water available in Arusha. Due to the seasonal weather patterns rainwater and river water, are more readily available during the wet season. During the dry season, residents rely on paid sources. The domestic average water demand for Arusha is 57.2 ± 26.4 lpcd according to field survey data. Therefore, throughout the rest of this study, the domestic water demand is taken as 60 lpcd.

With the current level of social acceptance of RWH, it is theoretically possible to further develop this practice throughout the dry season. However, it is unclear if RWH could feasibly meet the community water needs throughout the dry period.

3.2. Feasibility of RWH to meet water demands throughout the year

3.2.1. Rainfall pattern in Arusha

Arusha, receives an ample supply of rainwater to support RWH. From Fig. 7, the ten-year (2009–2019) monthly average was extracted from the values in Table 4. The wet season in Arusha starts in March and ends in May. Then the five-month dry period occurs between June and October. The 10-year average annual rainfall for the City of Arusha is 1036 mm/year (denoted by the red line). The minimum value of each month is denoted in the green line. This study utilized the average monthly rainfall data for design.

During the dry period, there is not sufficient rainfall to fill the RWH tanks (< 100 mm). During this time residents must obtain water through other sources. If the excess rain from the wet season can be collected, treated, and stored, it could meet a portion of the domestic water demand. However, that is dependent on the rain collection and surface variables.

3.2.2. RWH potential for different water demands

Fig. 8 shows the cumulative harvested rainfall calculated using the Eq. (2) using average monthly rainfall (Table 4), average room area of 84 m^2 and runoff coefficient of 0.85. Furthermore, various water demand scenarios (5, 10, 30 and 60 lpcd) were plotted in the graph to determine if RWH is a potential primary source of domestic water supply. The cumulative water demand was calculated for a household of average 6 persons. The demand of 5 lpcd was selected as it was reported the minimum water demand for only drinking and cooking, while 60 lpcd was minimum water demand including cleaning, laundry, gardening and bathing during the field survey.

As illustrated in the Fig. 8, it's evident that relying solely on rainwater harvesting (RWH) cannot meet the cumulative water demand of 60 liters per capita per day (lpcd) throughout the dry season, as this demand exceeds the cumulative harvested rainwater. However, RWH can supplement the residents existing water supply for meeting the demands of drinking and cooking (5–10 lpcd) throughout the dry season. Drinking and cooking water is the highest priority of needs due to the high fluoride concentration in the ground and surface water in the area.

3.2.3. Calculation of required storage volume for the dry period

Of the variable demands, tank sizes can be designed for the 5 and 10 lpcd demands. The minimum tank sizes are 3 m^3 to provide 5 lpcd and 7 m^3 to provide 10 lpcd. These tank sizes are designed based on the ten-year cumulative monthly rainfall patterns. Therefore, in the chance of severe drought, the tank can run dry.

Fig. 9 shows the percentage of the tank which is filled at the end of each month. Tank sizing calculations are limited to the amount of water that can be feasibly harvested from the roof size. During the wet season, the overabundance of rain keeps the tank at 100 % capacity. Therefore, the recommended cleaning time for all tanks is at the beginning of March. The tank will be filled back to 100 % capacity quickly after cleaning. During the dry season, Arusha receives little to no rain and storms may not produce enough rainfall to cover the required discharge for the first flush. At the end of the dry period (September and October), the tank water level is at the lowest level, and water conservation is crucial. The mini-wet season in November and December will supply enough recharge to provide the designed water demand until the next rainy season.

3.3. Assessment of RWH technology (Denutritor®) based on operational temperature and ammonia concentration on a lab scale

3.3.1. Effect of temperature on the performance of Denutritor®

In the columns operated at 20 °C and 30 °C, the conversion of ammonia into nitrite started after about one month of operation (Fig. 10A). The conversion of nitrite into nitrate then started

