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Design and Application of the Tank Simulation Model (TSM): Assessing the Ability of Rainwater Harvesting to Meet Domestic Water Demand

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ABSTRACT. Rainwater harvesting (RWH) is a necessary technology to supplement and/or replace insufficient ground and surface water resources for domestic water supplies, especially under changing climate conditions. An accessible and flexible Excel-based RWH simulation tool is developed and applied to investigate the utility of RWH in two regional case studies, under both present conditions and future climate scenarios, through examination of relationships between tank volumes, roof areas, rainfall patterns, and yield. The conversion of complex mathematical formula into a tool with a simple data entry form for infinite combinations of the critical variables enables non-experts to manipulate and optimize designs at the level of RWH implementation. The results clearly show that RWH can augment problematic or insufficient water supplies. Roof area and rainfall distribution have the greatest impact on the ability of a RWH system to meet demand; tank size has a minimal effect, providing a buffer during short dry periods within any given month. Demand met improves in both geographies under future scenarios. Thus, while RWH is insufficient as the sole source of domestic water now and in the future, it is a low-cost supply augmentation solution even in cold climates. RWH solutions are made more accessible through planning tools such as the Tank Simulation Model presented here, which is sufficiently flexible to incorporate climate change scenario planning.

Keywords: Canada, design tool, rainwater harvesting, rainfall patterns, reliability, Uganda, climate change scenarios

1. Introduction

Rainwater harvesting (RWH) is a simple technology requiring limited infrastructure that is well-suited to low resources settings, attributable to its ease of implementation and scalability (Petrucci et al., 2012). The majority of the population experiencing challenges related to physical water access live in lower resource settings, such as rural communities and low- and middle-income countries (WHO and UNICEF, 2019). Further, by 2050, 52% of people are projected to live in water stressed areas (Kölbel et al., 2018), resulting from combined impacts of climate change, population growth, land use change, and poor water resources management. In high income countries there is growing interest in residential RWH by homeowners and municipal policy-makers to reduce stresses on water and wastewater treatment plants and associated energy demands, to realize financial benefits (Malinowski et al., 2015), and to build resilience against current and future climate-related water shortages (Mercer and Hanrahan, 2017). For all of these reasons, interest in RWH as a domestic water management solution is expected to increase.

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Trial and error and simple mass balance approaches (e.g., average annual rainfall) remain the primary methods for RWH implementation at the local level, particularly in low resource settings (Ward et al., 2012). However, these systems require up-front financial investment even in the absence of robust appropriate design specifications, do not typically account for intra-annual variations, cannot account for climate change, and are unlikely to be optimized (e.g., Hafizi Md Lani et al., 2018; Abdallah and Antary, 2020). Continuous simulation modeling is an alternative approach to simple design strategies that removes the upfront capital costs and enables the investigation of different scenarios to optimize design, but requires significant technical expertise to execute. Two approaches to modeling RWH have been proven most accurate over time: continuous simulation models such as the US EPA SWMM module (Elliott and Trowsdale, 2007); and, analytical equation simulations (e.g., Guo and Baetz, 2007). The analytical equation simulation approach was utilized because it provides useful performance indicators and requires less data and takes less time to run than analytical equation simulations (Wang and Guo, 2020).

Given the technical expertise required for models and the lack of access to findings from simple approaches or models, local implementers are not able to access advances in knowledge of RWH design configurations, resulting in sub-optimal system designs (Hafizi Md Lani et al., 2018; Akuffobea-Essilfie et al., 2020). For example, of 67 RWH systems assessed in an Ethiopian city, only 32 were functional and nine were optimally functional due to poor individual design configurations (Taffere et al., 2016). Given that RWH is primarily adopted to augment poor water access, any sub-optimal design represents inefficient use of already scarce resources. This inaccessibility at the local (non-technical) level was identified as early as 2011 (Imteaz et al., 2011) in a call for a new approach to modeling RWH in order to facilitate access to both optimum design and management of a RWH system and increased capacity to meet minimum water requirements. Over time, in response to the growing demand for local level accessible tools, approaches have evolved through set scenarios based on fixed catchment and storage variables towards more flexible and accessible online decision-support tools (Fonseca et al., 2017; Chiu et al., 2020). However, a major limitation has been the universal assumption that past rainfall predicts future rainfall; an assumption that no longer holds under climate change yet has only recently been explored in the literature (e.g., Musayev et al., 2018). Moreover, findings from these works fail to provide consensus regarding impacts on RWH, ranging from little to no impact (Musayev et al., 2018) to reduced applicability (Wallace et al., 2015). However, the reality is likely to lie somewhere in between. Given that some regions are predicted to become drier while others become wetter (Rodell et al., 2018), flexible tools for local design that can incorporate local current and predicted rainfall regimes and changing demands will become increasingly necessary to design sustainable RWH systems.

Sufficient water quantities for domestic purposes are necessary to support life. While volumes used depend on the level of access to water, the average daily basic access volume for personal use (drinking, eating, hygiene) is considered to be 20 L/capita/day (LPCD) (WHO, 2017). All nation states have committed to universal access to drinking water by 2030 under the Sustainable Development Goals agenda (United Nations, 2015). This is defined as sufficient water available on-site when needed that is free from *E. coli*, arsenic, and fluoride (WHO and UNICEF, 2019). It is widely recognized that RWH increases available water quantities, but does not necessarily meet water quality standards, particularly for microbiological contaminants (Meera and Ahammed, 2006; Leong et al., 2017). However, an assessment of water quality from different sources in North-East Uganda found that RWH resulted in water of higher quality than covered and uncovered dug wells or surface waters (Parker et al., 2010). Regardless, it is prudent to use RWH in conjunction with a decentralised water treatment system (e.g., chlorine tablets, household UV) to improve water quality.

This paper builds on Fonseca et al. (2017) who optimized tank size based on user-inputted rainfall regime, catchment area, and water demand, and Wallace et al. (2015), who integrated predicted climate data from General Circulation Models (GCMs) with storage size to develop a series of RWH design curves for 2010 ~ 2050. However, neither study allowed for flexible optimization across roof size, tank size, and demand simultaneously. The key output of the current paper is a programmed continuous simulation software tool that combines analytical equations for describing the operation of RWH systems and daily rainfall characteristics with a user-friendly interface. This interface allows for interactive exploration of infinite combinations of all RWH system design parameters to better fit the realities of local socio-economic contexts. It also removes the high-level technical requirements from RWH system design and therefore makes design accessible down to the local level, while recognizing that a certain amount of technical expertise is required to source rainfall data. The objectives are to: i) build a flexible, locally accessible RWH reliability design tool for household and household-community coupled RWH systems; ii) demonstrate the utility of the tool in two different precipitation regimes; iii) utilize the tool to deconstruct the relative importance of RWH system elements i.e., rainfall, roof area, and tank size; and, iv) assess RWH system performance under climate change scenarios.

In response to findings from Semaan et al. (2020), the Tank Simulation Model addresses the need to incorporate demand and changing climate scenarios in rainwater harvesting design tools. The innovation lies in programming complex equations behind a front-end user interface that harnesses the analytical power while making it accessible for enhanced RWH decision-making and planning by local community members, governments, and civil society organizations, especially in low-resource settings. The user interface consists of a rainfall data page, simple data entry form for the critical variables (daily water demand, roof size, tank size), and a data output form (number of days demand is met, percentage of demand met per month) in a Microsoft Excel file. The analytic equation calculations are on hidden data sheets within the file. Moreover, continuous simulations conducted by this study aim to achieve an improved understanding of a RWH system's reliability over time through software models, saving the time and cost of establishing trial studies while providing more representative results that can be projected into a changing future and used as an input to broader water resources management planning.

2. Methodology

As demonstrated, this Tank Simulation Model (TSM) is a flexible Excel-based continuous simulation tool allowing users to calculate the reliability of RWH systems through the interaction of user-defined roof areas, tank sizes, and demands given current and predicted rainfall patterns (Supplementary File 1). TSM was developed to represent three different RWH system configurations: stand-alone household system (single family); stand-alone community system (multiple families); and, a coupled system (combination of household and community systems). The coupled system utilizes the community system to augment household system reliability. Therefore, the water withdrawal rate from community systems depends on the capacity of household systems to meet the specified water demand.

Individual Systems (household or community): First, the volume of runoff from the roof, representing the maximum potential daily rainwater harvest volume, RWH_P (L), was calculated:

$$RWH_P = P \cdot A \cdot \beta \tag{1}$$

where P (mm) is the daily precipitation, A is the surface area of the roof connected to the water collection tank (m^2), and β (-) is the loss coefficient, which is set to 0.8 to account for any water loss due to evaporation and system leakage (Ward et al., 2010). Since the storage tanks are closed and therefore evaporation is negligible, it is reasonable to use the same loss coefficient across all locations in this study.

