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Using every drop: rainwater harvesting for food security in Mbale, Uganda

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Abstract

The world population is expected to increase with corresponding increase in food production and water withdrawals. To ensure continuous food production throughout the year, increasing irrigation is inevitable. However, the water available for agricultural use is inadequate due to the limited water resources globally and climate change challenges threatening water availability. The economy of Mbale, Uganda, mainly depends on rainfed agriculture. The rain season is from April to October whilst the dry season is from November to March. Therefore, this study examines the potential of rainwater harvesting for domestic and agricultural uses in Mbale. The AquaCrop model was adopted for the yield response of crops to water during the dry season. The study reveals that comparing the resulting rainwater harvesting potential with the water consumption, up to 186% of the annual water demand for domestic use, according to the World Health Organization (WHO) standard, can be provided. Thus, the excess harvested water from a 200 m^2 rooftop was simulated for irrigation purposes, which shows that it can be used to cultivate areas of 269, 429, 125 and 388 m^2 for cabbage, tomato, maize and potato respectively during dry periods. The economic analysis shows a benefit cost ratio of 1.99 over 10 years. It concludes by recommending RWH as an alternative water supply source for domestic and agricultural uses.

Key words: aquacrop, economic analysis, food security, Mbale, rainwater harvesting

INTRODUCTION

The world population is expected to increase by 2.2 billion by 2050 with corresponding increase in food production by 50% and a 15 percent increase in water withdrawals (FAO 2017). Increasing food production means allocating more resources to agriculture by ensuring continuous food production throughout the year. Increasing irrigation can aid in increasing food production; however, the amount of water available for agricultural use is not increasing due to the limited water resources globally. Agriculture uses the most water, by far, with a water use of more than 80% of available fresh water (FAO 2017). According to FAO (2017), agriculture will be the biggest global user of water in 2050. In addition, due to the growing water demand and declining precipitation in some regions, the pressure on the available water resources will increase, thus resulting in high levels of water stress in many regions (USAID 2013). Water stress may have a negative impact on agricultural production and economic development as water shortages directly lead to reduced crop production. In water stressed areas, agricultural production levels can be increased by improving water management and increasing water efficiency ('more crop per drop'). Therefore, there is a need to tap into other convention water sources like rainwater harvesting.

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The potential of rooftop rainwater harvesting can be fully exploited to achieve maximum results. Rainwater harvesting is a viable solution to cope with the increasing water demands, water scarcity and climate change variability as a secondary source of water (Alem 1999; Ibrahim 2009; Kahinda & Taigbenu 2011). Climate change being a global challenge, Uganda is not exempted. Studies conducted to assess the impact of climate change on agriculture in Uganda indicate that the continuous rise in temperatures and increasing spatial variability of rainfall will lead to reduced agricultural yields (USAID 2013). Uganda, however, is well endowed with water resources and proper water management can aid in adapting to the expected climate impacts (USAID 2013). The agricultural sector in Uganda is greatly affected by water-related disasters such as floods, droughts, and landslides, which contribute to about 70% of the natural disasters, destroying over 800,000 ha of crop land annually and causing large losses to the economy (UN-WWDR, 2006; Ministry of Energy and Mineral Development 2007). By adopting rainwater technologies, these disasters can then be minimized.

This study therefore aims to assess the potential of rainwater harvesting for domestic and agricultural use in Mbale, recommend an appropriate storage capacity required for a household for maximum storage sufficient for domestic and agricultural uses all year round and simulate the crop water requirements for common crops cultivated in the region in order to use the harvested water for irrigation purposes. In addition, the study seeks to analyze the economic benefit of harvesting rainwater.

LITERATURE REVIEW

Uganda's economy mainly depends on agriculture and this sector contributes over 20% to the GDP and employed about 65% of the population in 2010 which makes it very essential for the country's development as stated in the Uganda Vision 2040 (National Agricultural Policy 2011; National Planning Authority 2013). Most farmers practice rainfed agriculture whilst in the dry season no agricultural production takes place at all, thus threatening food security in the region (Stampone *et al.* 2011). Mbale district is located in the Eastern part of Uganda and is among the majorly populated districts in the country. In Mbale region, major crops grown include banana, coffee and a variety of vegetables like cabbage, Sukuma, and tomatoes. Mbale region is well endowed with high amounts of rainfall ranging from 1215 to 1328 mm annual averages, with rainy months April to October and occurring in two seasons (Majaliwa *et al.* 2015). The rest of the months, November to March, are extremely dry with very high temperatures which greatly affects agricultural activities in the region, leading to increased threat to food security. The high rainfall amounts in the region also lead to increased floods during this season. Rainwater harvesting is defined as the method of collection, concentration and storage of rainwater that runs off a natural or man-made catchment surface for future use (Rahman 2017). Therefore, the potential of harvesting rainwater can be helpful in improving agricultural production in the dry period in the region and reduce impact of floods as well (Haq 2006).

Available water resources in Mbale include lakes, rivers and groundwater but due to the competing demand for water uses, these sources have an increasing water stress and yet the groundwater aquifers dry out during the dry spells (Michael 2012). This leaves less water available for all the competing water needs agriculture inclusive, compared with the current average demand from the served locations of 4,200 m^3 of water per day, which is only 40% of the water treatment plant capacity utilization (USAID 2013). Due to the high amounts of rainfall in Mbale, there is a high potential for harvesting sufficient amounts of water that can be used for both domestic and agricultural uses during the dry months of November to April. Rainwater harvesting technologies have been embraced but not fully developed in the region as a new approach to increasing water for domestic and agriculture uses (Ferdausi & Bolkland 2000). Mostly, rainwater is harvested for domestic use on a small scale only.

