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RESEARCH ARTICLE

A Google Earth-GIS based approach to examine the potential of the current rainwater harvesting practices to meet water demands in Mityana district, Uganda

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Abstract

Rainwater harvesting (RWH) has become an integral part of global efforts to improve water access. Despite the increasing adoption of RWH in Uganda, there remains a significant knowledge gap in the assessment of RWH systems to meet water demands. In this study, a simplified methodology to estimate rainwater harvesting potential (RWHP) as a function of mean seasonal rainfall and rooftop area, generated using Google Earth and GIS tools is applied. Desired tank storage (DTS) capacities based on user population, demand and dry period lengths, were compared with RWHP to assess whether rooftop areas and tank storage can sustainably supply water for use during the March—May (MAM) and September-November (SON) 90-day dry periods, for three demand levels (i.e. for drinking and cooking (15 litres per capita per day (l/c/d)); for drinking, cooking and hand washing (20 l/c/d); and for drinking, cooking, hand washing, bathing and laundry (50 l/c/d)). Our findings document minimum catchment areas of 60m^2 to have rainwater harvesting potential that can sustain households for 90-day dry periods for all three demand levels. However, considering their storage capacities, 25%, 48% and 97% of the existing RWHTs (with storage capacities below 8,000, 10,000 and 20,000 litres respectively) are unable to meet the demand of 15 l/c/d, 20 l/c/d and 50 l/c/d respectively for a 90-day dry period. The results document that the existing storage systems are under-sized for estimated water use under 50 l/c/d demand scenarios. Costs of between 2,000,000–4,500,000 Ugandan shillings (~ 600–1, 250 USD) would be needed to increase existing tank capacities to meet the 50 l/c/d demands for a 90-day dry period. These findings document onerous financial costs to achieve rainwater harvesting potential, meaning that households in Mityana district may have to resort to other sources of water during times of shortage.

from the Ministry of Water and Environment Uganda and requires a user to seek permission before access (http://wsdb.mwe.go.ug/). The contact for the ministry is Tel: +256 417 889 400 Email: mwe@mwe.go.ug.

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1. Introduction

The dependence on water for drinking, basic sanitation and hygiene increases in relation to the growing population, which when combined with the increasingly uncertain and variable climate, can rapidly degrade water availability. Rural communities in Sub-Saharan Africa that depend on groundwater for drinking water often face water shortage challenges during dry seasons when groundwater levels decline, resulting in seasonal well failure [1], effectively eliminating the primary household water source. Households resort to securing domestic water needs from secondary water sources, often surface water from nearby streams [2] that are typically of poor water quality and may increase time required to fetch daily water needs.

Rainwater has long been recognized as a strategic renewable water source [3, 4] which, if efficiently harvested and stored, can augment groundwater and surface water shortages during periods of insufficient water availability [5], boosting water reliability to fulfill water demands. Adoption of rainwater harvesting has increased worldwide e.g., in India [6], China [7], South Africa [8], Nigeria [9]. In particular, the recognition of increased reliability for freshwater availability when augmenting water supplies using rainwater harvesting has resulted in rapid development in areas with seasonally distributed rainfall, common in Sub-Saharan Africa.

Rainwater harvesting (RWH) systems collect and store rainfall or rainfall-induced runoff [10, 11], through technologies such as tanks or gullies. RWH provides positive benefits given a myriad of uses. For instance, RWH has been shown to buffer the impacts of increased variability in timing and amount of rainfall on rain-fed agricultural production and livestock [11]. Rainwater harvesting practices improved farmer incomes [12] e.g., in Tanzania, where increased gross margins and returns to labor in onion and maize growing have been documented. In both rural and urban communities, RWH systems are used to ensure continual access to portable water during periods of reduced water availability [13], fulfilling vital domestic water and basic hygiene demands during dry periods in Sub-Saharan Africa. For instance, in Abeokuta, Nigeria, harvested rainwater during the peak rainfall months of June, September and October was sufficient to satisfy household water demand for water closet (WC) flushing and laundry during the dry months of November-February [14].

In Uganda, the increased adoption of RWH systems has spurred numerous studies to assess system benefits. Studies examining the impact of rainwater harvesting on agricultural production/food security [15, 16] and climate change adaptation [17] found that rooftop rainwater harvesting has the potential to satisfy domestic needs and support agricultural production during dry periods, leading to persistent production of crops (e.g., vegetables, maize and potatoes) and livestock and thus sustained volumes of cash and food crops. Studies e.g., [18] examining the future impact of rainwater harvesting on water security under changing climates found that water savings and security would reduce in December—February and March—May seasons and increase in June—August and September—November seasons, a phenomena that calls for measures by households to harness the increased water savings in JJA and SON to cater for the predicted reduction in water savings in MAM and DJF seasons.

A key issue in recognizing the benefit of RWH is adoption of RWH practices [19], where hesitation is often due to cost [20–23]. Broad recommendations for tank sizing by Uganda's Ministry of Water and Environment (https://www.mwe.go.ug/library/rain-water-harvesting-handbook, August, 18 2021) do not account for reliability to meet desired water demands given a range of water uses and may limit RWH adoption given price [23]. Additional issues with RWH adoption include water quality [24, 25], documented to be attributed to maintenance and gender perspectives [26]. A complicating factor in evaluating RWH potential is the local variability in precipitation [27], especially where rainwater harvesting generalization remains elusive, such as the mountainous regions in eastern Uganda [13]. Although these studies have provided strong evidence regarding the utility of RWH to benefit water supply resilience in Uganda, there remains a knowledge gap to quantify RWH storage potential to avoid over/under catch and minimize economic loss.

A significant limitation in rainwater harvesting development in Uganda, as is true in many developing countries, is a lack of a generalization framework to guide optimum storage size in relation to household characteristics (e.g., number of family members, household water demands) and climate (e.g., seasonal variability in precipitation). A complicating factor in the development of a generalization framework is the capitalistic nature of RWH production, where manufacturers operate for economic gain using pre-fabricated RWH storage options without consideration of the design parameters for optimum storage. Our experience in Uganda also confirms that household decisions to purchase/construct RWH technologies largely depend on the economic capability and perceptions of purchasers, with no consideration of the design parameters for optimum storage and metrics of reliability during periods with no filling due to a lack of precipitation. As a result, RWH systems are often incorrectly sized due to the pre-fabrication sizing of storage systems, leading to over (under) utilization of the RWH potential. Inefficiently sized RWH systems represent economic losses, either due to unnecessary construction and material costs for oversized systems or opportunity cost for undersized systems.

To determine optimal RWH potential storage, at a minimum, an estimate of rooftop/catchment area is required. Rooftop/catchment area data is limited in Uganda, leading to simplifications, such as the use of a single rooftop area in many previous studies (e.g., [13, 15]). The ill-advised application of a single rooftop area value can be overcome with Google Earth and GIS technologies, whereby site-specific rooftop area estimates may be extracted (e.g., [28–33]). Roof area estimation approaches have, to date, been applied over Africa (e.g., [34]), Asia (e.g., [33, 35, 36]), and Europe (e.g., [37]), providing a framework to quantify RWH potential over any region, including Uganda.