Second, the volume of water on a given day, V (L), is calculated based on RWH_P, and the volume of water consumed on any given day, C (L), represents the demand met. V and C are interlinked, as the water consumed must be less than or equal to the volume of water in the tank, and the volume of water in the tank is reliant on the volume of water consumed on the previous day. Additionally, the volume of water in the tank cannot exceed the tank volume itself. The following set of equations was developed to represent these constraints:

$$V_i = V_{i-1} + P - C_{i-1} \quad \text{if} \quad B > V_{i-1} + P - C_{i-1} \tag{2}$$

$$V_i = B \quad \text{if} \quad B < V_{i-1} + P - C_{i-1} \tag{3}$$

$$C_i = D \quad \text{if} \quad V_i > D \tag{4}$$

$$C_i = V_i \quad \text{if} \quad V_i < D \tag{5}$$

where the subscripts i and $i - 1$ represent the current and previous days respectively, B (L) is the volume of the collection tank, and D is the total daily water demand (L/day). Additionally, TSM tracks the number of days per month in which the tank is empty or meets 100% of the total demand. Reliability, R (-), defined as the percentage of demand satisfied by water provided from the RWH tank (Guo and Baetz, 2007), is calculated on any given day as:

$$R_i = \frac{C_i}{D} \tag{6}$$

Coupled Systems. These systems assume that all households making up a community have identical roof areas, tank volumes, and daily water withdrawal rates, and therefore identical household RWH system reliability. When household RWH reliability is less than 100%, the deficiency is supplemented equally across all households by the community tank. The first step in determining the reliability of a coupled RWH system is to calculate the cumulative community deficiency from all household systems, H (L), on any given day as follows:

$$H_i = D_h \cdot \left(1 - R_{h,i}\right) \cdot N_f \tag{7}$$

where the subscript h refers to household systems, and N_f (-) is the number of households supplemented by the communal system. As such, the following set of equations replaces (2) ~ (5), wherein $D_{c,i}$ is represented by H_i:

$$V_{c,i} = V_{c,i-1} + P_c - C_c \quad \text{if} \quad B_c > V_{c,i-1} + P_c - C_c \tag{8}$$

$$V_{c,i} = B_c \quad \text{if} \quad B_c < V_{c,i-1} + P_c - C_c \tag{9}$$

$$C_c = H_i \quad \text{if} \quad V_{c,i} > H_i \tag{10}$$

$$C_c = V_{c,i} \quad \text{if} \quad V_{c,i} < H_i \tag{11}$$

where the subscript c refers to the community system. The total volume of water provided by the coupled RWH system to each household on any given day, $C_{tot,i}$, is given by:

$$C_{tot,i} = C_h + \left(C_c\right) / N_f \tag{12}$$

The reliability of the coupled RWH system on any given day ($R_{tot,i}$) is calculated as:

$$R_{tot,i} = \frac{C_{tot,i}}{D} \tag{13}$$

2.1. Data

TSM's continuous simulation results are based on a recommended minimum 10 years of daily rainfall data input (Geraldi and Ghisi, 2017). Rainfall data for Buikwe, Jinja, and Rakai districts in Uganda were obtained from the Uganda National Meteorological Authority while rainfall data for Toronto (central), Calgary (prairie), and Vancouver (coastal) in Canada were obtained from the Digital Archive of Canadian Climatological Data (see Supplementary Figure 1). While these are urban locations, they were chosen to represent the rural communities in their environs, as opposed to the urban centres themselves, particularly when examining the community and coupled scenarios which would be problematic in an urban environment. The specific time periods were chosen to represent the most recent data available for which data were not missing (Table 1).

Table 1. Rain Gauge Stations

Location	Time period	Station Name	Station ID
Jinja	2003 ~ 2006, 2008 ~ 2013		89330430
Buikwe	2000 ~ 2002, 2008 ~ 2012		
Rakai	2000 ~ 2002, 2005 ~ 2011		
Toronto	2003 ~ 2013	Toronto Lester B. Pearson Int'l A Ontario	5097
Calgary	2002 ~ 2012	Calgary Int'l A	2205
Vancouver	2002 ~ 2013	Vancouver Int'l A	889

Downscaled and bias-corrected daily precipitation data were used for the periods 2025 ~ 2034, 2050 ~ 2059, and 2090 ~ 2099. Given global response to climate change mitigation to date, "business as usual" is considered to be the most viable scenario. Thus, simulations used the Shared Socio-economic Pathway (SSP) SSP 5-8.5. Note that the SSP 5-8.5 is equivalent to the RCP 8.5 scenario of the CMIP5 generation and assumes an energy intensive fossil fuel economy with high emissions to produce a radiative forcing of 8.5 W/m^2 in 2100 (O'Neill et al., 2016). Creating an ensemble-based projection by applying weighting schemes is inappropriate for this study as this affects the probability distribution and the autocorrelation structure properties. In this study it is crucial to preserve the behavior of extremes; weightings across multiple model runs (due to the central limit theorem) significantly affects variability. Extremes, i.e., zero rain days, are critical to predicting RWH water availability within continuous simulations, forcing the use of individual models and runs and multiple models and runs if RWH uncertainty is to be assessed.

The historical precipitation was modeled using a globally tested Generalized Gamma (GG) distribution, which offers a reliable model for daily precipitation (Papalexiou and Koutsoyiannis, 2016; Papalexiou, 2018; Papalexiou et al., 2018). Its probability density function is given by:

$$f_{GG}(x;\alpha,\gamma_1,\gamma_2)=\frac{\gamma_2}{\alpha\cdot\Gamma(\gamma_1/\gamma_2)}\left(\frac{x}{\alpha}\right)^{\gamma_1-1}\exp\left(-\left(-\frac{x}{\alpha}\right)^{\gamma_2}\right) \quad (14)$$

where $\alpha > 0$ is a scale parameter, and $\gamma_1 > 0$ and $\gamma_2 > 0$ are two shape parameters that control the left and right tails, respectively. The GG distributions were fitted to the observations over the available historical period (approximate 12 years; see Table 1 and Supplementary Figure 1). The fitted distributions were used to bias correct the simulations, on a monthly basis, using quantile mapping. Note that missing values did not impact the fitting process – they simply resulted in smaller samples sizes (i.e., less information).

The future changes predicted by the model were preserved by applying the quantile mapping on a decadal basis; that is, by modifying the mapping functions in order to preserve the relative changes in the mean, standard deviation, and probability dry predicted by the model. The simulations were transformed to probability values using an empirical distribution function (Weibull plotting position) prior to application of the quantile of the fitted GG distributions. Thus, the projections given at coarse spatial resolution were transformed to follow the observed fitted distributions at the point scale and to preserve the future trends. Note that, in order to discriminate between solid and liquid precipitation, a nonlinear threshold formula was applied to the data from Canadian stations (Jennings et al., 2018). The bias correlation was validated over the historical simulation. The visual resemblance of the bias-corrected historical simulations (Supplementary Figures 2 ~ 5) with the actual historical time series (Supplementary Figure 1) is apparent and was verified by summary statistics, such as mean, standard deviation, probability dry, and skewness (see Supplementary Tables 1 ~ 5). These can be compared to the original simulations prior to bias correction (Supplementary Figures 6 ~ 9). Taylor diagrams further show the four bias-corrected historical simulations from the models with respect to the observations (Supplementary Figures 10 ~ 15). As anticipated, the variability of the bias corrected series resembles the observations and correlations are essentially zero, as the simulations at daily scales do not attempt to reproduce the actual daily values but rather the statistical properties. The bias-corrected future simulations (Supplementary Figures 16 ~ 19) reveal clear changes in the future rainfall patterns.

2.2. Parameters

The Ugandan and Canadian simulations were conducted using the same daily per capita demands (20LPCD), family size, roof area, and tank volume to enable a fair assessment and compareson. The simulations were conducted for a household of six members given average household sizes of five in Uganda (Baguma and Loiskandl, 2010) and six in Canada Indigenous communities (Statistics Canada, 2014). While this uniformly distributed demand may not approximate actual demand in households, the application of a non-uniform demand distribution does not contribute significantly to the uncertainty in RWH models (Silva and Ghisi, 2016). The simulations were conducted using a range of roof areas (20 to 120 m^2) representing typical conditions in both regions and tank volumes (1,000 to 15,000 L) representing standard manufactured volumes (Table 2). To investigate the impact of rainfall distribution, additional simulations were undertaken using uniform daily rainfall distributions.