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Rainwater harvesting can positively impact the agricultural sector by enabling increased productivity in the dry season in Mbale if the technology is adopted, thus improving food security in the district and the country. Rainwater harvesting allows for easy collection of water and prevents the effects that may arise from runoff, like erosion. Rainwater harvesting can be cost efficient, and a replacement for other water sources in water-scarce areas (Batchelor *et al.* 2011). Rainwater harvesting is also a source of water for agricultural and domestic use in semiarid areas (Lasage & Verburg 2015). There is a number of existing rainwater harvesting technologies, which include: rooftop rainwater harvesting, runoff harvesting, flood flow harvesting, (SIWI 2001; Oduor & Maimbo 2005) and therefore the study will adopt the most economically viable method, which is the rooftop rainwater technology. Rooftop rainwater technologies involve collection of rain water from rooftops, storing it in above or ground tanks and then applying it to the field. Other technologies may involve using the soil as a storage by diverting runoff directly into the fields through construction of trenches, ditches and bunds (Ngigi 2003). The design of an efficient water harvesting system will require modelling of the water demands for agriculture in Mbale with the average annual rainfall amounts. Understanding the crop water requirements of major crops in Mbale can then be used to design the rain water harvesting systems. Studies conducted in the Northern part of Kenya indicated that construction of communal water storage greatly reduced conflict over water resources (Ngigi 2003) and improved crop and livestock production in Zimbabwe (Mutekwa & Kusangaya 2006). Among the crops grown in Mbale is cabbage, which is an annual crop that requires moisture throughout the growing period for good harvests all year round and therefore harvesting rainwater can provide a good solution to improving yields and enhancing food security.

With the increasing uncertainties in changes in climate, rainwater harvesting has been recommended as a sustainable adaption measure. Climate change will have significant impact on the hydrological cycle and the water quantity and quality. These effects will then greatly affect the availability of water (Huntington 2006; Sohoulande Djebou & Singh 2016). It was confirmed by IPCC that most of Africa is suffering from increasing temperatures with varying rainfall trends as indicated in most published climate change scenarios (Christensen *et al.* 2007). These increased temperatures indicate reduced soil moisture levels for agriculture (USAID 2013).

METHODOLOGY

Various authors have recently investigated the potential for rainwater harvesting (Ibrahim 2009; Awawdeh *et al.* 2012; Adugna *et al.* 2018). In this study, the potential for rainwater harvesting use both for domestic and agricultural use in Mbale was investigated. The area climatic data was analyzed for domestic water use and a modelling approach involving a biophysical crop model (Aquacrop) (Foster *et al.* 2017) was applied to simulate the potential of using the surplus water for backyard gardening.

Climatic data and validation

The 25-year (1992–2016) climate dataset for Mbale was obtained from the Ministry of Water and Environment in digital form and further analyzed in an Excel spreadsheet. This data was collected from location 38 at altitude 1,340 m, 34.15° E and 1.10° N Mbale, Uganda. The dataset included daily rainfall, minimum and maximum daily temperature, average daily humidity, wind speed and direction, solar radiation and sun daily hours. The data was validated by developing an average monthly data curve and comparing it with that provided on the (World Bank Climate Change Knowledge Portal 2019) (www.climateknowledgeportal.worldbank.org). The average

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monthly data curve was identical to the curve provided on the climate change knowledge portal with very insignificant differences in the data values.

Rooftop rainwater harvesting

To estimate the amount of water harvested, the rational method (Equation (1)) was used. This is undoubtedly the most commonly used method and preferable in rainwater harvesting design because of its simplicity and accuracy (Ibrahim 2009). It has been widely and worldly applied with a lot of modifications (Aladenola & Adeboye 2010). As used in this paper, the rational method is written as

$$\text{RWH potential}: Q = C * I * A_r \quad (1)$$

where C = coefficient of runoff (dimensionless), I = Mean monthly rainfall (m/month) and A_r = effective surface area of the roof top (m^2) Q = quantity of harvested water (m^3)

For this study, a coefficient of runoff, C = 0.85 was used to cater for losses in the water harvesting system considering an iron sheet roof, which is the most common roof in the case study. Meanwhile, for rainwater harvesting and water storage purposes, the average monthly rainfall was used. Based on the rooftop area data obtained from National Housing and Construction, Mbale office, an average of 200 m^2 was used in this paper. The monthly household water demand was further estimated by multiplying the per capita water demand by the average number of individuals per household. According to the World Health Organization, a person requires an average of 50 litres of water per day and an average of six individuals per household was taken (UBOS 2017). The storage tank size was chosen based on the highest monthly difference between the cumulative rainwater harvested and the cumulative water demand.

Aquacrop model, calibration and validation

AquaCrop is a crop simulation model that describes the interactions between the plant, water and the soil. In the model design, simplicity, accuracy and robustness were highly considered and optimally balanced. To be widely applicable, AquaCrop uses only a relatively small number of explicit parameters and mostly-intuitive input-variables that can be determined by simple methods. Moreover, the calculation procedures are based on basic and often complex biophysical processes to guarantee an accurate simulation of the crop response in the plant-soil system. The AquaCrop model simulates potential yields for crops as a function of water consumption under different water application methods (rain-fed and irrigated regimes) (Raes *et al.* 2009). It directly links crop growth to water use and estimates biomass production from actual crop transpiration through a normalized water productivity parameter, which is the core of the AquaCrop growth engine. AquaCrop simulates soil water balance and crop growth processes as a function of crop, soil, weather, and management input data, on a daily time step. In addition, AquaCrop simulates soil evaporation and crop transpiration explicitly as individual processes. A comprehensive description of the AquaCrop model has been reported by Foster *et al.* (2017). The input files are clustered into a 'project', with each project comprising up to 11 input files. Aquacrop allows input files to be created or modified within the user interface (Raes *et al.* 2009). The simulation results are recorded in output (text) files and can be grouped into 10-day, monthly or annual summary data. The output consists of five files containing data regarding crop growth and production, the soil water balance, soil water content at different depths and net irrigation requirements.