This study applies a Google Earth—GIS based approach to examine the rainwater harvesting system potential to meet water demands in Uganda. In this study, we restrict our evaluation to existing (i.e., installed and operational) rooftop rainwater harvesting at household level, where rainwater on rooftops is conveyed and stored to a centralized tank system for domestic uses (e.g., drinking, cooking and sanitation and hygiene). The objectives of the study are to 1) estimate rooftop areas associated with existing RWH storage tanks using Google Earth Pro and GIS, 2) estimate the potential volume of rainwater that can be harvested given estimated rooftop areas, 3) evaluate the over (under) utilization of existing rainwater harvesting tank storages to fulfill desired water demands during dry seasons, and 4) quantitatively express the economic implications of over (under) utilization. Our study is conducted over the Mityana district in Uganda (Fig 1) given that it is one of the districts in Uganda where rainwater harvesting has been actively promoted by individuals and development partners (e.g., Uganda Community Based Association for women and Children's welfare (UCOBAC)).

2. Materials and methods

2.1. Study area

The study was conducted over Mityana district (Fig 1). Mityana district is within central Uganda, between latitudes 0.2˚N-0.8˚ N and longitudes 31.5˚E - 32.5˚E and is about 70km west of the capital city, Kampala. The district covers a geographic area of 1,580 km^2 with a population of almost 330,000 [38]. Precipitation variability over Mityana district is characterized by bimodal wet seasons March—May and September–November. The mean annual total rainfall is about 1260 mm, while the district's mean annual temperature is 21˚C.

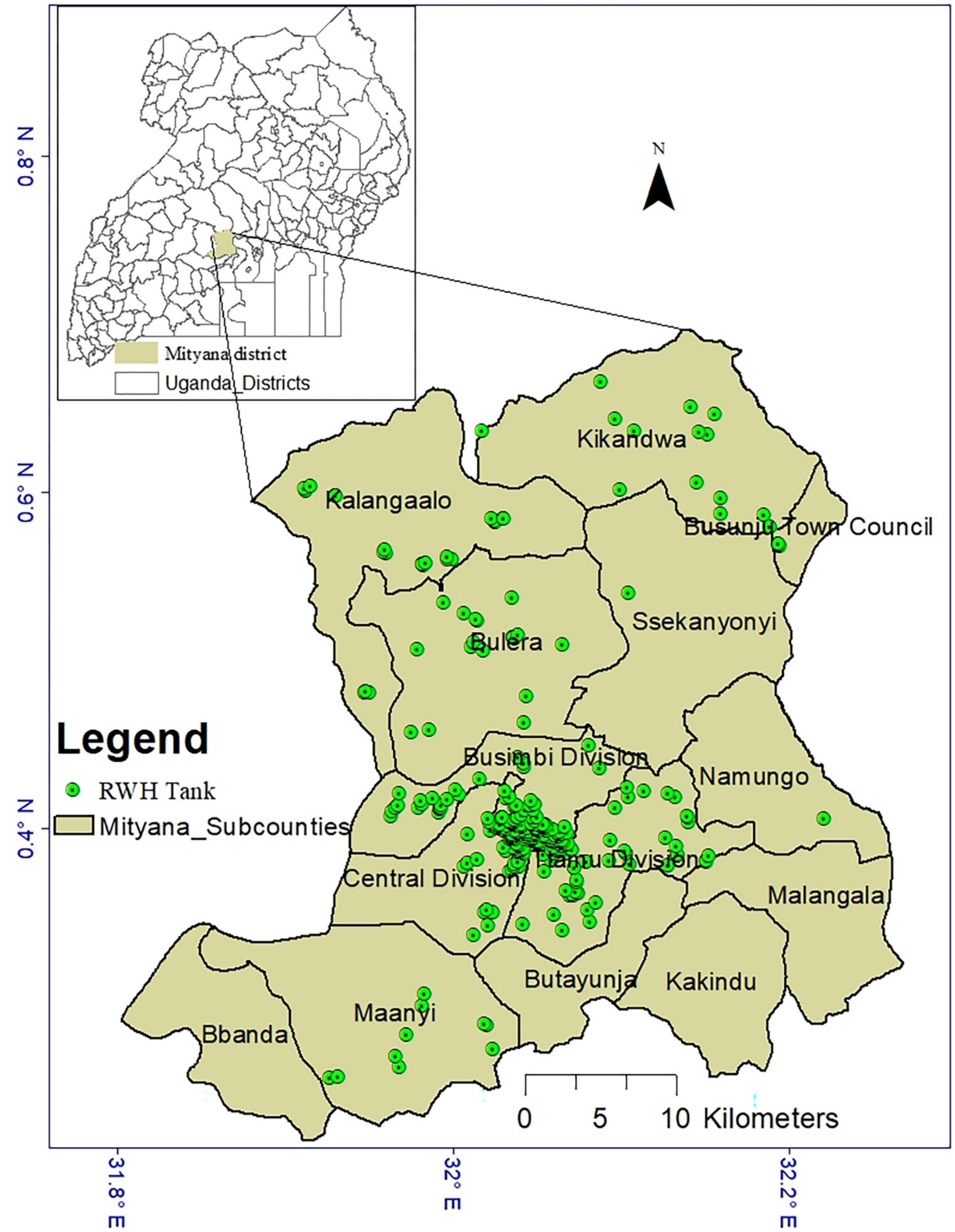

Fig 1. A map of Mityana district showing the location of rainwater harvesting tanks (base map sourced from the Uganda Bureau of Statistics (UBOS) from the link https://ubos.maps.arcgis.com/home/item.html?id=4e92034071494dffb239a219449fd2c1, accessed January, 15 2021).

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2.2. Rainwater harvesting tanks in Mityana District

Rainwater harvesting tank records were sourced from Uganda's water supply atlas database available at the Ministry of Water and Environment, Uganda website (http://wsdb.mwe.go.ug/, accessed January 12, 2021). The records include variables such as spatial coordinates (e.g., Lat-Lon), villages/parishes, ownership (e.g., household, community, and institutions among others), funding agency and volumetric storage capacity (in litres).

For quality control, tank records with missing spatial coordinates or no reported storage volumes were removed from the analysis. Also, tank records without reported storage volumes

Table 1. Storage capacities of the private tanks.