Table 2. Parameter Values Employed in TSM Scenarios

RWH System	Tank Volume (L)	Roof Area (m^2)	People per House-hold	Demand per Capita (L)	Number of House-holds
Individual Household	1,000 5,000 10,000 15,000	20 60 120	6	20	n/a
Individual Community	10,000 15,000 20,000	240 480	6	20	10
Coupled	Household: 10,000 Community: 15,000 20,000	Household: 60 Community: 240 480	6	20	10

3. Results

The total demand met and number of days with an empty tank were examined across all six locations for the household, community, and coupled scenarios. Rainfall regimes are summarized in Table 3, with bold numbers highlighting periods with little to no rainfall. While all three Ugandan locations experience a bimodal rainfall distribution (two distinct wet and dry seasons), the dry seasons are longer in Rakai (western Uganda) than Jinja and Buikwe (eastern Uganda). Average annual rainfall is also lower in Rakai by at least 300 mm. In Canada, rainfall regimes in Calgary, and to a lesser degree Toronto (ameliorated by the Great Lakes), are influenced by cold winter temperatures which mean that winter precipitation falls as snow rather than rain. On average, Calgary receives 335 mm of rainfall per year while Toronto receives 723 mm. Both Calgary and Toronto receive less annual rainfall on average than the Ugandan locations. It should be noted that, while a value of zero in the Uganda data indicates no precipitation at all, the same cannot be said for Calgary and Toronto. During the winter months, air temperatures will fall below freezing and precipitation will be in the form of snow. This is an important water reservoir, replenishing groundwater resources when it melts. However, RWH utilizes liquid precipitation, so these analyses only include rainfall data. Sub-freezing air temperatures will also mean that stored rainwater may freeze, potentially prohibiting its use during winter months in cold temperature regimes. In Vancouver air temperatures are ameliorated by the adjacent ocean, generating a regime consisting of wet winters and drier summers. As a result, Vancouver receives the most annual rainfall (not precipitation) of the Canadian locations (an average of 1,088 mm).

Household: For all locations, tank volumes of 1,000 L are a prohibitively limiting factor in the beneficial use of RWH, regardless of roof area. However, other studies have identified that, for tank sizes less than 1,000 L, increasing storage has a larger effect on RWH system reliability (Cowden et al., 2008). Similarly, a roof area of 20 m^2 is unable to capture sufficient rainwater to fill tanks that are large enough for viable RWH. When roof area is 60 m^2, increasing tank size beyond 10,000 L did not meet any additional demand for Toronto, Calgary, or Jinja. Increasing roof area to 120 m^2 can provide markedly greater resilience, particularly across drier periods, for most locations (Toronto, Calgary, Vancouver, and Rakai). The combination of this roof area with the largest tank size (15,000 L) has only incremental benefits during periods of low rainfall (Buikwe, Calgary). All of these limitations are demonstrated in the examples of Jinja and Calgary (Figure 1).

As Figure 1 demonstrates, all 20 m^2 roof area scenarios meet the least demand, while the smallest tanks (circles) also limit demand met, regardless of roof area. As expected, the largest tanks (squares and asterisks) and roof areas (long dashes and dash-dot-dot-dashes) meet the most demand. For Jinja, virtually 100% of demand is fulfilled at both 60 and 120 m^2 roof areas (at 60 m^2 roof area, demand met falls to 98% and 97% for February and March, respectively for both tank sizes), while for Calgary, the 120 m^2 roof area confers greater resilience across winter months than the 60 m^2 roof area and the 15,000 L tank confers greater resiliency than the 10,000 L tank. However, it is recognized that a roof area of 120 m^2 is unlikely to represent typical rural homes in either Canada or Uganda. As such, the remaining discussion focuses on the 60 m^2 roof area and 10,000 L tank scenario (Figure 2a), with the 120 m^2 roof area and 15,000 L tank scenarios used to explore their roles in increasing resilience, particularly under future climate scenarios.

The two locations dominated by cold winters (Calgary and Toronto) are least ideal for RWH given that several months of the year are unlikely to provide sufficient liquid precipitation. Having identified this as a limitation, the scenarios demonstrate that, for Toronto, 40% or more of demand can be met year-round, but never 100%. However, this scenario still results in less than 5 days with an empty tank per month between January and April, enabling some access to water during all months. In Calgary, lack of rainfall during winter months means that RWH is only appropriate during summer months; demand can be met completely for June to October. While even the largest roof and tank sizes used in the scenarios cannot meet demand across the winter months, a 15,000 L tank does provide a buffer between November and January, meeting 50 to 70% of demand even though the tanks do run empty at times during these months.

In Vancouver and Jinja a 120 m^2 roof with a 10,000 L tank meets demand year-round. A 60 m^2 roof with a 15,000 L tank is able to meet virtually all demand in Jinja (only 98% in February and 97% in March) and 100% of demand in Vancouver except between July and October when at least 90% of demand is met (approximately 5 days with an empty tank per month). Even a 5,000 L tank will satisfy demand most of the year and more than 90% through the driest months (no more than 4 days with an empty tank in any given month). Total average annual rainfall is approximately 280 mm less in Vancouver, but more days have rainfall (199 days without rain on average, compared with 223 for Jinja). Tank size is more important in Vancouver than in Calgary and Toronto and can allow a smaller roof area. A 5,000 L tank with 120 m^2 roof behaves the same as 10,000 L tank with a 60 m^2 roof even during the driest months and are able to meet almost 80% of demand.

A 60 m^2 roof is unable to meet 100% of demand year-round in Buikwe or Rakai, although it is possible to meet at

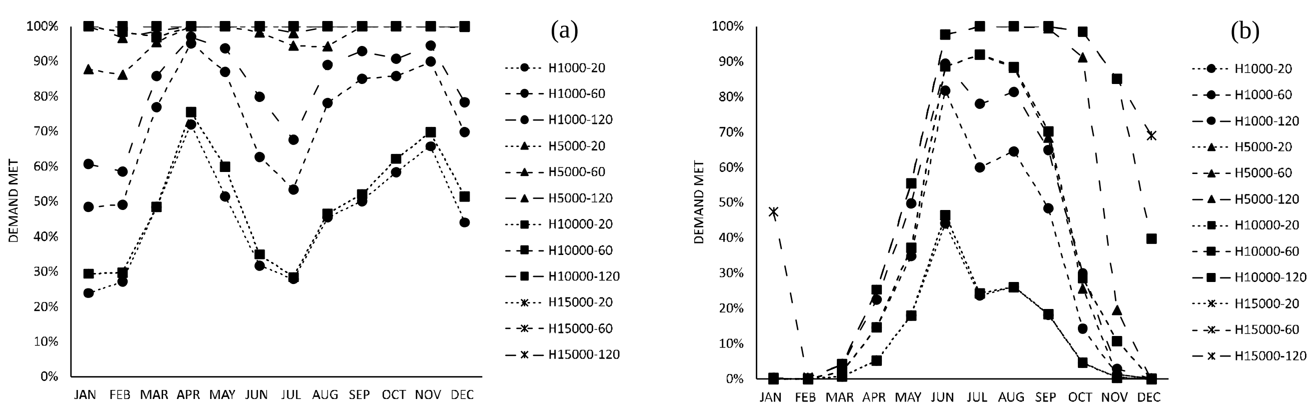

Figure 1. Demand met for (a) Jinja and (b) Calgary household scenarios for 1,000, 5,000, 10,000, and 15,000 L tanks and 20, 60, and 120 m^2 roof areas.