Table 4
Average monthly rainfall in mm.
(Source: WaPOR [14]).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total annual
2009	39.3	40.3	44	257.3	116.4	28.2	8.8	7	0	41.4	116.5	146	845.2
2010	64.4	55.5	157.4	309.5	138.1	17.7	7.6	6	5.8	9.5	67.2	71.2	909.9
2011	43.2	57.4	131.9	136.9	124.2	15.9	8.1	6.2	7.5	85.3	161.5	68.4	846.5
2012	17.7	49.8	65.7	352.8	132.5	11.9	7.8	17.9	0	18.6	169.6	98.4	942.7
2013	60	25.8	192.1	334.1	75.3	14.1	9.8	8.7	14.8	16.6	73.4	106.7	931.4
2014	20.5	107.9	162.5	222.1	99.7	22.9	11.1	9.8	28.5	18.8	100.3	104.8	908.9
2015	24.1	58.4	117	512.6	229.5	26.8	17.7	14.3	14.2	23.6	107.7	130.1	1276
2016	117.6	53	89	366.9	115.1	24.4	13.6	15.8	15.2	31.8	90.8	62.1	995.3
2017	48.6	58.6	77.5	218.7	131.9	17.6	11.5	19.3	37.8	20.3	121.8	45.8	809.4
2018	103.7	32.2	387.1	703.1	106.2	32.6	16.6	13.3	35.6	43.3	76.1	213.8	1763.6
2019	15.5	71.6	47	356.7	83.3	24.8	37.7	16.2	11.7	61.8	173.6	268.3	1168.2
Average	50.4	55.5	133.7	342.8	122.9	21.5	13.7	12.2	15.6	33.7	114.4	119.6	1036.1
Min. rainfall	15.5	25.8	44	136.9	75.3	11.9	7.6	6	0	9.5	67.2	45.8	445.5
Max. rainfall	117.6	107.9	387.1	703.1	229.5	32.6	37.7	19.3	37.8	85.3	173.6	268.3	2199.8

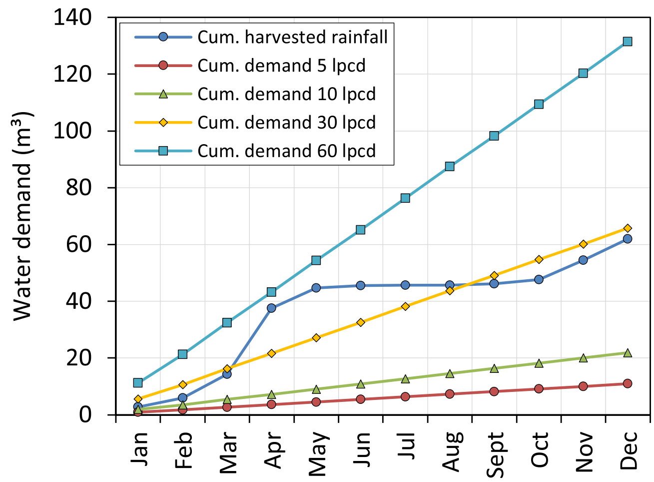

Fig. 8. Cumulative water demand at various demand categories.

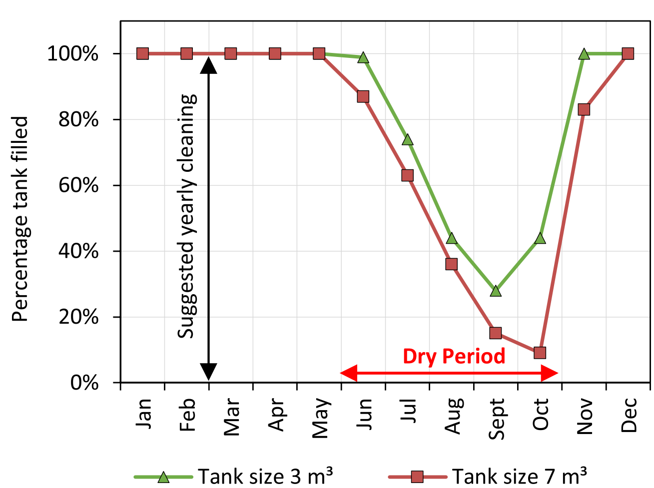

Fig. 9. Percentage tank filled per month for various tank sizes.

approximately after two months (Fig. 10B). Inoculum (BactoPlus) was added at the beginning and again after 10 weeks (after sampling). However, the columns had already started independently in week 10th, i.e. before the second dose of inoculum was added. After 13 weeks, the columns had functioned as they should: ammonia had converted completely to nitrate and there was no longer any nitrite in the effluent, and this was reached after 5 min of residence time. In columns with fully developed activity, some nitrite was still present after 1 min of water residence time and the production of nitrate was also not yet complete. In the columns operated at 20 °C and 30 °C, the amount of nitrate in the effluent after 22 weeks was close to the amount of ammonia introduced (0.42 mg NH_4-N/L). Thus, it can be concluded that ammonia was almost completely converted into nitrate.