Storage Volume Range (litres)	*Frequency*	*Percentage*
2001–4000	9	5.0
4001–6000	32	17.7
6001–8000	41	22.7
8001–10000	59	32.6
10001–12000	8	4.4
12001–14000	2	1.1
14001–16000	9	5.0
16001–18000	3	1.7
18001–20000	11	6.1
>20000	7	3.9

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were removed from the analysis. A total of 327 tanks over Mityana district were identified as meeting data quality criteria for this study (Fig 1). Out of these, 181 (55.7%), 91 (27.83%), 17 (5.2%), 7 (2.14%), 3 (0.92%), 2 (0.61%) and 13 (3.98%) are owned by individual private homes, education institutions, health institutions, domestic farms, community, business-hotel and other owners, respectively. The majority (62%) of the tanks have a storage capacity between 5,000–15,000 litres.

The dearth of information about water demand per user for education institutions, health institutions, domestic farms, community, and business-hotel among others, limited our analysis to private household RWH systems. A total of 181 private tanks with storage capacity ranging from 2000 litres to over 20,000 litres (Table 1) were therefore considered in this study. A chi-square test [39, 40] to examine whether the percentages of tanks corresponding to the different ranges of storage in Table 1 are statistically different was performed. A chi-square value of 251.23 and a P-value $<<$ 0.001 were obtained, indicating that the percentages of tanks across the different ranges of storage are significantly different at 5% level.

2.3. Rainfall estimates

The Climate Hazards InfraRed Precipitation with Station data (CHIRPS v.2) [41, 42] rainfall dataset was used to estimate rainfall given the temporal length (1981 to near-present) and coverage over the storage area at a resolution of 0.05-deg (~5.3km). The CHIRPS dataset was acquired through the website (http://chg.geog.ucsb.edu/data/chirps/, accessed, February 15, 2021) for the years 1981–2017. The CHIRPS precipitation data was applied in our analysis given that it has been shown to perform better than other satellite products over Africa [43, 44] and to be less affected by variation in elevation [45, 46].

Mityana district experiences two rainfall seasons March–May (MAM) with a peak in April and September—November (SON) with a peak in October (Fig 2A). The average annual rainfall in Mityana district based on CHIRPS data is 1300mm with annual ranges of 1000–1700 mm per year (Fig 2B), although a precipitation dipole is noted where northern regions receive generally higher precipitation than the southern parts (Fig 3) especially the Sub-counties of Kalangaalo, Bulera, Sekanyonyi and Kikandwa.

Seasonal rainfall (for both the MAM and SON seasons) averaged over the years 1981–2017 at sub-county level (Fig 4) were computed from CHIRPS and were used in the estimation of rainwater harvesting potential. The study was limited to 1981–2017 given the availability of information on rainwater harvesting tanks for the same period. The study used sub-county rainfall averages to replicate the scale of available population data (section 2.4). Butayunja,

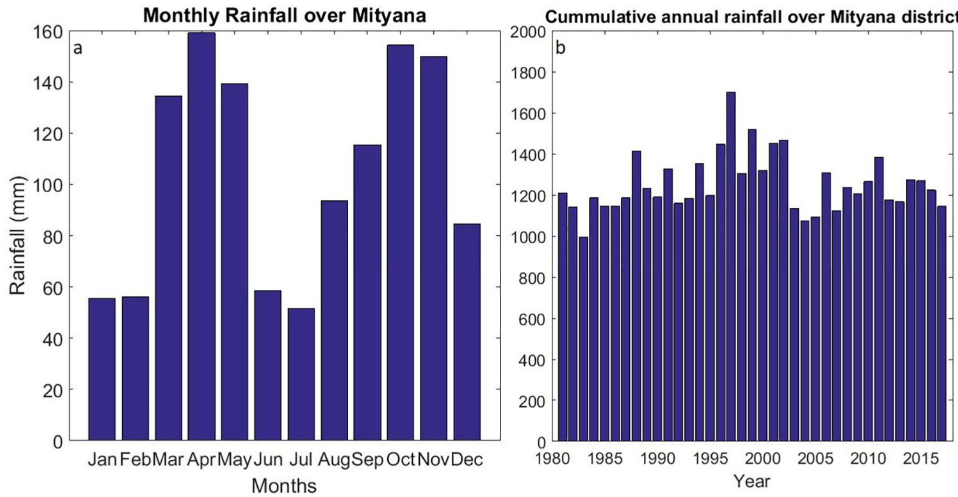

Fig 2. Mean Monthly (a) and mean cumulative annual (b) rainfall (mm) over Mityana District.

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Kakindu and Manyi, sub-counties in the Mityana District receive the lowest seasonal rainfall both during the MAM and SON seasons, ranging between 125–130 mm per season, while Kalangaalo, Bulera, Kikandwa and receive most rainfall on a seasonal basis, ranging between 140–156 mm (Figs 3 and 4).

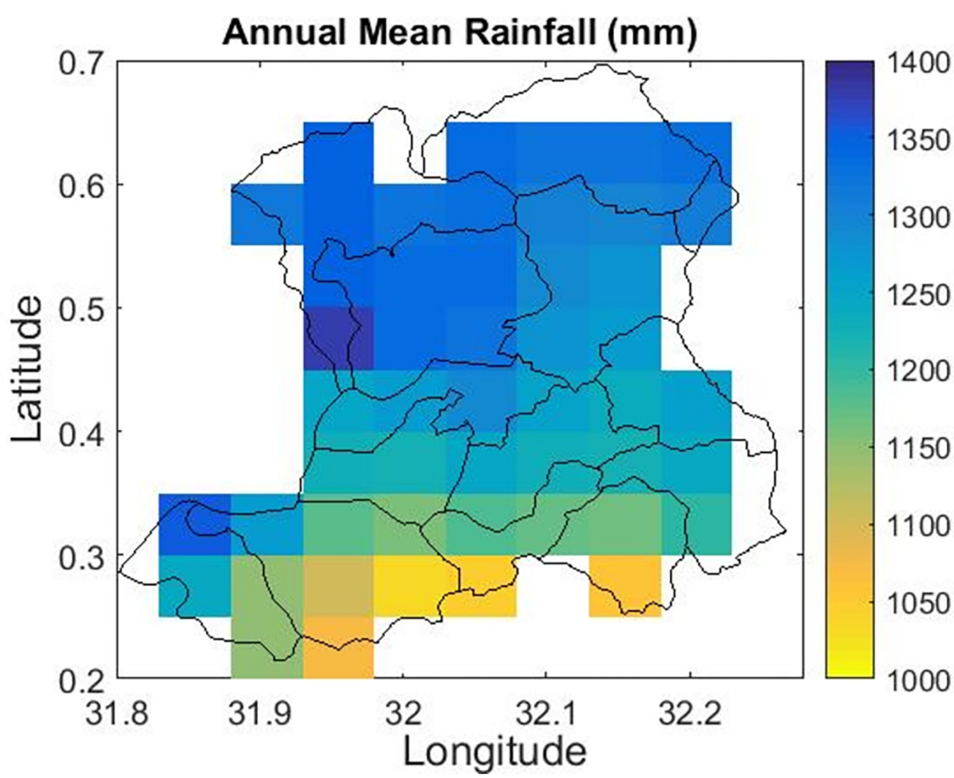

Fig 3. Spatial map of mean annual rainfall (in mm) over each sub-county in Mityana district from CHIRPS (base map sourced from the Uganda Bureau of Statistics (UBOS) from the link https://ubos.maps.arcgis.com/home/item.html?id=4e92034071494dffb239a219449fd2c1, accessed January, 15 2021).