This model was used in this paper to simulate the potential of using the surplus rainwater harvested for backyard garden irrigation. The model was set up and calibrated using crop data obtained from Mbale District Agricultural office, Department of Water for Production. The data included most

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commonly grown crops, district soil map, and crop yield. The most commonly grown crops in the area such as potato, tomato, cabbage and maize were simulated in the model to determine their crop growth water requirement and yield. This was later compared with the calculated water surplus to determine the potential land acreage that can be potentially supported. In all the scenarios, a uniform irrigation rate and sandy loam texture were considered, which are typical for conventional farming in Mbale.

Economic analysis

In order to recommend rainwater harvesting in the study area, it was necessary to carry out the economic analysis of this investment. The economic analysis was done based on life cost analysis and benefit costs for a period of 10 years.

Life cost analysis (LCC)

The Australian/New Zealand Standard AS/NZS 4536:1999 defines LCC as 'the sum of acquisition cost and ownership cost of a product over its life cycle'. The life cost analysis was done considering the initial investment required in the construction of a rooftop rainwater harvesting system in Mbale, Uganda, and the financial benefits of the system for a period of 10 years. In considering the financial benefits, an assumption was made that households buy all the quantity of water required for household and garden irrigation if the rainwater harvesting system is not installed. Currently, according to the National Water and Storage Services (NWSC) of Uganda, the cost of water is 83 UGX per 20 L (0.02 m^3) for domestic use and 93 UGX per 20 L (0.02 m^3) for commercial use (National Water and Sewerage Corporation 2018). These values were used in estimating the financial benefits of the system per year. Also, maintenance costs for the system were taken into consideration. The LCC was estimated as given by similar studies done in Australia and Kenya (Amos *et al.* 2016).

Net present value (NPV) payback period (PP) and benefit cost ratio (BCR)

Apart from the life cost analysis, other parameters to evaluate the economic benefits of any investment are net present value (NPV), payback period of the investment (PP) and benefit cost ratio (BCR). In this paper, the currency used is Uganda Shillings (UGX). The NPV is the sum of present values (PV) over the system life, which is 10 years. The Present values are calculated by multiplying cash flows (CF) by the discount rate, which is a function of the interest rate (i) and the year in which the cash flow occurred (t), as shown below in Equation (2):

$$\text{Discount rate} = \frac{1}{(1+i)^n} PV = \frac{CF}{(1+i)^n} \tag{2}$$

The net present value (NPV) is then estimated from Equation (3)

$$\mathrm{NPV}(i, N) = \sum_{t=0}^{N} \frac{CF_t}{(1+i)^t} \tag{3}$$

where:

N = is the number of years the life cycle is considered over (10 years)

CF = the difference between cash outflow and inflow, each reduced by the discount rate appropriate to the time of cash flow.

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The payback period is simply defined as the time required to recover an investment or loan. In this study, the payback period was estimated as the year out of the 10 year period when the investment cost was fully recovered. Meanwhile, the benefit-cost ratio (BCR) is also calculated using discounted rates as given in Equation (4). This is simply the sum of discounted costs (C) divided by the sum of discounted benefits (B) as they occur at time *t* over the lifetime of the rainwater harvesting system N:

$$\mathrm{BCR} = \frac{\sum_{t=0}^{N} \frac{C_t}{(1+i)^t}}{\sum_{t=0}^{N} \frac{B_t}{(1+i)^t}} \tag{4}$$

RESULTS AND DISCUSSION

The results obtained from the study are presented and analyzed in the following sections.

Climate data

The 25 years (1992–2016) of rainfall statistics (Figure 1) gives a strong basis for assessing the RWH potential of the region. The variation in rainfall between months is significant, with the largest difference between the wettest month, May, and driest month, January, reflecting a climate with strong seasonality in rainfall. This region receives significant rainfall starting from April to May and then less rain from June to July. However, the rainfall increases in August and then reduces from September onwards till January, which is usually the driest month. Evidently, water scarcity rises during the dry months due to the fact that water demand rises during this period. Also, the temperature data shows that there is high temperature during the dry months with high evapotranspiration (ET). Therefore, the crop water requirement that is needed for crop growth and development during this period will increase and there is a need to cater for it.

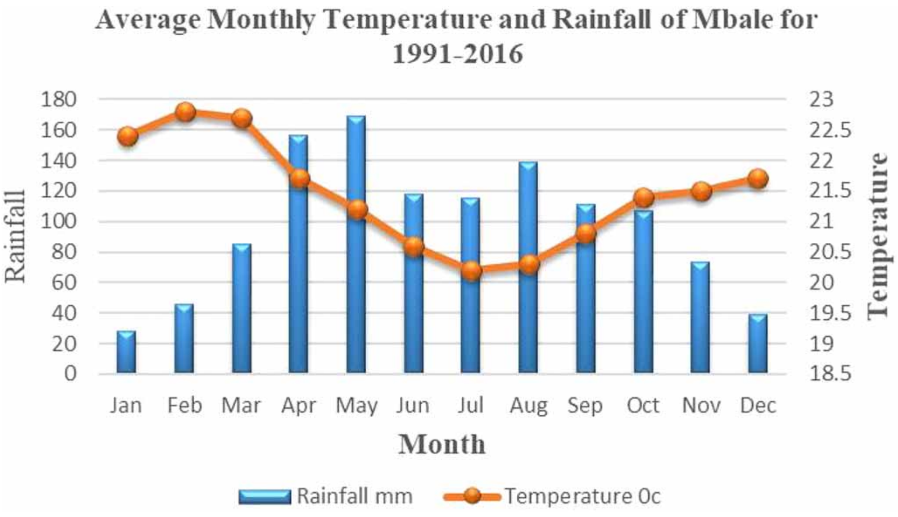

Figure 1 | Graph of average monthly temperature and rainfall of Mbale for 1992–2016.