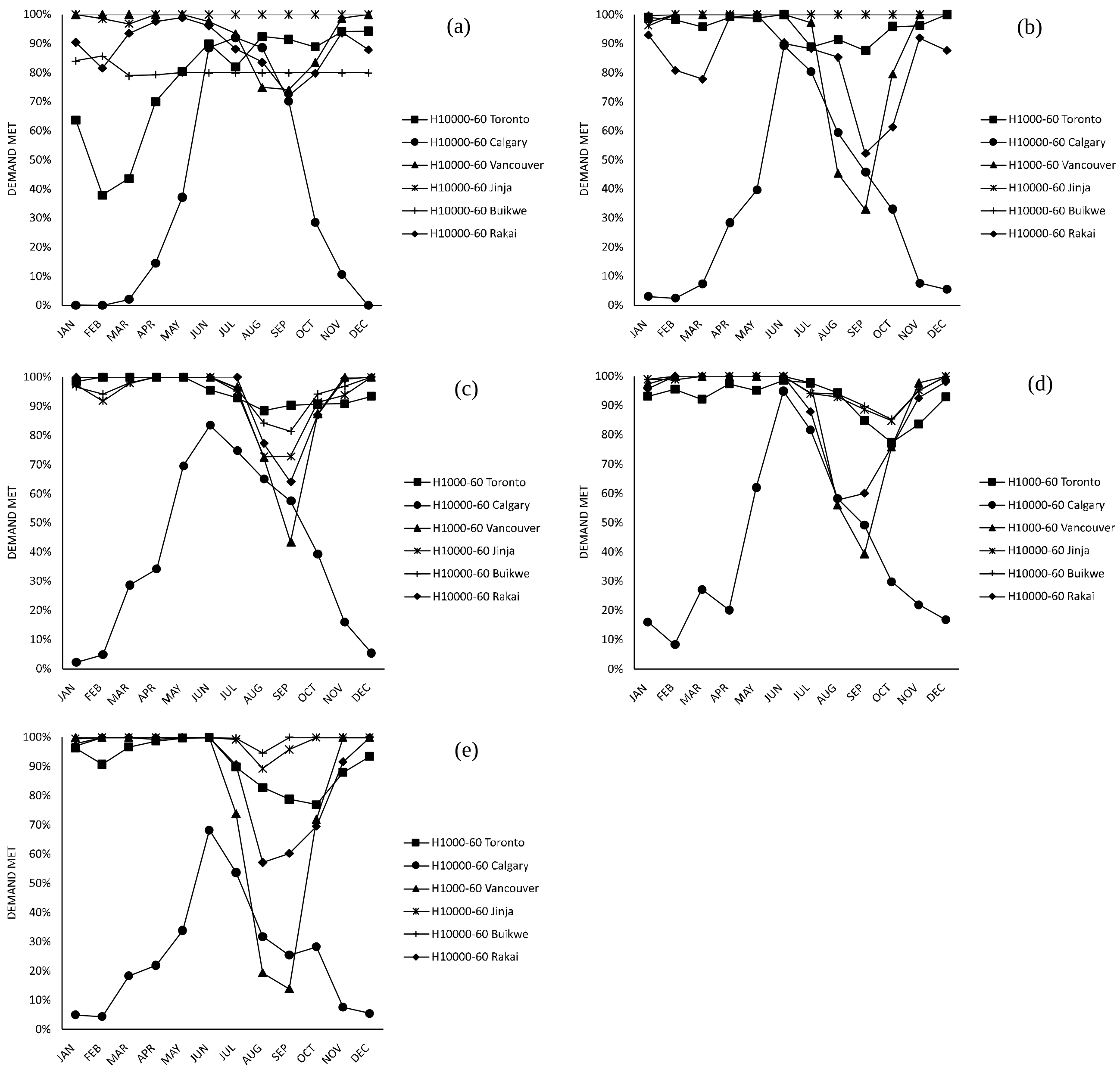

Figure 2. Demand met for all locations (60 m^2 roof area and 10,000 L tank size scenario) (a) under current rainfall regimes; and under 2090 ~ 2099 predicted scenarios derived from (b) CNRM; (c) EC Earth; (d) IPSL; and (e) MPI.

least 75% and 80% of demand, respectively. For Buikwe, regardless of roof or tank size above this threshold, demand met between June and December will only approach 80% (6 days per month empty) i.e., the amount of rain becomes the limiting factor. However, in Rakai, the largest roof and tank scenario is sufficient to meet virtually 100% of demand throughout the year (99% in January), even though average annual rainfall is much lower (920 mm versus 1,254 mm in Buikwe).

An obvious assumption would be that the number of days without rain within each month account for the differences observed, with Rakai experiencing fewer "no rain" days than Buikwe. However, when the average number of days without rainfall in each month is calculated (Table 3), it is clear that the number of days without rainfall is also higher in Rakai than Buikwe. As such while this finding suggests that rainfall distribution plays a critical role in the ability of RWH systems to meet demand, the interplay between daily rainfall distribution (i.e., intermittency of precipitation), rainfall amounts, tank size, and roof area represents a much more complex and nuanced relationship.

To explore this relationship further, the TSM was used to develop a series of hypothetical values for demand met given the household scenarios defined in Table 2 and uniformly distributed daily rainfall (Figure 3). Based on these analyses, the critical interface appears to be between the daily rainfall distribution coupled with roof area. For example, a uniformly distributed daily rainfall of 3 mm will satisfy 100% demand with a roof area of 60 m^2 (representing an equivalent or lower annual rainfall than actual average annual rainfall in Jinja, Buikwe, and Vancouver – Table 3). Even if the daily distribution is altered to 3 mm every other day, demand satisfied falls to approximately 60%, regardless of tank size.

As a result of discrete and discontinuous daily rainfall events, some of the rain will not be captured and stored. This means that the main purpose of the tank is to provide storage between rainfall events because there is no such thing as uniformly distributed rainfall. It also means that, in reality, tanks do not always reach maximum capacity, as a full 1,000 L tank should be sufficient in this scenario to meet demand for 8.3 days (a 10,000 L for 83 days) if it fills completely. This is when roof area becomes important, because it is the rainfall capture area that feeds the tank. This is evidenced by the hypothetical demand met in a uniformly distributed rainfall regime of 1 mm per day versus hypothetical demand met in a uniformly distributed rainfall regime of 7.5 mm per day. A roof area of 150 m^2 is required to satisfy 100% of demand when paired with a 1,000 L tank in the former, but given the latter a 20 m^2 roof paired with a 1,000 L tank can meet the same demand.

While this multi-variable relationship is intuitive, its effect on RWH feasibility becomes critically important in locations where rainfall distributions are defined by multiple consecutive days in a month without rain or periods when precipitation does not fall as rain. The catchment area (i.e., roof area) becomes the mechanism for capturing sufficient rainfall to meet demand during these periods of no rain within a month (i.e., notwithstanding any dry/cold and wet/warm seasonal factors that affect annual rainfall distribution). On the other hand, if the tank is not large enough to capture all of the rain supplied by the roof catchment, rainwater will still be lost to the RWH system and demand not fully met.

Once this relationship has been defined, it is possible to begin to put limits on the contexts within which RWH is a viable solution. For example, a 20 m^2 roof cannot capture sufficient rain for the size of family used in these scenarios, even if 5 mm of rain falls every day of the year. By way of another example, 1,000 L tanks are inadequate for RWH given sporadic rainfall regimes, i.e., multiple consecutive days without rain, because they do not provide the bridging storage capacity required to see a family through more than eight days of demand and this

Table 3. Rainfall Regimes (mm) (Averaged over Periods Identified in Table 1, with Dry Months Bolded)

	Jinja				Buikwe				Rakai			
	Avg (mm)	Max (mm)	Min (mm)	No Rain (Days)	Avg (mm)	Max (mm)	Min (mm)	No Rain (Days)	Avg (mm)	Max (mm)	Min (mm)	No Rain (Days)
January	**68.8**	**141.7**	**1.4**	24	**72.0**	**133.3**	**2.9**	22	**59.4**	**122.5**	**0.0**	23
February	**59.7**	**112.5**	**20.2**	22	**100.1**	**245.3**	**38.2**	18	**56.4**	**113.3**	**13.5**	22
March	135.5	201.2	68.6	19	159.9	331.3	33.5	16	104.7	266.0	6.4	20
April	176.4	281.4	107.9	14	192.9	280.2	140.7	12	140.0	269.8	77.1	17
May	127.0	216.4	44.0	17	136.1	240.3	0.0	13	124.5	186.6	56.5	19
June	**71.3**	**163.5**	**12.4**	20	123.7	194.9	60.4	17	**55.8**	**150.6**	**11.0**	25
July	**72.8**	**150.8**	**9.8**	22	**63.6**	**110.8**	**39.4**	21	**21.5**	**92.6**	**2.3**	28
August	115.7	210.4	52.5	19	122.6	224.6	70.0	17	**32.5**	**73.0**	**14.8**	27
September	116.9	219.8	70.5	16	149.3	215.6	100.7	13	**58.0**	**146.3**	**11.5**	23
October	156.3	333.7	87.6	14	150.8	215.4	75.9	14	85.5	227.3	7.3	21
November	171.0	397.6	71.0	15	189.8	339.9	42.3	14	94.6	182.7	31.9	19
December	**97.7**	**170.6**	**9.8**	21	**107.3**	**176.8**	**66.3**	18	87.4	305.7	6.0	21
Annual	1369.0	1699.9	1227.0	223	1254.4	1953.7	1403.3	194	920.3	1312.1	601.0	263
If Unif. Dist.	3.8				3.4				2.5			
	Toronto				Calgary				Vancouver			
January	**23.5**	**66.6**	**0.0**	25	**0.1**	**0.4**	**0.0**	31	159.9	283.6	100.4	12
February	**23.2**	**53.8**	**0.0**	25	**0.0**	**0.4**	**0.0**	28	78.8	131.8	27.1	13
March	**38.8**	**68.0**	**9.6**	24	**1.5**	**4.9**	**0.0**	30	114.3	214.8	55.6	12
April	64.2	129.6	21.6	19	**13.8**	**43.7**	**0.0**	25	83.4	139.6	15.0	15
May	78.9	152.8	14.4	18	43.9	94.4	10.9	22	**52.1**	**93.8**	**12.6**	19
June	75.5	191.6	31.8	19	112.7	247.6	38.8	17	**42.8**	**80.0**	**10.8**	20
July	85.9	193.2	20.4	20	54.9	107.8	19.8	19	**25.0**	**53.0**	**0.6**	25
August	73.0	144.0	20.8	21	62.7	98.2	33.2	20	**29.2**	**75.8**	**2.9**	25
September	74.3	121.0	25.2	20	40.7	84.0	2.2	21	**68.0**	**169.4**	**5.0**	21
October	70.7	126.4	35.2	17	**10.7**	**16.6**	**6.8**	26	124.2	248.2	18.3	15
November	70.9	135.2	10.2	19	**1.0**	**3.4**	**0.0**	29	176.3	308.0	116.2	11
December	**44.7**	**61.0**	**20.0**	23	**0.0**	**0.4**	**0.0**	31	139.1	188.2	73.2	12
Annual	723.4	840.9	478.2	250	335.5	486.2	202.0	297	1088.7	1274.4	818.0	199
If Unif. Dist.	2.0				0.9				3.0			