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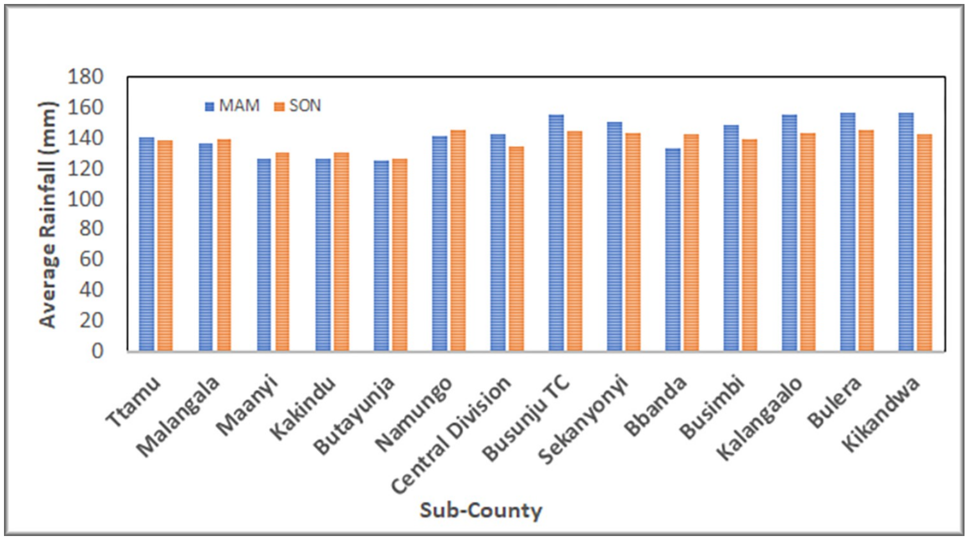

Fig 4. Mean seasonal rainfall (in mm) over each sub-county in Mityana district from CHIRPS.

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2.4. Population data

Records of number of water users per household for existing RWH systems (Fig 1, Table 1) are lacking, thus requiring alternative approaches to assess household water users. Data on the number of persons per household over Mityana district was sourced from the national census population dataset of 2019, provided by the 2019 Uganda Bureau of Statistics (UBOS) statistical abstract, (https://www.ubos.org/wp-content/uploads/publications/01_20202019_Statistical_Abstract_-Final.pdf, accessed January, 12 2021) and analyzed on a sub-county basis.

On average, a given household within Mityana district consist of 4 persons, although there are variations across the different sub-counties (Fig 5), with Sekanyonyi, Bbanda and Kalangaalo having the highest number of persons per household and Busunju town council having the least number of persons per household (Fig 5). In this study, the average reported persons per household per sub-county (Fig 5) were applied in the process of computing water demands for each of the tanks in a given sub-county.

2.5. Methods

2.5.1. Estimation of rooftop surface area. Accurate estimation of the rooftop area that contributes to runoff generation for RWH is a necessary component to quantify potential volume of rainwater that can be harvested. Google Earth Pro combined with ArcGIS tools were employed to estimate contributing rooftop areas for existing rainwater harvesting tanks in Mityana district (Fig 1) using methods as applied in previous studies [30, 33]. Latitude and longitude coordinates of rainwater harvesting tanks extracted from the water supply atlas database were used to locate the respective roofs to calculate rooftop area, from which digitization of rooftop area in nearest proximity (i.e., within 200 m) to a tank location was completed. A nearest proximity restriction was applied to co-locate tank locations and rooftop areas given factors including 1) geo-referencing accuracy between timing of Google Earth images, construction of houses, installation of tanks and recording of tank location is likely to have changed and 2) tank locations are unlikely to be under building structures. Tank locations that could not be attributed to a nearby rooftop, i.e., within 200m, were removed from further analysis. For adjacent rooftops, the rooftop closest to the tank was considered in the digitization process. The