The lowest ammonia concentrations were already measured in the effluent of column 20 A (0.01 mg NH_4-N/L) in week 8 (Table 5). In week 13, a low concentration of ammonia (0.01 mg NH_4-N/L) was also observed in column 20B. Column 30 °C showed a slightly higher effluent concentration (0.05 mg NH_4-N/L) in that week. After 16 weeks, concentrations of ammonia between 0.02 and 0.03 mg NH_4-N/L were measured in the columns operated at 20 °C and 30 °C. The intermediate samples taken after 1 and 2 min of residence time gave higher values. Although most of the ammonia was removed in the first two minutes, ammonia concentrations continued to drop in the next few minutes.

At 10 °C the start-up was slower, but the pattern was the same. Nitrite formation began after 3.5 months and nitrate formation only after 22 weeks. At 40 °C the start-up was slow as well. It was only after 22 weeks that nitrite and nitrate formation started at the same time. The complete start-up (i.e. ammonia and nitrite largely unset in nitrate) of the columns at 10 °C and 40 °C was not possible within 22 weeks.

3.3.2. *Effect of high ammonia loading rate*

A sudden increase in load due to an increase in ammonia concentration from 0.54 mg/L to 1 mg/L was quickly absorbed by column 20B, at least within one hour (data not shown) and nitrate production had doubled within that hour. After 2 min of residence time, there was still some nitrite in the water, but after 5 min (the final effluent), the nitrite disappeared and was converted into nitrate. A further improvement on the performance was observed in continuous feeding of high ammonia. After 6 h of feeding at high load, the water that had stayed in the column for only 2 min was free of nitrite, and that remained this way after a day and also after a week.

The ammonia concentration was further increased to 2 mg NH_4/L. Similarly, a rapid reaction occurred in the column, but too much nitrite remained in the water, also in the final effluent. It stayed that way and sometimes became less (after a day) or more (after a week). Most likely this had to do with the fact that there was a depletion of available dissolved oxygen. 7.1 mg O_2/L is required for the conversion of 2 mg NH_4/L. The maximum solubility of oxygen in water is 9.2 mg/L at 20 °C and based on one-time measurement, the dissolved oxygen was 7.6 mg/L.

3.3.3. *Experiment with presence of glucose*

Column 20A (containing 3 mg glucose/L) was compared to column 20B. Column 20B had, for that matter, always been fed with water containing ammonia, also during the ammonia shock test carried out

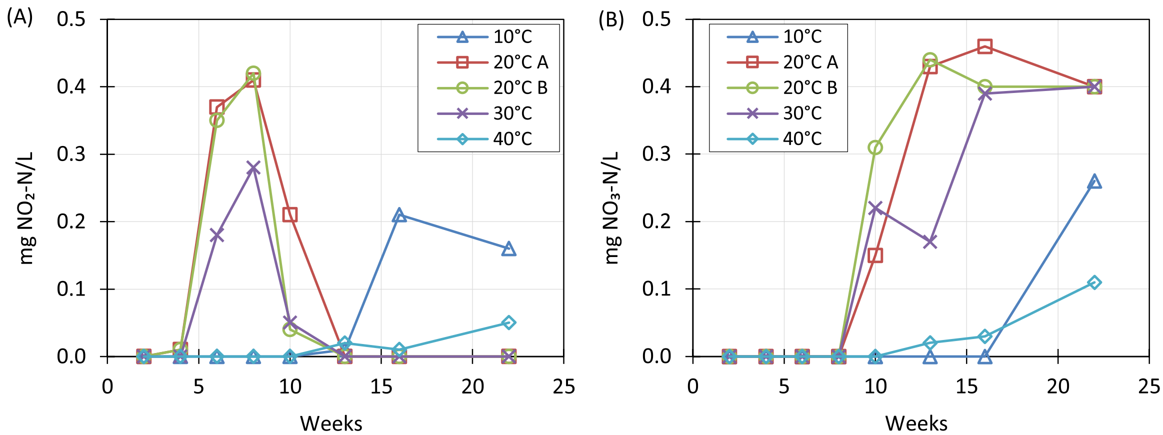

Fig. 10. Nitrite (A) and nitrate (B) concentrations in the final effluent (5 min residence time) of five Denutritor® columns operated at various temperatures.