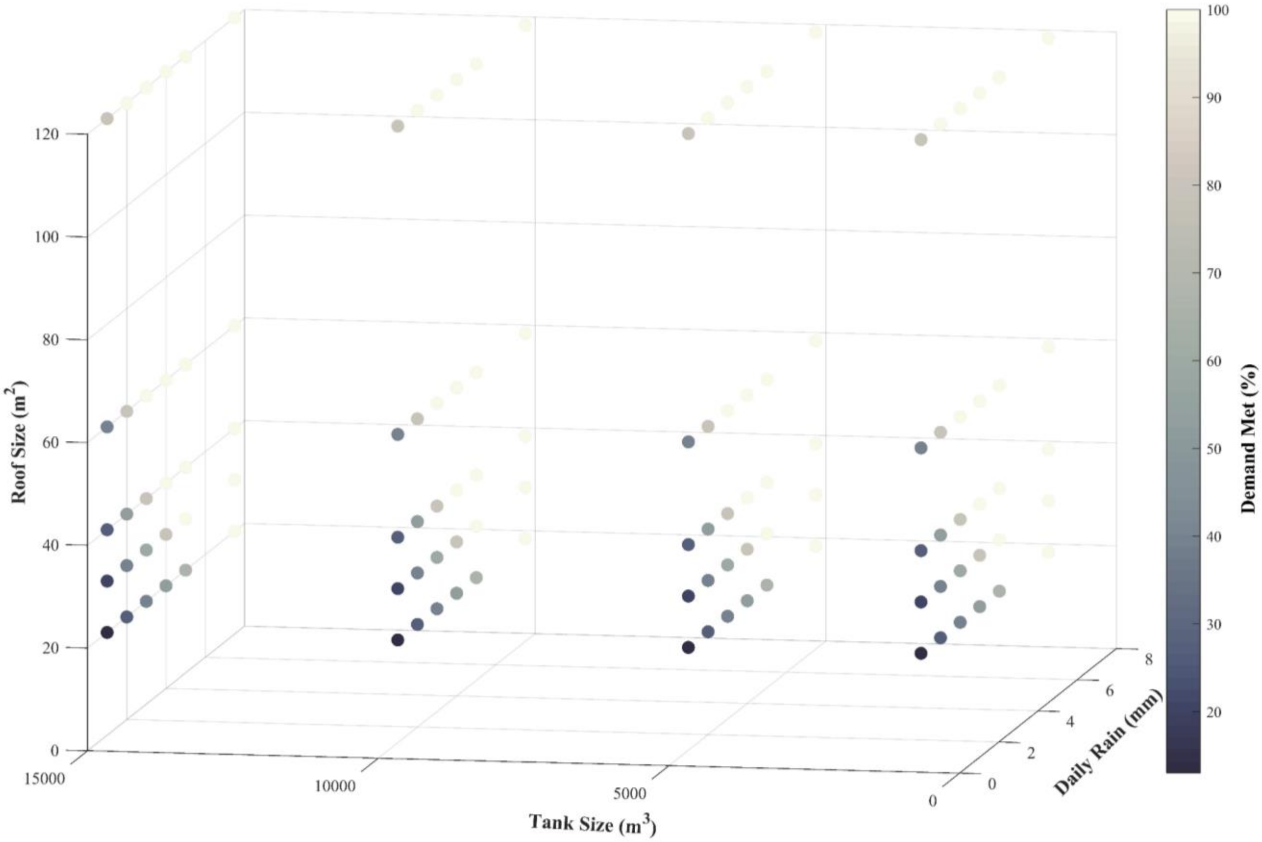

Figure 3. Visualizing the relationship between uniformly distributed daily rainfall, roof area, and tank size in determining percent household daily demand met (20LPCD).

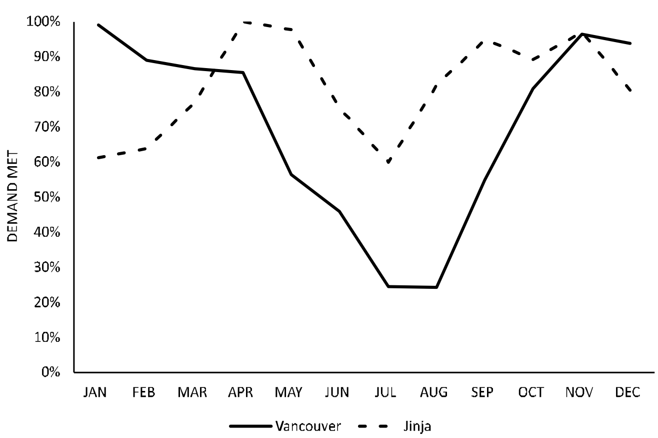

Figure 4. Demand met by a community RWH system consisting of a 20,000 L tank and 480 m^2 roof area in Jinja and Vancouver (the two rainfall regimes best suited to household RWH systems) is insufficient to replace household systems but can be used to augment them.

is only if the preceding rainfall event (coupled with roof area to maximise rainwater capture) is sufficient to fill the tank. As such, 10,000 L tanks are a minimum requirement to bridge periods of zero rainfall, but 15,000 L tanks may not be worth the additional cost in some locations and within the context of the roof areas investigated. Regardless, it is better to invest in increasing roof catchment area, as this will maximise benefit from whatever amount of rain falls each day.

Community and Coupled Systems: As expected given the household RWH scenarios, the community systems in and of themselves are insufficient to meet demand for ten families, even in rainfall regimes where household RWH systems perform well, i.e., Jinja and Vancouver (Figure 4). However, the addition of a community tank to individual household systems (10,000 L tank, 60 m^2 roof) increases resilience, particularly during low rainfall periods, as evidenced by the additional days with full demand met in a month (Table 4). The greatest increase is demonstrated in Toronto, where the coupled system increases demand met by up to 25% between January and May. In all communities, even those deriving minimum benefit (Jinja, Buikwe), the benefits are during periods when household RWH systems are under stress. The same is true for roof and tank size configuration – any additional benefits of the larger system occurs during low rainfall months i.e., February in Toronto, October in Calgary, and September in Vancouver. In general, the Toronto regime is the only location demonstrating consistent benefit from the largest coupled RWH configuration. However, management of a coupled system should not be underestimated, as it introduces issues of access and equity that do not have to be considered at the household level.

Exploring Potential Impacts of Climate Change: This paper uses four climate prediction models to demonstrate the importance of including climate change in RWH system performance. According to the predicted future daily rainfall datasets for each of the locations, changing rainfall patterns can be observed. In terms of overall rainfall regimes (Table 5), EC Earth predicts the wettest futures. In at least two out of the four models used all three Ugandan locations move from two distinct wet and dry seasons to a single longer wet (November to May) and dry (June to October) season each year. Canadian locations are generally characterized by varying reductions in rainfall between June and October for most model scenarios used. They also experience increasing rainfall amounts during winter months, especially in Vancouver which typically sees far less snowfall than Calgary or Toronto during current winter months due to its coastal location. Toronto also sees large increases in rainfall across all models during winter months, suggesting a regime shift between snow and rain for these months.

Monthly amounts may increase by as much as 205 mm and decrease by as much as 93 mm across individual locations for the period 2090 ~ 2099 (Table 6) as compared to the current study period (Table 1). Of note is that a 10 mm increase in monthly rainfall captured over a 120 m^2 roof area translates into an additional 60 people demand days met in that month at 20 LPCD demand.

Building on the results from current RWH configurations and demand met, results are reported for the 2090 ~ 2099 scenario period as applied to the household-based configuration of 60 m^2 roof areas with 10,000 L and 15,000 L tank sizes (Figures 2b ~ 2e). With the smallest roof and tank size configuration, Toronto and Vancouver are able to meet nearly 100% of demand except between July/August and September/October due to drying through the summer and fall (Table 6). Due to increases in rain events in winter months, RWH potential is increased in Calgary for this period, but decreased over the summer months due to a drier period June to September in most of the models. A larger tank in combination with the 60 m^2 roof area does not revert the observed decline in demand met for Calgary, but it does increase monthly demand met slightly for Toronto (up to 9% higher) and significantly for Vancouver (up to 50% higher). However, this larger tank size will not support significant increases in demand, with neither Toronto nor Vancouver able to meet a 30 L per capita demand in most months.