Potential of rooftop RWH from a household for domestic uses

The estimated potential of rooftop RWH from a household with six people having a roof area of 200 m^2 and runoff coefficient of 0.85 with a daily water demand of 50 l according to the World

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Health Organization's standard (WHO 2008) for good hygiene is given in Table 1. The results show that comparing the resulting RWH potential with the water consumption, up to 186% of the annual water demand for domestic use according to the World Health Organization (WHO) standard can be provided. However, it should be noted that this is the maximum quantifiable volume, not considering limitations associated with tank size, water losses due to connections and fittings, partial coverage of roof area, pollution of water, or other probable factors that can reduce the volume that can be obtained in practice. Table 1 explains the procedures taken to calculate the storage tank capacity by considering the received and the withdrawing cumulative water quantity. Figure 2 shows the difference between harvestable water and monthly water demand for a typical household, as highlighted above. The storage tank capacity is taken as the maximum value in column (7) as the difference between the water harvested (received), in column (4), and the water demand for the household (withdrawing), in column (6), in any month (Figure 3). This value is obtained in the month of which is 95.8 m^3. However, considering water losses, pollution and cost factors, and the recommended storage size is dependent on the use of harvested water. It is recommended that households can use a storage tank size of 20 m^3/20,000 L for domestic use only. Households can purchase two 10,000 L storage tanks to meet this size (20 m^3) for maximum storage. Nonetheless, since the focus of this paper is beyond domestic uses only, it is recommended that a storage size of 95.8 m^3 should be acquired for domestic and irrigation uses. From Figure 4, the storage capacity can be calculated from the rainfall data graphically by comparison of demand with supply based on the harvest. Maximum harvest of water should be ensured from October to February, which are the dry months, to have sufficient water for domestic and agricultural uses. Meanwhile, Table 2 shows the harvestable water from different rooftop areas with runoff coefficient of 0.85 for the months of the year.

Table 1 | Estimation of tank capacity for a household

c = 0.85, roof area = 200 m^2, per capita 50 L, 6 people per household

1	2	3	4	5	6	7
Jan	28.35	4.8	4.8	9	9	−4.2
Feb	45.36	7.7	12.5	9	18	−5.5
Mar	85.23	14.5	27.0	9	27	0.0
Apr	156.11	26.5	53.6	9	36	17.6
May	168.58	28.7	82.2	9	45	37.2
Jun	117.88	20.0	102.3	9	54	48.3
Jul	115.24	19.6	121.8	9	63	58.8
Aug	138.64	23.6	145.4	9	72	73.4
Sep	110.68	18.8	164.2	9	81	83.2
Oct	106.59	18.1	182.4	9	90	92.4
Nov	73.33	12.5	194.8	9	99	95.8
Dec	38.81	6.6	201.4	9	108	93.4

Legend:
Column 1: The months of the year.
Column 2: Mean monthly rainfall (mm).
Column 3: Rainfall harvested (m^3) = (c * mean monthly rainfall * roof area)/1,000.
Column 4: Cumulative rainfall harvested (m^3).
Column 5: Water demand (m^3) = (50 L/day * 6 persons * 30 days).
Column 6: Cumulative water demand (m^3).
Column 7: Difference between cumulative demand and cumulative supply (m^3) (tank storage = maximum value).

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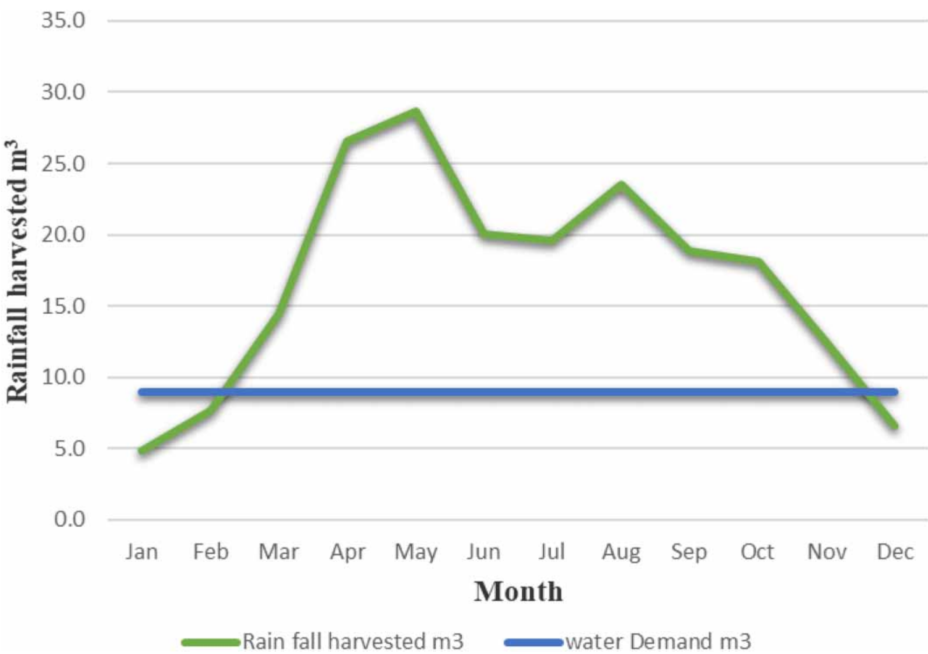

Figure 2 | Graph of comparison of the harvestable water and the demand for each month.