Table 5
Ammonia concentrations after various residence time of five Denutritor® columns operated at various temperatures.

	Ammonia concentration (NH_4-N/L)		
	1 min	2 min	5 min
Week 8			
Column 20 °C A	0.01		
Week 13			
Column 20 °C A		0.02	0.01
Column 20 °C B		0.01	0.01
Column 30 °C		0.1	0.05
Week 16			
Column 20 °C A	0.21		0.02
Column 20 °C B	0.15		0.03
Column 30 °C	0.08		0.02

with column 20A. The glucose test came right after the ammonia shock test. Just before the glucose test, column 20A was also inoculated with a water extract from forest soil (in which many glucose-assimilating bacteria were expected). After one week of running, there was no significant difference between columns 20A and 20B (data not shown). After this week, both columns became clogged with biomass, earlier than we expected. Such clogging is normal in Denutritor® s and is caused by the growth of biofilms and finally the closing of the pores. The plan to continue the glucose trial for a month was therefore aborted. Because of this, we were not sure whether column 20A had already built up glucose-degrading capacity within a week. In order to break down 3 mg of glucose, 3 mg of oxygen is needed. Therefore, oxygen depletion was not expected to occur.

3.4. Pilot demonstration

Samples were collected from inlet and outlet of the pilots every month from August to November 2021. The ammonium concentrations detected in the collected rainwater before treatment were less than 0.5 mg/L (the Tanzanian guideline value). However, after treatment, the ammonium concentration was less than 0.5 mg/L in all pilots. Additionally, the nitrate and nitrite contents in inlet and outlet of the pilots were all less than the Tanzanian guideline values (45 $mgNO_3^-$/L and 3 $mgNO_2^-$/L).

Analysis of heavy metals; nickel, copper, zinc and lead in the samples collected from the inlet showed values less than Limit of Detection (LOD) of the measurements.

The results from microbiology analysis, pathogenic bacteria such as *Salmonella*, *Enterococci*, *Pseudomonas*, *Vibrio cholerae*, and *Legionella* were rarely detected in the inlet sample, while *Aeromonas* and *E. coli* was detected in the samples from the inlet of five pilots. A complete removal of *Aeromonas* was observed in school, educational institute, kiosk, and hospital. The removal of *Aeromonas* in the greenhouse was as low as 0.2 log removal and the highest was 1.3 log removal.

3.5. Willingness to pay

The willingness to pay for an RWH system was sorted into three categories: respondents who are willing to pay, respondents who are unwilling to pay and are not interested in RWH, and respondents interested in RWH but require a donation to implement the system. Additionally, RWH requires yearly operations and maintenance. Participants were asked if they were willing to complete this maintenance if trained. The results are displayed in Table 6.

3.5.1. Residential

Among 148 respondents, many of the residents cannot afford to purchase an RWH without a donation (Table 6). The large initial costs for the tank and treatment system will deter implementation. Overall, residential homeowners are highly interested in the technology and are willing to take responsibility for the maintenance. However, residents

Table 6
Willingness to pay and to perform basic operational and maintenance (O&M) for an RWH system for various applications.

	Residential households	Medical facilities	Schools	Hotels	Water kiosks
A. **Willingness to pay**					
Number of respondents	148	19	10	9	10
• Willing to pay	7	0	0	0	0
• Not willing to pay	23	3	1	4	8
• Require a donation	118	16	9	5	2
B. **Willingness to perform O&M**					
Number of respondents	148	20	10	10	10
• Willing to perform O&M	111	14	0	5	0
• Not willing to perform O&M	19	2	1	1	8
• Maybe willing to perform O&M	18	4	9	4	2

lack the capital to invest in the technology. For households to switch to RWH, the price of the rainwater harvested must be equal or less to the current price they are paying for water (€ l/month).