As in current conditions, a larger roof area in combination with a 10,000 L tank enables capture of more rainfall for each discrete event, increasing monthly demand met to 100% in some cases for all three Canadian locations. A 120 m^2 roof area in Toronto is sufficient to meet monthly demand (100% demand met) in each month for all models except one, where demand dropped to 98% for one month. As such, demand was increased from 20 to 30 LPCD. This higher demand is approximated (above 90% demand met) in 2090 ~ 2099 between December and June for all models, and two models predict at least 90% demand met for all months of the year. This is expected, as summer becomes drier and fall/winter becomes wetter (average monthly rainfall amounts show large decreases for all models in July [between 19 and 65 mm], August [between 4 and 41 mm], and September [between 11 and 26 mm] and increases for December [between 50 and 103 mm], January [between 93 and 117 mm], and February [between 93 and 137 mm], Table 6). Similar patterns emerge in Vancouver. Given a 120 m^2 roof area, a 30 L demand can also be met here between November and June for all models, but the drier summer months do not even sustain a 20 LPCD demand, falling to as low as 27% of demand met for August in one prediction.

In Uganda, a significant rainfall regime shift is predicted by multiple models as regions change from multiple wet and dry seasons to a single wet and dry season (Table 5). This shift results in 20 LPCD demand nearly being met with a 60 m^2 roof area and 10,000 L tank for Buikwe and Jinja under at least one model. In terms of demand met, all three locations see improvements under all model predictions. For example, in Rakai, all models predict at least 90% of demand met for eight months of the year, compared with current conditions where, just considering wet seasons, only 41 ~ 89% of demand is met. None

Table 4. Additional Days with Full Demand Met in A Coupled System (15,000 L Tank, 240 m^2 Roof; 20,000 L Tank, 480 m^2 Roof) Versus a Household RWH System (10,000 L Tank, 60 m^2 Roof)

	Toronto		Calgary		Vancouver		Buikwe		Jinja		Rakai	
	J15000-240	J20000-480	J15000-240	J20000-480	J15000-240	J20000-480	J15000-240	J20000-480	J15000-240	J20000-480	J15000-240	J20000-480
Jan	9	9	0	0	0	0	1	1	0	0	1	1
Feb	6	10	0	0	0	0	1	1	1	1	4	5
Mar	5	7	1	1	0	0	2	3	1	1	1	1
Apr	6	8	3	3	0	0	0	0	0	0	0	1
May	6	7	5	5	0	0	0	0	0	0	0	0
Jun	2	3	3	3	1	1	0	0	0	0	1	1
Jul	4	4	2	3	1	2	0	0	0	0	1	2
Aug	1	2	4	4	5	6	0	0	0	0	1	2
Sep	1	2	7	8	5	8	0	0	0	0	7	8
Oct	2	3	10	13	2	3	0	0	0	0	2	3
Nov	1	2	0	0	0	0	0	0	0	0	2	2
Dec	2	2	1	2	0	0	0	0	0	0	3	4

Table 5. Rainfall Regime Ranges (mm) under Future Climate Scenarios

	Jinja						Buikwe					
	2025 ~ 2034		2050 ~ 2059		2090 ~ 2099		2025 ~ 2034		2050 ~ 2059		2090 ~ 2099	
	Avg (mm)	No Rain (Days)	Avg (mm)	No Rain (Days)	Avg (mm)	No Rain (Days)	Avg (mm)	No Rain (Days)	Avg (mm)	No Rain (Days)	Avg (mm)	No Rain (Days)
Jan	68 ~ 80	22 ~ 23	60 ~ 105	21 ~ 23	96 ~ 210	15 ~ 20	70 ~ 84	20 ~ 21	70 ~ 107	20 ~ 21	94 ~ 153	14 ~ 21
Feb	59 ~ 76	21 ~ 23	61 ~ 89	20 ~ 21	72 ~ 99	18 ~ 19	91 ~ 120	17 ~ 19	91 ~ 113	16 ~ 19	90 ~ 125	15 ~ 20
Mar	146 ~ 178	16 ~ 18	116 ~ 148	17 ~ 20	120 ~ 245	12 ~ 10	160 ~ 212	12 ~ 17	136 ~ 175	14 ~ 18	118 ~ 225	10 ~ 17
Apr	155 ~ 202	12 ~ 14	199 ~ 229	11 ~ 13	194 ~ 280	7 ~ 13	169 ~ 228	11 ~ 12	226 ~ 247	10 ~ 13	214 ~ 267	8 ~ 12
May	105 ~ 144	17 ~ 19	80 ~ 152	15 ~ 21	89 ~ 171	15 ~ 20	124 ~ 164	14 ~ 16	109 ~ 185	13 ~ 18	122 ~ 175	13 ~ 17
Jun	58 ~ 69	20 ~ 22	40 ~ 81	19 ~ 25	35 ~ 80	18 ~ 26	110 ~ 133	17 ~ 22	68 ~ 128	17 ~ 25	69 ~ 115	17 ~ 26
Jul	41 ~ 80	22 ~ 28	20 ~ 75	21 ~ 30	11 ~ 99	20 ~ 29	35 ~ 73	21 ~ 28	22 ~ 67	20 ~ 30	11 ~ 73	22 ~ 28
Aug	86 ~ 117	19 ~ 25	64 ~ 105	19 ~ 28	23 ~ 145	17 ~ 28	98 ~ 142	16 ~ 25	69 ~ 110	17 ~ 28	29 ~ 135	16 ~ 27
Sep	105 ~ 116	16 ~ 18	105 ~ 152	13 ~ 17	98 ~ 141	14 ~ 18	128 ~ 163	13 ~ 18	135 ~ 186	12 ~ 16	127 ~ 177	13 ~ 16
Oct	141 ~ 161	14 ~ 16	135 ~ 163	14 ~ 16	126 ~ 193	13 ~ 16	136 ~ 154	13 ~ 14	131 ~ 183	12 ~ 16	187 ~ 121	12 ~ 15
Nov	166 ~ 209	13 ~ 15	160 ~ 196	14 ~ 15	161 ~ 242	12 ~ 15	166 ~ 243	12 ~ 14	167 ~ 233	11 ~ 16	181 ~ 277	11 ~ 14
Dec	103 ~ 126	18 ~ 20	85 ~ 166	17 ~ 21	106 ~ 232	14 ~ 20	93 ~ 150	16 ~ 18	109 ~ 179	14 ~ 19	115 ~ 244	10 ~ 18
Ann	1294 ~ 1484	217 ~ 232	1230 ~ 1516	210 ~ 238	1313 ~ 1996	185 ~ 228	1542 ~ 1668	193 ~ 211	1442 ~ 1792	186 ~ 219	1513 ~ 1939	178 ~ 283

	Rakai						Toronto					
Jan	62 ~ 81	20 ~ 22	65 ~ 114	18 ~ 22	90 ~ 169	13 ~ 20	38 ~ 45	11 ~ 24	70 ~ 77	16 ~ 19	117 ~ 140	10 ~ 15
Feb	43 ~ 73	20 ~ 23	46 ~ 104	18 ~ 23	31 ~ 165	13 ~ 24	42 ~ 51	11 ~ 22	78 ~ 97	15 ~ 19	116 ~ 160	10 ~ 16
Mar	94 ~ 152	16 ~ 20	92 ~ 195	13 ~ 21	80 ~ 250	8 ~ 22	42 ~ 51	12 ~ 23	57 ~ 75	19 ~ 21	78 ~ 96	15 ~ 20
Apr	131 ~ 189	14 ~ 17	122 ~ 243	12 ~ 18	122 ~ 345	5 ~ 18	62 ~ 93	8 ~ 21	63 ~ 89	19 ~ 21	54 ~ 100	19 ~ 25
May	105 ~ 119	19 ~ 20	97 ~ 177	16 ~ 21	86 ~ 220	14 ~ 22	75 ~ 83	10 ~ 20	78 ~ 82	17 ~ 20	80 ~ 112	18 ~ 20
Jun	34 ~ 59	25 ~ 28	28 ~ 67	24 ~ 29	33 ~ 65	24 ~ 29	69 ~ 95	10 ~ 21	59 ~ 75	19 ~ 21	47 ~ 58	21 ~ 24
Jul	1 ~ 23	27 ~ 31	0 ~ 24	28 ~ 31	5 ~ 18	28 ~ 29	60 ~ 87	11 ~ 22	49 ~ 70	22 ~ 25	21 ~ 66	22 ~ 29
Aug	23 ~ 43	27 ~ 28	17 ~ 33	27 ~ 29	3 ~ 28	27 ~ 30	59 ~ 74	10 ~ 23	48 ~ 69	22 ~ 25	32 ~ 69	21 ~ 26
Sep	40 ~ 75	23 ~ 24	38 ~ 73	22 ~ 25	26 ~ 95	19 ~ 26	64 ~ 79	10 ~ 21	61 ~ 69	21 ~ 21	48 ~ 64	20 ~ 23
Oct	67 ~ 101	20 ~ 22	53 ~ 92	21 ~ 24	52 ~ 111	21 ~ 24	64 ~ 91	10 ~ 20	65 ~ 72	16 ~ 20	56 ~ 86	18 ~ 21
Nov	85 ~ 117	17 ~ 19	86 ~ 99	19	88 ~ 112	18 ~ 20	69 ~ 84	9 ~ 20	67 ~ 102	17 ~ 22	72 ~ 113	16 ~ 22
Dec	95 ~ 110	19 ~ 20	94 ~ 162	13 ~ 21	94 ~ 220	8 ~ 20	57 ~ 62	10 ~ 21	61 ~ 88	18 ~ 21	95 ~ 148	11 ~ 17
Ann	858 ~ 993	254 ~ 264	866 ~ 1305	240 ~ 267	807 ~ 1670	216 ~ 272	754 ~ 851	119 ~ 251	799 ~ 910	226 ~ 242	952 ~ 1098	208 ~ 236