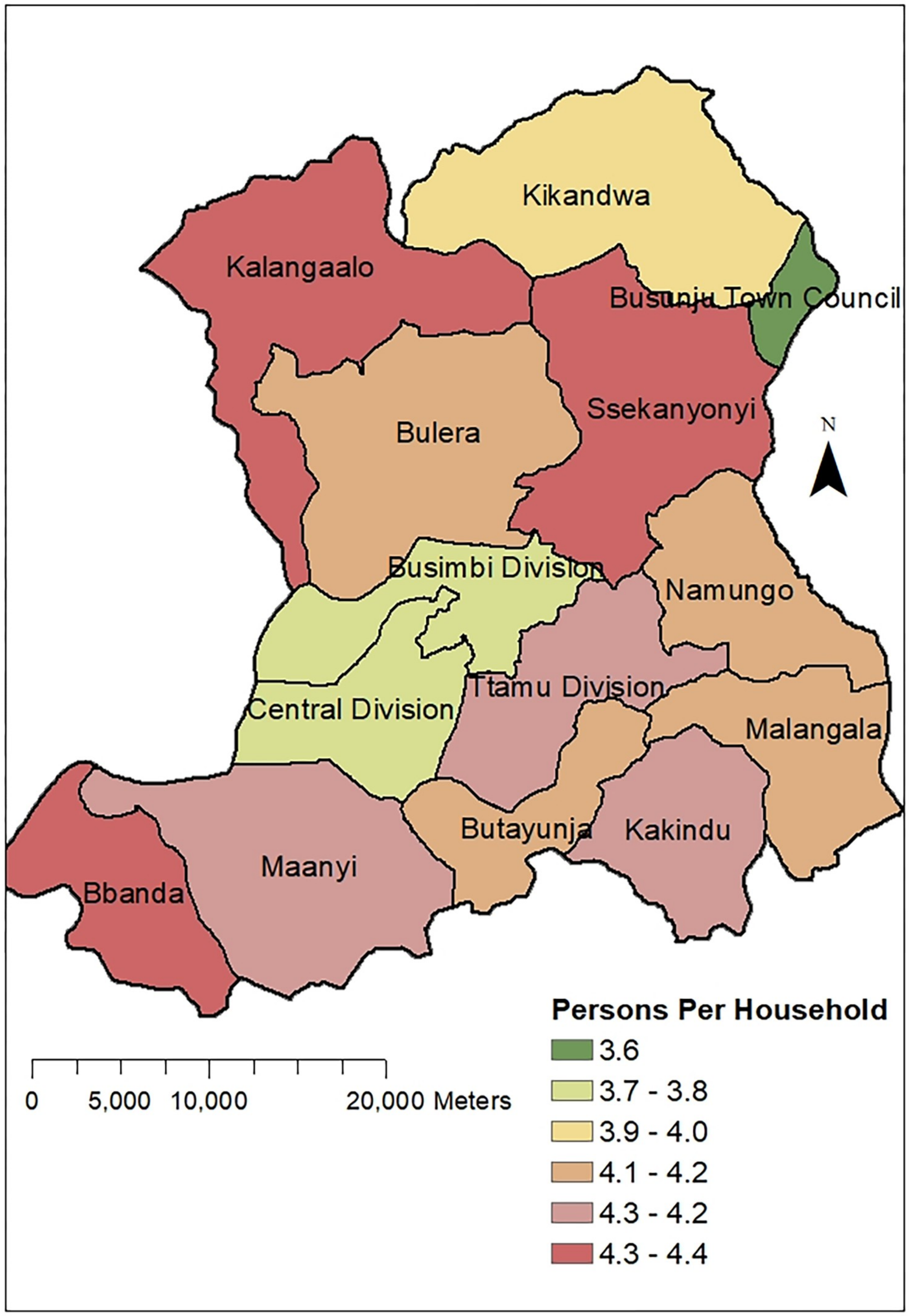

Fig 5. Persons per household in the different sub counties of Mityana district (base map sourced from the Uganda Bureau of Statistics (UBOS) from the link https://ubos.maps.arcgis.com/home/item.html?id=4e92034071494dffb239a219449fd2c1, accessed January, 15 2021).

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digitization was carried out by a single coauthor to minimize user bias and streamline area estimation workflow. The digitized rooftops (Fig 6) were imported into ArcGIS and their respective rooftop areas (in m^2) were estimated using the calculate geometry tool in ArcGIS.

2.5.2. Estimation of volumes of water that can be harvested by the estimated rooftop areas. The study utilized commonly applied methods [15, 29, 33, 47–49] to quantify

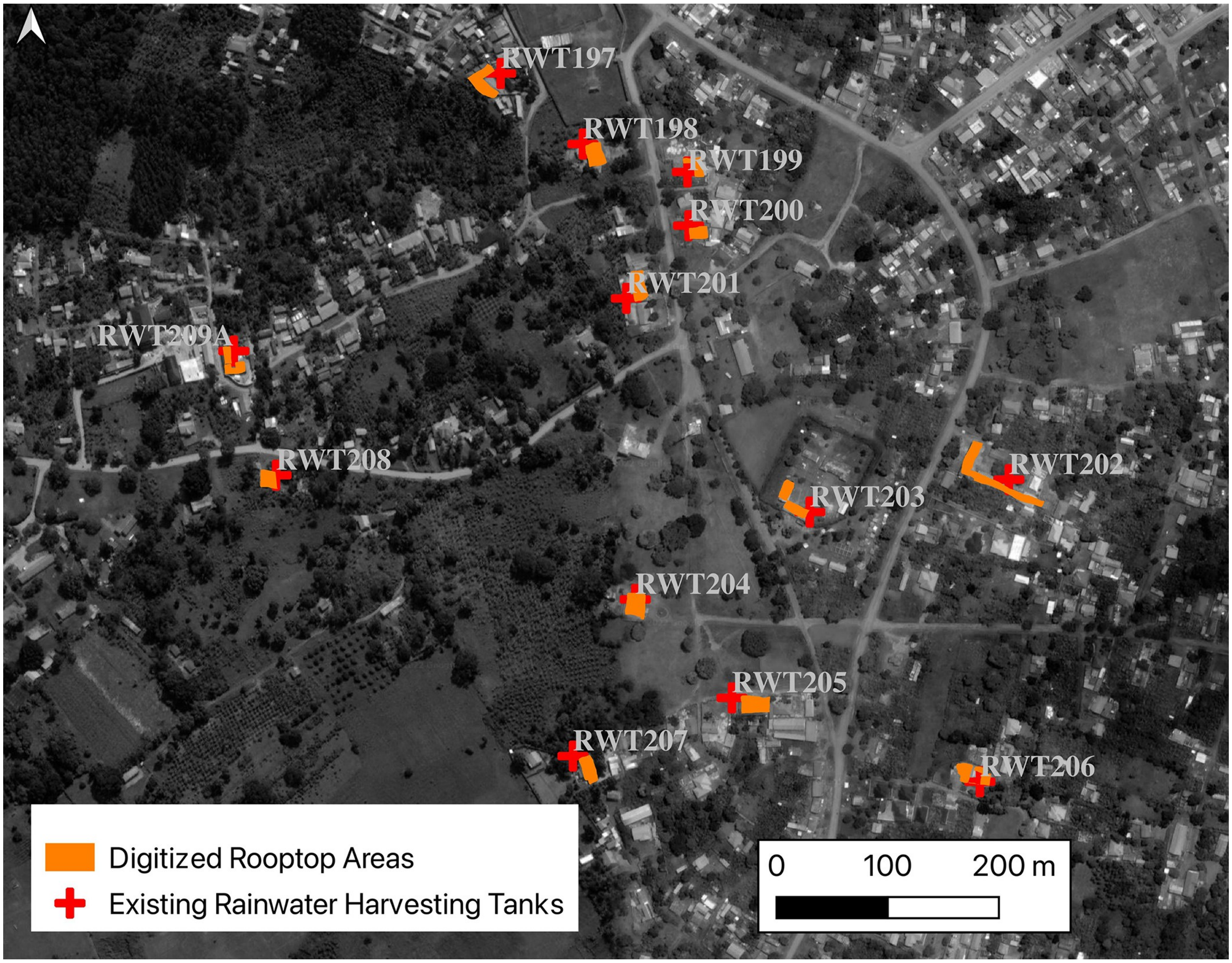

Fig 6. Sample of digitized rooftops for selected rainwater harvesting tanks (RWTs) over Mityana district (base layer generated using XYZ tiles for background images in GIS).

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rainwater harvesting potential. This study assumed that 1) roof types are homogeneous across the district, although differences in roof type are known to affect the amount of rainwater collected [50] and 2) the entire rooftop area contributes to rainfall runoff generation, although it is possible that for some households, gutters may not be installed across the entire roof catchment area. The method is summarized in the equation below.

$$RWHP = Rainfall \times Rooftop\ Area \times Runoff\ coefficient \quad (1)$$

The monthly mean rainfall generated in section 2.3 and the digitized rooftop areas were utilized in Eq 1. The runoff coefficient accounts for inefficient rainwater collection due to evaporative losses, splashing due to high intensity rainfall, and retained/absorbed rainwater within the roof materials. A runoff factor of 0.85 was universally applied given the common roof construction in Mityana district (e.g., iron sheeting). Our selected runoff factor is consistent with previous Uganda studies (e.g., [15]).