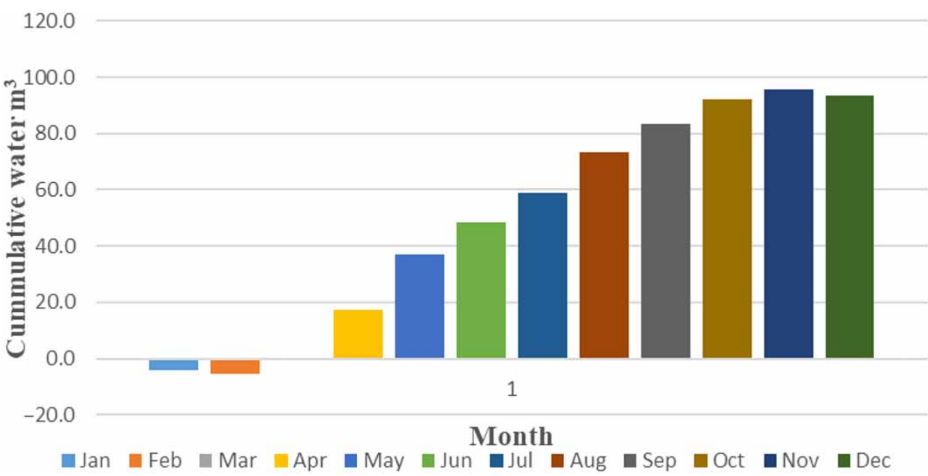

Figure 3 | Difference between cumulative demand and cumulative rainwater harvested.

Simulation of potential rooftop RWH to supplement irrigation

The excess rainwater harvested after domestic use from the 200 m^2 was simulated to estimate the quantity of water needed for irrigation during dry periods. Four staple crops in Mbale, Uganda, were simulated for drip irrigation. These are cabbage, tomato, maize and potato. From Table 3, the simulation shows that the excess harvested water from 200 m^2 rooftop can be used for irrigation to cultivate areas of 269, 429, 125 and 388 m^2 for cabbage, tomato, maize and potato respectively during dry periods. Meanwhile, Figures 5 and 6 explain the crop water requirements and areas. These areas of land are sufficient to cultivate food that can feed many households. Tomato, which is a perishable commodity, needs to be in the market all year round. Interestingly, from the study, it reveals that tomato needs the least amount of water among the crops simulated and it can be used to irrigate a large farm. Also, potatoes require less water than cabbage and rainwater can sufficiently irrigate about 388 m^2 farmland for potato during dry periods. Due to the longer growing period

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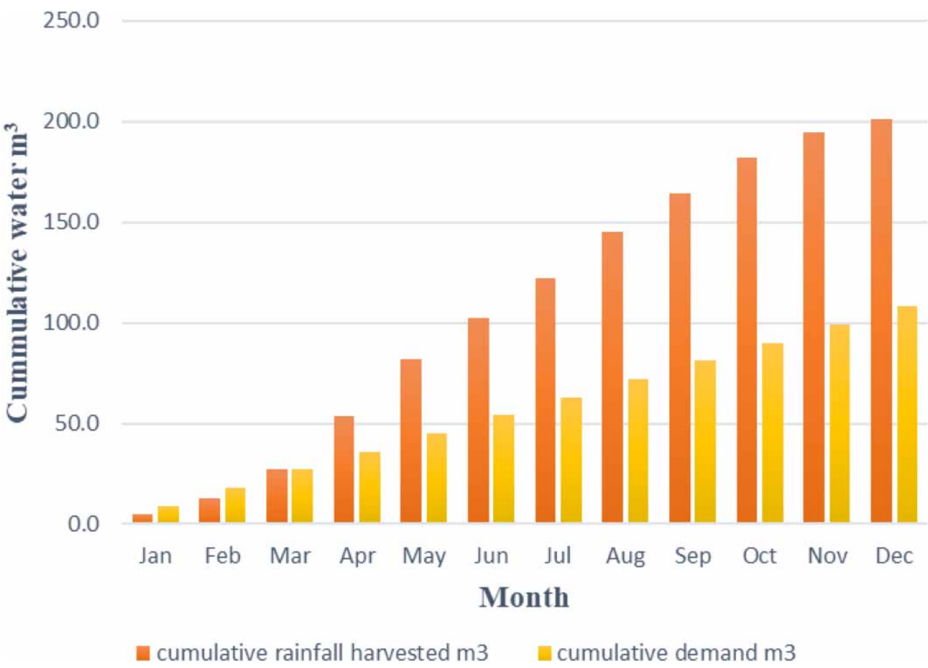

Figure 4 | Graph showing the predicted cumulative inflow and outflow from the tank.

of maize, it needs more water than all other crops simulated. However, any farmer that desires to use rainwater for irrigating maize farmland will need to increase the rainwater catchment area. From the results, it shows that through rainwater harvesting, food security can be achieved in Mbale. In addition, it will make foodstuffs affordable for people, especially during the dry periods.