3.5.2. Medical facilities

16 out of the 19 medical facility respondents cannot afford to purchase an RWH system without a donation. Therefore, financial support would be necessary for most medical facilities to install an RWH system. If a rain harvester were donated to the facility, only four facilities would be unwilling to complete basic O&M (Table 6) and require a professional to run the unit. Overall, medical facilities are highly interested in RWH technology and are willing to take ownership of O&M responsibilities.

3.5.3. Schools

For school ranging from primary to university level, Table 6 shows that of the 10 school respondents, 9 cannot afford to purchase an RWH system without a donation. One respondent was unwilling to pay and was not interested in rainwater harvesting. However, if a harvester were donated to the facility, all nine respondents would possibly be willing to perform basic O&M.

Overall, schools are highly interested in RWH technology and are willing to take ownership of O&M responsibilities. Financial support would be necessary for most schools to install an RWH system.

3.5.4. Hotel

Five hotel respondents are willing to install an RWH with a donation and four respondents are not interested in RWH (Table 6). Of the ten hotel respondents, five are willing to perform essential O&M work and four are willing after training (depending on O&M requirements). Hotels are a large market that is currently not practicing RWH. This study has shown that the hotel market is receptive to RWH technology, but hotels may not be able to afford it without a donation.

3.5.5. Water kiosk: willingness to pay

8 out of 10 water kiosks respondents were not willing to install an RWH and only 2 were willing to install an RWH with a donation (Table 6). The businesses were also unwilling to perform basic O&M. These results are unexpected. Currently there is work on a pilot project with Denutritor® RWH technology with a water kiosk in Arusha.

Water kiosk owners may fear that with the implementation of RWH technologies throughout the dry season will impact sales. The main business time for water kiosks is during the dry season when other free resources are not available. Education on the benefits of RWH treatment technology and detailed explanation of the business model is recommended for further implementation and long-term sustainability.

4. Conclusion

- Based on water demand and usages as well as historical rainfall data (*average of 1036 mm/year*) this study demonstrated that RWH is a viable source of drinking water throughout the dry period if properly treated, stored, and handled. Residents are highly receptive to the technology across various applications, however, many lack appropriate funds to purchase the RWH treatment technology. The rainwater is feasible to supply water throughout the dry season, primarily for drinking and cooking purpose only (upto a maximum of 10 lpcd).
- The pilot demonstration confirms that the Mbinguni Maji RWH technology produce water that meets WHO water quality standards. The produced water is free from nutrients like carbon and ammonia, ensuring the possibility of long-term storage without bacterial and algal growth.
- The technology for treating harvested rainwater, Denutritor®, showed a good removal of ammonia. At a temperature of 20–30 °C, Denutritor® s can remove ammonia starting at a concentration of 0.54 mg/L within 5 min (or even less) down to a concentration of 0.02 ± 0.01 mg NH4-N/L. Higher concentration of ammonium up to 1 mg/L can be still easily absorbed, while 2 mg/L was too high. If fluctuations are expected, a water residence time of 5 min is needed. The presence of 3 mg of readily assimilable organic compounds per liter did not create problems with ammonium removal within one week, however, further investigation might be needed to observed long-term effects.
- In terms of social acceptance, RWH technology is already widely practiced in Tanzania during the rainy season. However, the initial investment costs and operation & maintenance (O&M) concerns hinder the usage of RWH technology. Therefore, to ensure the long-term sustainability of RWH technologies, there is a need of development of comprehensive business plan and community awareness campaign.

Ethical Approval

Ethical approval for the conduct of this research was given by the Ethics Committee of UNESCO IHE Delft Institute for Water Education.

List of abbreviations

AUWSA	Arusha Urban Water Supply & Authority
MM	Mbinguni Maji Project
O&M	Operations & Maintenance
RWH	Rainwater harvesting

Data Availability

The data obtained, used, and analysed for this study is available upon reasonable request for the corresponding author.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Disclosure

The authors declare that they have no conflicts of interest.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dwt.2024.100670.

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