	Calgary						Vancouver					
Jan	0 ~ 1	29 ~ 30	1 ~ 5	25 ~ 28	2 ~ 12	22 ~ 28	149 ~ 180	12 ~ 13	173 ~ 252	11 ~ 12	210 ~ 320	7 ~ 12
Feb	0 ~ 1	26 ~ 28	1 ~ 3	24 ~ 26	2 ~ 7	22 ~ 26	70 ~ 90	13 ~ 14	73 ~ 130	12 ~ 14	83 ~ 146	9 ~ 14
Mar	2 ~ 5	28 ~ 29	4 ~ 11	25 ~ 29	7 ~ 23	21 ~ 27	102 ~ 141	9 ~ 13	103 ~ 128	11 ~ 12	120 ~ 155	10 ~ 12
Apr	13 ~ 19	24 ~ 25	9 ~ 21	23 ~ 26	15 ~ 42	22 ~ 26	76 ~ 88	13 ~ 15	72 ~ 95	14 ~ 16	77 ~ 102	13 ~ 15
May	29 ~ 57	21 ~ 23	37 ~ 60	21 ~ 22	27 ~ 70	21 ~ 24	44 ~ 53	18 ~ 21	50 ~ 57	16 ~ 21	41 ~ 70	15 ~ 22
Jun	103 ~ 117	16 ~ 17	85 ~ 116	16 ~ 18	85 ~ 118	16 ~ 20	33 ~ 46	20 ~ 22	26 ~ 45	19 ~ 23	12 ~ 44	20 ~ 26
Jul	41 ~ 63	18 ~ 20	31 ~ 49	20 ~ 23	12 ~ 46	22 ~ 27	7 ~ 18	26 ~ 29	0 ~ 11	28 ~ 31	0 ~ 3	30 ~ 31
Aug	40 ~ 54	21 ~ 23	34 ~ 57	22 ~ 24	13 ~ 41	24 ~ 28	17 ~ 25	26 ~ 28	0 ~ 16	28 ~ 31	0 ~ 6	29 ~ 31
Sep	37 ~ 45	19 ~ 21	18 ~ 38	21 ~ 24	21 ~ 48	21 ~ 25	61 ~ 73	20 ~ 22	39 ~ 55	22 ~ 24	17 ~ 43	24 ~ 27
Oct	11 ~ 12	25 ~ 26	9 ~ 16	25 ~ 27	10 ~ 16	24 ~ 28	115 ~ 141	13 ~ 15	101 ~ 145	13 ~ 17	115 ~ 151	15 ~ 16
Nov	2 ~ 4	26 ~ 28	2 ~ 7	24 ~ 27	3 ~ 17	21 ~ 26	180 ~ 209	8 ~ 11	205 ~ 245	9 ~ 11	265 ~ 315	8 ~ 11
Dec	0 ~ 1	29 ~ 30	1 ~ 5	27 ~ 29	4 ~ 14	24 ~ 27	144 ~ 171	10 ~ 12	164 ~ 193	10 ~ 12	195 ~ 230	10 ~ 14
Ann	298 ~ 353	288 ~ 295	270 ~ 347	282 ~ 295	236 ~ 385	272 ~ 295	1080 ~ 1120	195 ~ 206	1115 ~ 1260	198 ~ 219	1207 ~ 1518	199 ~ 224

of the locations are predicted to be able to support an increase in per capita demand to 30 L for any models, although one model predicts a minimum monthly demand met of 87% for Buikwe. Increasing to a 15,000 L tank does not change demand met by more than a few percent for Buikwe, but does allow for a higher 30 L demand to be met under some models. However, it increases monthly demand met by almost 25% for Jinja and more than 30% for Rakai for a roof size of 60 m^2. As such, tank size provides additional resilience at this higher level of demand, but, as previously noted, rainfall periodicity is expected to play a dominant role in the degree to which benefits are conferred by a larger tank size.

Table 6. Projected Range of Changes in Monthly Rainfall (mm) Based on Bias-Corrected Future Simulations Using SSP 5-8.5

	Jinja			Buikwe			Rakai		
	2025 ~ 2034	2050 ~ 2059	2090 ~ 2099	2025 ~ 2034	2050 ~ 2059	2090 ~ 2099	2025 ~ 2034	2050 ~ 2059	2090 ~ 2099
Jan	0 to 11	–9 to 36	27 to 141	–2 to 12	–2 to 35	22 to 81	2 to 21	6 to 55	31 to 110
Feb	–1 to 16	1 to 30	12 to 39	–10 to 20	–9 to 13	–10 to 25	–13 to 17	–10 to 48	–26 to 108
Mar	10 to 43	–20 to 13	–15 to 110	0 to 53	–24 to 15	–42 to 65	–11 to 48	–12 to 90	–25 to 145
Apr	–21 to 26	22 to 52	17 to 104	–23 to 35	33 to 54	21 to 74	–9 to 49	–18 to 103	–18 to 205
May	–22 to 17	–46 to 25	–38 to 44	–12 to 28	–27 to 49	–14 to 39	–20 to –6	–28 to 53	–38 to 96
Jun	–13 to –2	–31 to 10	–36 to 8	–14 to 9	–56 to 4	–55 to –9	–21 to 3	–27 to 11	–23 to 9
Jul	–32 to 7	–53 to 3	–61 to 27	–28 to 9	–42 to 3	53 to 10	–21 to 2	–22 to 3	–16 to –3
Aug	–30 to 3	–51 to –11	–92 to 30	–24 to 20	–54 to –13	–94 to 13	–10 to 11	–16 to 1	–30 to –5
Sep	–12 to –1	–12 to 35	–19 to 24	–21 to 14	–15 to 37	–22 to 28	–18 to 17	–20 to 15	–31 to 37
Oct	–16 to 4	–21 to 6	–30 to 37	–15 to 3	–20 to 32	–29 to 39	–18 to 15	–32 to 6	–33 to 26
Nov	–5 to 38	–11 to 25	–10 to 71	–24 to 53	–23 to 43	–9 to 87	–9 to 23	–9 to 4	–7 to 17
Dec	5 to 28	–13 to 68	9 to 135	–14 to 43	2 to 72	7 to 137	–7 to 22	7 to 75	6 to 133
	Toronto			Calgary			Vancouver		
Jan	14 to 21	46 to 53	93 to 117	0 to 1	1 to 5	2 to 12	–11 to 20	13 to 51	50 to 161
Feb	19 to 28	55 to 74	93 to 137	0 to 1	1 to 3	2 to 6	–9 to 12	–5 to 51	4 to 67
Mar	3 to 12	18 to 36	39 to 57	0 to 3	2 to 9	5 to 22	–12 to 26	–12 to 13	6 to 41
Apr	–2 to 29	–1 to 25	–10 to 36	1 to 6	–4 to 9	3 to 30	–8 to 5	–11 to 12	–7 to 18
May	–4 to 4	–1 to 4	1 to 33	–13 to 14	–5 to 18	–15 to 28	–8 to 1	–2 to 5	–11 to 17
Jun	–7 to 20	–16 to 0	–29 to –18	–6 to 8	–24 to 6	–24 to 9	–9 to 4	–17 to 2	–30 to 2
Jul	–26 to 1	–37 to –16	–65 to –19	–14 to 8	–24 to –6	–43 to –9	–18 o 7	–25 to –14	–25 to –22
Aug	–14 to 1	–25 to –4	–41 to –4	–22 to –9	–28 to –6	–49 to –21	–12 to –4	–29 to –13	–29 to –23
Sep	–10 to 5	–13 to –5	–26 to –11	–3 to 4	–22 to –2	–20 to 7	–7 to 5	–29 to –13	–51 to –25
Oct	–6 to 0	–6 to 1	–15 to 15	0 to 2	–2 to 5	0 to 5	–9 to 16	–23 to 21	–9 to 26
Nov	–1 to 13	–4 to 31	1 to 42	1 to 3	1 to 6	2 to 16	3 to 33	29 to 69	89 to 139
Dec	12 to 7	16 to 43	50 to 103	0 to 1	1 to 5	4 to 14	5 to 32	25 to 54	56 to 91

While a 120 m^2 roof area is not typical for rural Uganda, increasing roof size does have an impact on the predicted ability to meet demand in 2090 ~ 2099 under all models. In Buikwe and Jinja, this means that at least 94% of monthly demand is met for at least three model predictions. This is sustained in Buikwe (two models) and Jinja (one model) for a 30 LPCD demand. However, in the other models it becomes difficult to meet this level of demand between July and September, dropping as low as 37% and 48% of demand met under one model prediction for Jinja and Buikwe, respectively. Despite this, TSM indicates that increasing catchment size for RWH will confer resiliency under a changing climate and should be considered as part of a Ugandan RWH strategy.