Economic analysis

The economic analysis of the rainwater harvesting system was carried out on a 200 m^2 roof surface area in Mbale, Uganda considering the current economic status of the study area. Life cost analysis, maintenance costs, net present value, payback period and the benefit cost analysis were done in Uganda currency (Uganda Shillings, UGX).

Life cost analysis

The cost of investing in rainwater harvesting systems in Mbale was estimated as shown in Table 4. This shows that the investment cost of constructing a rainwater harvesting system will cost up to 2,609,000 UGX. Table 5 shows the maintenance cost per year of the rainwater harvesting system. It shows that the estimation of yearly maintenance cost will be up to 25,000 UGX.

Net present value (NPV) payback period (PP) and benefit cost ratio (BCR)

The benefits of rainwater harvesting were estimated based on 9 m^3 per month for 12 months at 83 UGX per 20 L for domestic use and 93 UGX per 20 L for commercial use. For this study, the discounted rate was calculated as 10%. Also, the financial benefits of buying domestic water per year were estimated as 448,200 UGX and financial benefits of buying irrigation water were estimated as 470,250 UGX, as shown in Table 6. Table 7 shows that the payback period for the investment will be the third year of the 10-year period that was projected. In addition, the NPV was estimated as 2,880,863 UGX, which gave the BCR as 1.99.

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Table 2 | Potential volume of monthly rainwater for different roof area and c = 0.85

Month													
Area (m^2)	Average monthly rainfall (mm)	Jan 28.35	Feb 45.36	Mar 85.23	Apr 156.11	May 168.58	Jun 117.88	Jul 115.24	Aug 138.64	Sep 110.68	Oct 106.59	Nov 73.33	Dec 38.81
10		0.2	0.4	0.7	1.3	1.4	1.0	1.0	1.2	0.9	0.9	0.6	0.3
20		0.5	0.8	1.4	2.7	2.9	2.0	2.0	2.4	1.9	1.8	1.2	0.7
30		0.7	1.2	2.2	4.0	4.3	3.0	2.9	3.5	2.8	2.7	1.9	1.0
40		1.0	1.5	2.9	5.3	5.7	4.0	3.9	4.7	3.8	3.6	2.5	1.3
50		1.2	1.9	3.6	6.6	7.2	5.0	4.9	5.9	4.7	4.5	3.1	1.6
60		1.4	2.3	4.3	8.0	8.6	6.0	5.9	7.1	5.6	5.4	3.7	2.0
70		1.7	2.7	5.1	9.3	10.0	7.0	6.9	8.2	6.6	6.3	4.4	2.3
80		1.9	3.1	5.8	10.6	11.5	8.0	7.8	9.4	7.5	7.2	5.0	2.6
90		2.2	3.5	6.5	11.9	12.9	9.0	8.8	10.6	8.5	8.2	5.6	3.0
100		2.4	3.9	7.2	13.3	14.3	10.0	9.8	11.8	9.4	9.1	6.2	3.3
120		2.9	4.6	8.7	15.9	17.2	12.0	11.8	14.1	11.3	10.9	7.5	4.0
140		3.4	5.4	10.1	18.6	20.1	14.0	13.7	16.5	13.2	12.7	8.7	4.6
160		3.9	6.2	11.6	21.2	22.9	16.0	15.7	18.9	15.1	14.5	10.0	5.3
180		4.3	6.9	13.0	23.9	25.8	18.0	17.6	21.2	16.9	16.3	11.2	5.9
200		4.8	7.7	14.5	26.5	28.7	20.0	19.6	23.6	18.8	18.1	12.5	6.6
220		5.3	8.5	15.9	29.2	31.5	22.0	21.5	25.9	20.7	19.9	13.7	7.3
240		5.8	9.3	17.4	31.8	34.4	24.0	23.5	28.3	22.6	21.7	15.0	7.9
260		6.3	10.0	18.8	34.5	37.3	26.1	25.5	30.6	24.5	23.6	16.2	8.6
280		6.7	10.8	20.3	37.2	40.1	28.1	27.4	33.0	26.3	25.4	17.5	9.2
300		7.2	11.6	21.7	39.8	43.0	30.1	29.4	35.4	28.2	27.2	18.7	9.9
320		7.7	12.3	23.2	42.5	45.9	32.1	31.3	37.7	30.1	29.0	19.9	10.6
340		8.2	13.1	24.6	45.1	48.7	34.1	33.3	40.1	32.0	30.8	21.2	11.2
360		8.7	13.9	26.1	47.8	51.6	36.1	35.3	42.4	33.9	32.6	22.4	11.9
380		9.2	14.7	27.5	50.4	54.5	38.1	37.2	44.8	35.7	34.4	23.7	12.5
400		9.6	15.4	29.0	53.1	57.3	40.1	39.2	47.1	37.6	36.2	24.9	13.2
420		10.1	16.2	30.4	55.7	60.2	42.1	41.1	49.5	39.5	38.1	26.2	13.9
440		10.6	17.0	31.9	58.4	63.0	44.1	43.1	51.9	41.4	39.9	27.4	14.5
460		11.1	17.7	33.3	61.0	65.9	46.1	45.1	54.2	43.3	41.7	28.7	15.2
480		11.6	18.5	34.8	63.7	68.8	48.1	47.0	56.6	45.2	43.5	29.9	15.8
500		12.0	19.3	36.2	66.3	71.6	50.1	49.0	58.9	47.0	45.3	31.2	16.5

Table 3 | Simulated results for irrigation water

No	Crop	Planting period	Simulated evapotranspiration (ETo), (mm)	Rainfall (mm)	Net irrigation, (mm)	Excess rainwater harvested after domestic use (m^3)	Area of land that can be cultivated (m^2)
1	Cabbage	October – December	318.2	158.7	356.4	95.8	269
2	Tomato	October – February	428.5	463.5	223.2	95.8	429
3	Maize	October – February	652.3	229.2	765.9	95.8	125
4	Potato	October – February	474.1	505.7	247	95.8	388