2.5.3. Estimation of desired storage capacities that fulfill water demands. To evaluate whether existing tank storage capacities can meet the water demand for domestic uses (drinking, cooking, bathing and hygiene) during a 90-day dry season, we first computed the optimal tank storage capacity needed to satisfy household water demands. Household water use rates differ depending on purpose, economic capability, and accessibility [51, 52], making it difficult to capture a single value to represent per day water needs. It has been shown that water demand per capita per day increases once supply is within the confines of the household's living area [53, 54], since collection efforts would be minimal. However, studies over rural Uganda show that water used per person per day is consistently about 15 liters per capita per day (l/c/d) regardless of the effort required for collection [55]. Although the 15 l/c/d demand may be able to fulfill drinking and cooking needs, it is less than the World Health Organization (WHO) recommended 20 l/c/d demand to fulfill three basic needs i.e., drinking, hand washing and cooking [56]. WHO also recommends 50 l/c/d to fulfill the three basic needs plus laundry and bathing and 100 l/c/d to ensure all consumption and hygiene needs are met [51, 56]. Given the range in potential household water needs, we evaluate the optimal tank storage to sustain three demand levels: 15 l/c/d (to satisfy drinking and cooking demands), 20 l/c/d (to satisfy drinking, cooking and hand washing demands) and 50 l/c/d (to satisfy drinking, cooking, hand washing laundry and bathing demands).

To determine the optimal storage capacity of a given tank, a demand per capita driven estimate was calculated given the assumption that tank storage would be the sole source of water to fulfill household water demands during the dry season. A typical dry season in Mityana district lasts for approximately 90 days i.e., June-July-August and December-January-February. In this study we considered each 90-day dry season in the analysis of water demand. The desired tank storage (DTS) capacity that meets the demand per household was computed for the different demand levels, following similar methods in [33] as,

$$DTS = C \times n \times D \tag{2}$$

where C is the demand per capita per day, n the number of users per tank (taken to be the average number of people per household per sub-county) and D the average number of dry season days (considered as 90 days). As a safety factor, it is recommended by the Indian Center for Science and Environment (https://www.cseindia.org/technology-1147, accessed February 5th, 2021) that the tank capacity be 20% larger than the required DTS. Therefore, all DTS values generated using Eq 2 were increased by 20% to generate maximum desired tank storage capacities (i.e. MDTS). One source of uncertainty in MDTS estimates results from the lack of actual data on the number of users per tank. However, tank storage assessed in our study were installed for individual households to serve household needs.

2.5.4. Economic implications of unmet demand or excess storage. MDTS capacities were compared against the existing (i.e., already installed) tank storage capacities to evaluate whether the latter meets the demand or not for one dry period. A paired t-test was done to evaluate whether pairwise differences between MDTS and existing tank storage are significantly different at 5% significance level. The results (p-value $<< 0.001$) show that the two are significantly different. For any unmet demand or excess storage in litres, an equivalent monetary value was attached to examine the economic implications of sub-optimal tank capacities. The unmet demand and excess storage for the different tanks can be translated into a monetary cost based on the known market prices of different storage tanks. Most of the tanks within Mityana district and Uganda at large are either prefabricated high-density polyethylene (HDPE) and galvanized steel or constructed in-situ using cement and bricks. Studies show that in-situ constructed tanks are cheaper than the prefabricated options and that the consumer price per litre declines with tank storage capacity for the prefabricated tanks [23]. The tank price per litre is a function of numerous economic variables, thus per liter prices have varied over time in Uganda. Estimated costs for constructed tanks were reported to be 430,00UGX (~ 230 USD) for a 10,000 litre tank in 2006 [20], with prices increasing to 350 USD in 2011 [23]. The prefabricated tanks are reported to have cost between 72,000–3,600,000 UGX (30–1500 USD) for 100–10000 litres respectively in 2011 [20]. On average, a 10,000 litre prefabricated tank currently costs UGX 2,000,000, or roughly 600 USD (https://crestanks.co.ug/product/crestank/, accessed February 24, 2022), suggesting that one litre storage currently translates to UGX 200. We apply an economic rate of UGX 200 per litre in this study to estimate monetary cost for unmet demand (excess storage) in addition to costs (over-expenditure on unnecessary tank storage) to meet MDTS.

3. Results

This section presents results of the estimated rooftop areas generated using Google Earth Pro and GIS, the potential volumes of rainwater they can harvest, the capacity of existing tanks to meet the water demands of 15, 20 and 50 l/c/d and the economic implications of unmet demand or excess storage.

3.1. Estimated rooftop areas

The digitized rooftop areas (Table 2) range between 15–750 m^2 with (75%) of the rooftops having areas less than 200 m^2. The average rooftop area for our study region is 170 m^2, similar to rooftop areas used by other studies over Uganda (e.g., [13, 15]).

3.2. Reliability of RWHP

RWHP was estimated for rainfall seasons of March-April-May (MAM) and September-October-November (SON). RWHP (Eq 1) based on digitized rooftop areas (Table 2) range between 16,000–270,000 litres (5,000–220,000 litres), with an average RWHP of 62,332 litres (50,832 litres) per rooftop per year for the MAM (SON) season. By comparing RWHP with MDTS (Eq 2), where the demand per capita per day includes a range of demands (i.e., 15, 20, 50 l/c/d), the reliability of RWH systems can be assessed. By assuming all rainfall accumulated over a given rainfall season is stored and used during the following dry season, during which we have assumed that no additional tank filling occurs, our results demonstrate that all study rooftops would reliably collect enough water to meet water demands for drinking, hand washing and cooking (i.e., 15 and 20 l/c/d) during both the MAM (Fig 7A and SON Fig 7B) season. Under a water demand scenario of 50 l/c/d, suitable to fulfill basic needs plus laundry and bathing,

Table 2. Frequency table showing ranges of rooftop areas.