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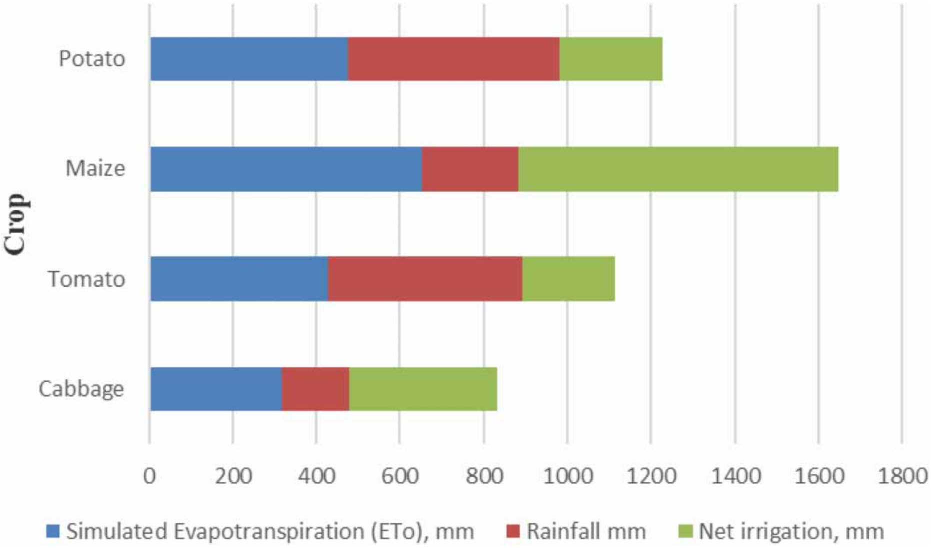

Figure 5 | Simulated crop water requirements for the crops.

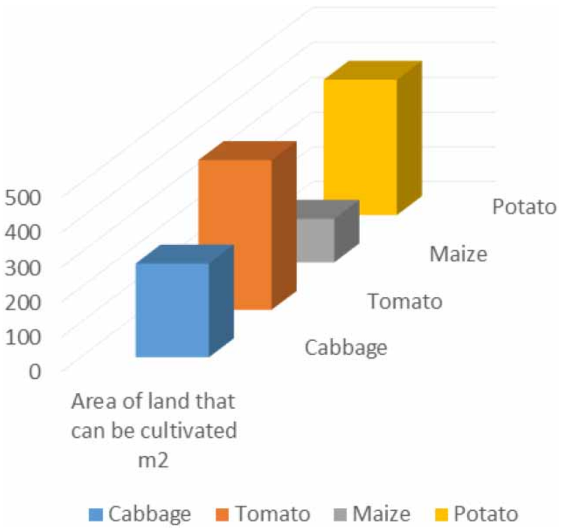

Figure 6 | Simulated area of cultivable land for the crops.

Table 4 | Investment cost of rainwater harvesting system

Items	Cost (UGX)	USD
Tank (10,000 l)	1,940,000	527
Concrete tank stand	259,000	70
Pipes, fittings and gutters for harvesting on a 200 m^2 rooftop	260,000	71
Labour	150,000	41
Total	**2,609,000**	**709**

Table 5 | Estimate maintenance costs of the rainwater harvesting system per year

Items	Cost (UGX)	USD
Tank cleaning	15,000	4
Repair of pipes and gutters	10,000	3
Total	**25,000**	**7**

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Table 6 | The estimated financial benefits per year

Benefits	Cost (UGX)	USD
Domestic water	448,200	122
Water for garden irrigation	470,250	128
Total	**918,450.00**	**250**

DISCUSSION

Evidently, rainwater harvesting can sufficiently supplement water supply and boost food security in Mbale region. This is in agreement with the previous studies conducted in Denmark (Mikkelsen *et al.* 1999) and UK (Butler *et al.* 2016), which show that rainwater possibly contributes up to 69% of the water supply in the countries. A study done by Aladenola & Adeboye (2010) in Nigeria also shows that rainwater can sufficiently contribute to augmenting the water supply in the country especially during the dry months of November, December, January, and February, which are the same as in the Mbale region.

Similarly, the results of this study are in agreement with a study conducted in Mexico (Lizárraga-Mendiola *et al.* 2015), where it was established that the harvestable rainwater from a roof area of 45 m^2 and 50 m^2 would be adequate for basic domestic water demands like flushing of the toilet and laundry for the larger period of a year. Meanwhile, the study shows that 100 m^2 and 200 m^2 roof area would be sufficient to provide and meet the water demand for other uses in the study area, which is in accordance with the results of this study. This study also adopts the roof area of 200 m^2 for a typical household. However, it is in contrast with the report of research conducted in Addis Ababa, Ethiopia, where the harvestable rainwater was estimated from the roofs of large institutions of learning, which will only contribute 2.3% of the total water demand/water consumption of Addis Ababa (Dagnachew *et al.* 2018).

The results of this study for garden irrigation or small-scale farming is consistent with a similar study, in Sicily, Italy (Liuzzo *et al.* 2016), which evaluated the dependability of using rainwater for flushing of toilets and for backyard farming irrigation for a typical single-family household scenario, which is similar to this study. The authors report that the rainwater harvested is sufficient for backyard farming and can be extended to large-scale agriculture. Furthermore, the results of this study are in accordance with another similar study by Liang & Dijk (2016) in Beijing, who assessed the role of non-technological factors in rainwater harvesting for food security through agricultural irrigation. In their report, it is recommended that it is imperative to increase the confidence of the general public and motivate farmers to utilize rainwater for agriculture irrigation in order to achieve Sustainable Development Goals (SDGs).