Rooftop area (m^2)	Number of RWTs	Percentage
1–100	48	27%
101–200	89	49%
201–300	26	14%
301–400	12	7%
401–500	1	1%
501–600	4	2%
601–700	0	0%
701–800	1	1%
Total	181	100%

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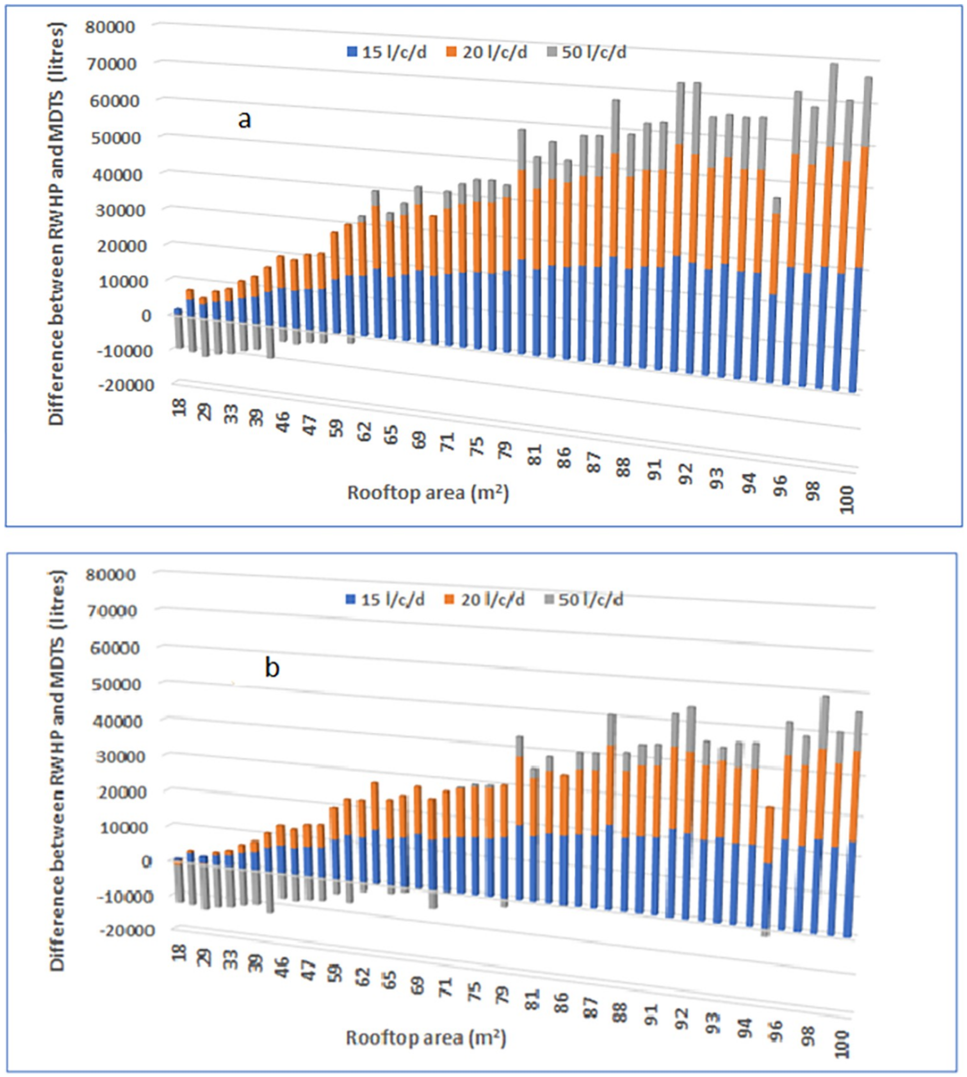

Fig 7. Difference between seasonal RWHP and MDTS for different demand levels for the MAM season (a) and SON season (b) for only rooftops with areas $\leq$ 100 m^2.

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rooftop areas of at least 60 m^2 and 70 m^2 reliably collect enough water to fulfill demands for the MAM and SON seasons respectively (Fig 7A and 7B). RWHP reliability results demonstrate that majority of the households whose rooftop areas were digitized in this study need not increase their rooftop catchment areas to meet the desired water demand for the three demand levels considered in this study. Results document that most (92% and 87%, respectively for MAM and SON) of rooftop areas can potentially harvest a reliable volume of water to meet the maximum demand of 50 l/c/d given the average seasonal precipitation rates.

3.3. Capability of the existing tanks to store the desired water demands

To evaluate whether the current tank capacities are optimal to store volumes necessary to fulfil household demand rates of 15, 20 and 50 l/c/d, for a 90-day dry period (i.e. one season), the MTDS required to fulfill the demands were analysed in comparison with the existing tank storages at different demand levels. A paired t-test [57] between MTDS and current tank sizes was

Table 3. No of tanks meeting the different demand levels for a 90-day dry period.

Demand level (l/c/d)	No of tanks meeting demand	Tank size (litres)
15	135 (75%)	6,000–25,000
20	94 (52%)	8,000–25,000
50	5 (3%)	25,000

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performed to evaluate whether a pairwise difference between them has a mean equal to zero. The results show that at 5% significance level, MTDS is significantly different from the current tank sizes (i.e. p-value $<<$ 0.001).

The results summarized in Table 3 document that most of the currently installed tanks (75%) able to fulfill water demands of 15 l/c/d range between 6,000–25,000 litres. Similarly, the tanks that fulfil water demands of 20 l/c/d and 50 l/c/d have storage capacities ranging between 8,000–25,000 litres and 25,000 litres respectively (Table 3, Fig 8).

The ranges of storage for the tanks meeting and not meeting the demands (Fig 8) overlap for some tank sizes, an indication that some households have installed tanks below or above their demand. For-instance, a tank of 6000 litres may be over sized for a household of 3 persons and undersized for a household of 4 persons at a given demand level.

It is worth noting that information about the sole purpose of these tanks is not available and thus not considered in our assessment. For if the sole purpose is to store water for drinking and cooking (i.e., a demand of 15 l/c/d), then the majority (75%) of the tanks would be sufficient to fulfill demand for a 90-day dry period. In addition, half of the current capacities (52%) would also be sufficient to fulfill demand for three basic needs of cooking, drinking and hand washing (i.e., a demand of 20 l/c/d) during a 90-day dry period. An increasing rate of failure in tank capacities to fulfill demands which account for laundry clearly demonstrates that extra tank capacities are necessary to sustain water stores during long dry periods.

It should also be noted that all tanks that fail to meet the 15 l/c/d common demand for a 90-day dry period have storage capacities less than 8,000 litres (Fig 8A). About 90% (78) of the tanks failing to meet the 20 l/c/d demand are below 10,000 litres of storage (Fig 8B) while 93% (80) of the tanks failing to meet the 50 l/c/d demand are below 20,000 litres (Fig 8C). On the other hand, most privately owned tanks with capacities greater than 10,000 litres can meet

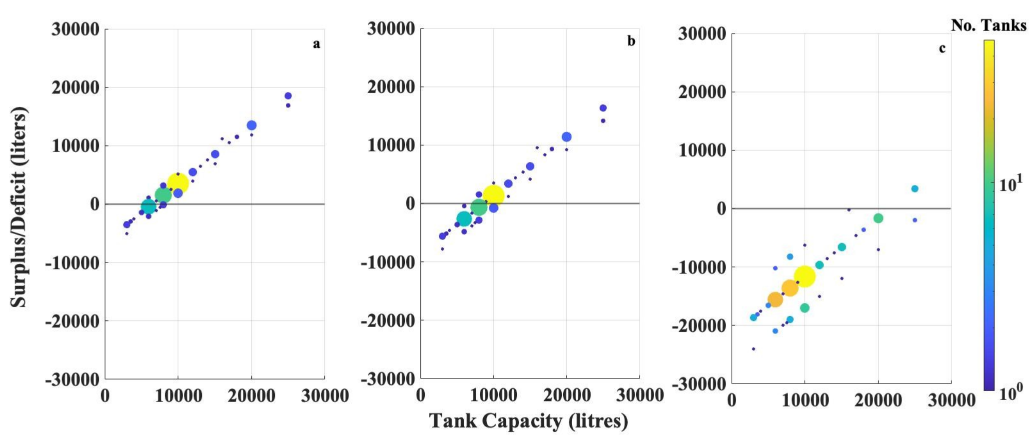

Fig 8. Plots illustrating tank capacity surplus and deficit for privately owned tanks at 15 l/c/d (a), 20 l/c/d (b) and 50 l/c/d (c) demand for a 90-day dry period. The size and color of points reflects the number of tanks. At the high daily demand, almost all tank capacities are unable to fulfill demand for a 90-day dry period.

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Table 4. Monetary value in shillings of the unmet demand (numbers in brackets) and excess storage at 50 l/c/d demand for a 90-day dry period.

Monetary value (shillings)	Frequency	Percentage
(-5,000,000 - -4,500,001)	1	0.6
(-4,500,000 - -4,000,001)	3	1.7
(-4,000,000 - -3, 500, 000)	15	8.3
(-3,500,000 - -3,000,001)	36	19.9
(-3, 000,000 - -2, 500,001)	32	17.7
(-2, 500,000 - -2, 000,001)	51	28.2
(- 2, 000,000 - -1, 500,001)	13	7.2
(-1, 500,000 - -1, 000,001)	9	5.0
(-1, 000,000 - - 500,001)	3	1.7
(- 500,000 - -1)	13	7.2
0–500,000	0	0.0
500, 001–1, 000,000	5	2.8

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household drinking water demands for a 90-day dry period and to register excess storage (Fig 8A). This is an indication that 10,000 litres represents a potential generalized storage capacity necessary to reliably fulfill domestic basic water needs for a 90-day dry period. This finding is confounded by our findings where catchment areas were deemed large enough to generate suitable runoff for capture to meet the demands (see results in section 3.3), clearly demonstrating that existing storage systems are under-sized for the actual occupancy/demand levels.

3.4. Economic implications of the unmet demand and excess storage

Table 4 summarize the economic implications of unmet demand/excess storage for the demand of 50 l/c/d, which would ensure that basic hygiene, laundry and bathing is met for a 90-day dry period. About 3% of the tank owners overspent between 500,000–1,000,000 UGX (150–300 USD) given excess storage availability required to sustain 50 l/c/d demands for a 90-day dry period (Table 4). More than 75% of all private tanks would require between 2,000,000–4,500,000 Ugandan shillings (~ 600–1, 250 USD) to acquire extra storage to fulfill water demands (Table 4) given unmet demand projections. These estimates of additional costs represent large sums, especially given that average annual household incomes in the district are 5,500,000 Uganda shillings (~1, 500 USD).

4. Conclusions and recommendations

Our results reveal important reflections for rainwater harvesting in Mityana district and for Uganda at large. Rooftops in Mityana district range between 15-750m^2 with an average rooftop area of 170 m^2, similar to rooftop areas used by other studies over Uganda (e.g., [13, 15]). Results demonstrate that majority of rooftops would reliably collect enough water to meet water demands for drinking, hand washing and cooking (i.e., 15 and 20 l/c/d) when accounting for rainfall season precipitation (MAM and SON). However, under a water demand scenario of 50 l/c/d, suitable to fulfill basic needs plus laundry and bathing, rooftop areas of 60–70 m^2 could reliably collect enough water to fulfill demands for the 90-day dry periods. This result is in close range to earlier findings [18] that rooftops of minimum size 50 m^2 are sufficient to collect enough water to improve water security during dry periods.

On ground, evidence indicates that households who venture into rainwater harvesting install systems without considering rooftop area and rainfall characteristics over their catchment area. This practice leads to underutilization or overutilization of the rainwater harvesting potential for different households given a range of water demand levels. In Mityana, a significant number (i.e. 97%) of existing rain water harvesting systems are undersized especially for high water demands 50 l/c/d for the 90-day dry period. This result is similar to published findings [58] which demonstrated that at high demand levels, such as 50 litres per person per day, domestic rainwater harvesting in parts of Africa would rarely meet all household water demands. Future changes in precipitation patterns [59] may exacerbate rainwater harvesting reliability, potentially compromising water demand requirements including basic hygiene. In order to increase the RWH's capacity to meet the high water demands of 50 l/c/d within Mityana district, additional costs of at least 2,000,000 UGX (600 USD) are required. For some households, such costs would put pressure on their economic means, and thus restrict their ability of to increase storage capacity, requiring these households to resort to other sources of water during times of shortage.

It is worth noting that information about the sole purpose of these tanks was not available for this study. For if the sole purpose is to store water for drinking and cooking only, then the majority of the tanks would be sufficient for a 90-day dry season (i.e. MAM and SON seasons). However, if the purpose is to cater for drinking, cooking, bathing and laundry, most private tank owners would have to pay extra money in the range 600–1,250 USD to meet the 50 l/c/d demand for a 90-day dry period. The results reveal that RWH systems with storage capacities of 25, 000 litres and more maybe more viable in meeting the 50 l/c/d demand in Mityana district for one dry season.

This study however did not consider other water sources that the different households use to supplement their water demands, information that would be significant in further shaping the conclusions from this study. In addition, we assumed that the demand is constant per capita per day, however water use tends to vary from day to day. We thus recommend that to fully understand the capacity of rainwater harvesting in addressing water needs, more work be done in understanding the sole purpose of the private water harvesting tanks, the dynamics of daily water use, the alternative water sources and their water use purposes.

In addition, the study used a simplified method that uses seasonal precipitation in computing water harvesting potential. Much as this method is recommended and commonly used for domestic-rainwater harvesting systems where demand is regular, it doesn't cater for the rainfall variability over time, which parameter affects RWH system performance [60]. It is also shown that simplified approaches generate large tank sizes compared to other methods like models [61]. We therefore recommend that future studies apply more advanced methods such as regression models [60] to estimate optimum RWH systems storage capacities while considering daily climate variability.

Nonetheless, our findings indicate that a significant number of the existing RWH systems in Mityana district are not correctly sized. Thus, numerous RWH systems would fail to reliably provide sufficient water for drinking, laundry and hygiene during the dry seasons (Fig 8C). Inaccurate and ineffective tank capacity sizing reflects an opportunity cost; whereby undersized systems may require households to secure water for basic needs from unreliable and unsuitable sources. However, if RWHs are correctly sized, our findings suggest that adequate volumes of water could be captured and stored (Fig 7A and 7B). Therefore, this study recommends that measures to improve access to clean water through rainwater harvesting consider correct sizing of RWHs.

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