The stable rainfall conditions in the wet season, even with the use of small storage capacity, permit a capable substitute for other freshwater sources and increase water supply, for instance reducing groundwater withdrawals. This is in accordance with the report of a study done in Iran that shows that due to indiscriminate usage and over exploitation, there is a reduction in groundwater resources (Gholami *et al.* 2015). In addition, Durodola (2019), in a study carried out in Nigeria, recommended rainwater harvesting as a climate change adaptation measure and method of getting sufficient water for agriculture. Concerning the volume of rainwater that can be harvested and stored to be used during the dry period, this depends on the capacity of the storage tank, which is a vital factor to be considered in rainwater harvesting. Also, the costly storage tanks require investment power and economic analysis, which might be difficult for local farmers to afford, as reported by Abdulla & Al-Shareef 2009 and Amos *et al.* 2016. Therefore, other types of rainwater harvesting can be adopted to reduce the financial burden. The impact of climate change has to be considered as there might be fluctuations in the rainfall patterns in the coming years.

Table 7 | Rainwater harvesting economics

Year	0	1	2	3	4	5	6	7	8	9	10
Costs	2,609,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000
Benefit	0	918,450	918,450	918,450	918,450	918,450	918,450	918,450	918,450	918,450	918,450
Payback period	(2,609,000)	(1,715,550)	(822,100)	71,350	964,800	1,858,250	2,751,700	3,645,150	4,538,600	5,432,050	6,325,500
Net profit	(2,609,000)	893,450	893,450	893,450	893,450	893,450	893,450	893,450	893,450	893,450	893,450
NPV		2,880,863									
BCR		1.99									

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In addition, the quality of harvested rainwater largely depends on the surrounding environment, the material of the tank, and the maintenance system for the rainwater harvesting system. In another report by Hamdan (2009) and Van der Sterren *et al.* (2013), the water harvested from the roof area may have the presence of heavy metals and nutrients. In order to obtain safe water, the use of effectively designed first flush devices and regular checks/maintenance of the system can considerably improve the quality of the harvested water. These checks, as suggested by Melidis *et al.* (2007) and Abdulla & Al-Shareef (2009), include installation of first flush systems, regular checkup of the point of entry for insects such as mosquitoes and vermin, and washing of the roof surfaces.

The studies from all the reviewed literature used in this paper have proven that rooftop rainwater harvesting has great potential in supplementing other water sources like groundwater. In the humid, water scarce and semi-arid regions like Ethiopia, the rainwater potential is high as it is used to supplement the water supply for non-potable uses like car washing and flushing the toilet. With proper treatment, however, the harvested rainwater can be used for potable purposes. In addition to this, it can also be a very resourceful water source for agriculture as the savings realized are enormous comparing to other options like pumping groundwater.

The economic cost analysis of any investment is essential. In order to fully recommend rainwater harvesting to farmers in a local community such as Mbale, the economic costs plays an important role. The results of the investment costs reveal that the total cost is affordable for low and middle income farmers in the region. In addition, since the investment cost is affordable for small-scale farmers, it means that large-scale farmers can also afford the cost and implement it on their farms to reduce their cost of production. The estimated maintenance costs also show that the cost of maintaining the system is really cheap, since the system can stay for long periods of time without any damage. Furthermore, the estimated benefits shows that the benefits outweigh the costs of investment according to the estimated benefit cost ratio (BCR) which is 1.99. Since the BCR is greater than 1, it is economically viable (Amos *et al.* 2016). Due to the fact that water is becoming scarce than ever before and water might become more expensive in the near future, investing in rainwater harvesting will be an economically wise decision. The net present value and payback period estimated show that the investment is economically favorable. With a payback period of 3 years out of the 10 years projected, it implies that the investor will recover the investment costs within a short period of 3 years. Many studies have been done on the potential of rainwater harvesting; however, many of them did not critically examine the economic implications. Therefore, this study has revealed that rainwater harvesting has a lot of potential for achieving water security and it is economically favorable as well.

CONCLUSION AND RECOMMENDATIONS

The study indicates that it is imperative to adopt rainwater harvesting technology to improve food security in the Mbale district and the country at large. The potential rooftop rainwater harvesting technology is examined and the maximum water that can be collected from 200 m^2 rooftops is 95.8 m^3 without taking into account the evaporation and evapotranspiration losses. The runoff coefficient of 0.85 was used to compensate for the runoff losses. The results obtained from AquaCrop, a biophysical simulation model, indicated that up to 186% of annual water demand for domestic use can be provided and excess water used to cultivate land areas of 269, 429, 125 and 388 m^2 for cabbage, tomato, maize and potato respectively during dry periods. Results from the simulation indicated that tomato requires the least amount of water, while maize requires the greatest amount of water of all crops due to the longer growing period. The simulation results also indicated that attainment of food security is very possible if rainwater harvesting is adopted. Furthermore, the economic analysis shows that the investment and maintenance costs are affordable for farmers, the estimated benefit cost ratio (BCR) is 1.99 and the investment has a payback period of 3 years which shows that the

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investment is economically beneficial. The Government of Uganda should encourage rainwater harvesting by providing financial support to the farmers and awareness campaigns should be promoted to increase knowledge and the importance of rainwater harvesting. Further studies should also be conducted to understand the effects of climate change on rainwater harvesting.

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