Overall, a 15,000 L tank can improve demand met over a 10,000 L tank between 9% and 50% for the lowest month of demand met across locations and models. Similarly, increasing roof size from 60 to 120 m^2 met an additional 9 to 31%. A comparison of improvements in demand met between increased tank size (15,000 L) and roof size (120 m^2) indicated that there is no clear pattern for improvements in demand met associated with continent. For Buikwe, Jinja and Vancouver, a 20 L demand met was improved with increasing tank size, while for Rakai, Calgary and Toronto, increasing roof size improved demand met. Increases in both roof and tank size afforded the ability to at least partially meet an increased demand (30 LPCD). While increasing roof size was able to better meet the increased demand for the majority of locations (Buikwe, Toronto, Vancouver), increasing tank size provided better performance in Rakai and Jinja. Neither increased tank nor roof size were able to benefit Calgary at this higher demand. This further demonstrates the need to optimize catchment and storage size, not only for rainfall amounts but also for temporal distributions i.e., intermittency.

4. Discussion

The following discussion is set against a backdrop of very different national water demand patterns between Canada and Uganda. However, marginalized communities in both settings are more limited in their ability to access water, and thus demands are likely to be constrained relative to national averages. For example, as of April 2021, long-term drinking water advisories (in place for more than one year) were in effect across 33 communities in Canada (Indigenous Services Canada, 2021). RWH can be a vital source of water for Canada's Indigenous communities in Canada, those distant from urban centres, or those wishing to reduce their water bills. This is demonstrated in an Inuit community in Canada where RWH implementation resulted in a 17% increase in water for hygiene and a 40% reduction in water retrieval efforts as well as cost savings (Mercer and Hanrahan, 2017). With even the driest areas in Uganda receiving approximately 400 mm of rain per year (Ntale, et al., 2005), the country is ideal for nation-wide RWH programs. Indeed, RWH has proven to be an effective tool in reducing residential water shortage in the Oruchinga Valley, south of Mbarara, since 1993 (Sturm et. al., 2009). However, due to the bimodal pattern of rainfall, and, more recently, the unpredictable onset and duration of the rainy seasons, a better understanding of how to best harvest and manage rainwater is needed to determine the capacity of a RWH system in fully meeting residential water demands year-round. Meanwhile, Canada, despite holding approximately 7% of the world's renewable fresh water supply (Canadian Geographic, 2019) and holding high income country status (World Bank, 2019), is not immune to the global water crisis, especially within rural and Indigenous communities (Bakker and Cook, 2011).

Flexibility in RWH configuration is important – optimizing for a single variable means that some more reliable configurations will be excluded because the roles of storage/tank and catchment/roof area become more or less important depending on the rainfall regime. This tool is the first to provide flexibility to optimize across all design elements (catchment, storage, and demand), advancing the work of Fonseca et al. (2017) who optimized for tank size, while maintaining a similar level of tool accessibility. Under current climate conditions across all locations, roof area (i.e., catchment area) is the controlling factor that maximizes demand met, especially given the intermittency of intra-monthly precipitation.

This required flexibility is clearly demonstrated by the varying demands met both across Canadian locations and between Canada and Uganda. As previously stated, these differences are driven by both differences in precipitation types (i.e., rain versus snow) and also in rainfall regimes. For example, a 10,000 L tank and 60 m^2 roof configuration (Figure 2) meets at least 80% of demand for all months of the year in Uganda, while for Calgary, and to a lesser extent, Toronto, demand met falls in the winter due to average temperatures below freezing. Vancouver, a coastal, predominantly rainfall regime, actually meets higher levels of demand than Buikwe in most months of the year, but falls below that of Buikwe in late summer, which is typically drier.

Projected climate change impacts vary according to region and have different implications for RWH – e.g., snow versus rain in cold regions or extension or contraction of dry seasons. As demonstrated, changing distribution of rainfall amounts over short time periods not only affects reliability but also the relative importance of RWH system elements. In advancing the literature on climate change impacts on RWH system configuration beyond that of Musayev et al. (2018) and others, the utilization of climate scenario data in TSM demonstrate that roof area (i.e., catchment) provides resilience in meeting demand, particularly in Canada, as exemplified by Toronto results. However, the increased ability to meet higher demands (30 LPCD) in Buikwe and Jinja with larger tank sizes, as opposed to larger catchment areas, demonstrates the interplay not only between rainfall amounts but also the daily distribution of that rainfall. Both of these underscores the importance of a fully flexible RWH optimization tool such as TSM. Additionally, the ability to optimize and predict demand met aids broader water resources management for local water security in terms of whether additional water sources need to be developed, either now or in the future. However, as identified by Staddon et al. (2018), local RWH uptake is also affected by land tenure, access to non-governmental and other organizations that provide intermediary support, and appropriate financing mechanisms, implying that beyond environmental feasibility, social and political frameworks must be in place to ensure the success of local RWH.

5. Conclusion

The TSM improves on previous user-input and climate scenario rainwater harvesting system tools by allowing flexible optimization of catchment, storage size, and water demand simultaneously based on current or future climate scenario data. The information provided by TSM from a user-friendly interface empowers a household or community to self-reliantly design and manage the most effective RWH systems for their environment and water needs. For decision-makers, it provides a mechanism to understand characteristics of regions where RWH is an invalid, partial, or valid solution within climate regimes as well as local socio-economic contexts. The continuous simulations demonstrate that even regions receiving excessive rainfall (i.e., Vancouver and Buikwe) cannot necessarily rely on some RWH system configurations to satisfy a household demand of 20 LPCD for a family of six people. Despite the failure of some of the RWH scenarios utilised in this paper to completely meet demand year-round, the Canadian and Ugandan exemplar regions demonstrate that there are benefits to augmenting problematic or insufficient water supplies with rainwater.

Our changing climate is altering rainfall regimes that we have come to expect and depend on, particularly in seasonal extremities. Scenario data clearly show trends in Canada to drier summers and wetter fall/winters, amplifying current rainfall patterns. In Uganda, a more significant shift is observed towards a single wet and single dry season. Specific findings indicate that RWH systems are most sensitive to intra-monthly (daily) variations in rainfall distribution (i.e., intermittency) and not just intra-annual variations. As such, it is important to base RWH design on sufficient reliable and representative rainfall data, especially given the high spatial variability of rainfall. While the tank must be sized correctly for water demand, roof area is the dominant factor in how much rain is captured during each rainfall event. In the current scenarios explored in this paper, it is a larger roof area that increases resilience against short periods of water unavailability (whether dry or cold) by increasing the likelihood of the tank being filled to its maximum, while larger tank sizes increase resilience for intermittency within months. This holds into the future under CNRM, EC-Earth, IPSL, and MPI SSP 5-8.5 scenarios with current demand better met in some locations by increasing roof size and others by increasing tank size. The same holds for increased demands, presumably indicating the interplay between absolute rainfall volumes and intermittency.

These results indicate that RWH is a necessary but insufficient source in supplying a community with adequate water to fully satisfy water needs, despite likely improvements in demand met over time in most study locations. While minimum needs can be met in certain locations with specific RWH configurations, 20 LPCD is not sufficient for sustainable and vibrant communities. However, implemented in conjunction with other water sources, RWH can and should be a vital tool harnessed in meeting domestic water demand in rural, remote, and otherwise marginalized communities in particular both now and into the future. Accessible tools such as TSM will facilitate the development of robust RWH systems within a sustainable water management plan.

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Notation

The following symbols are used in this paper:

LPCD = Litres per capita per day;
RWH_P = Maximum potential daily RWH volume;
P = Daily precipitation;
A = Surface area of the roof connected to the water collection tank;
α = Scale parameter
β = Loss coefficient;
$\gamma_{1,2}$ = Shape parameters
i = Current day;
$i - 1$ = Previous day;
B = Collection tank volume;
D = Total daily water demand per household;
R = Tank reliability;
V = Volume of water in the RWH tank on any given day;
C = Demand met on any given day;
H = Cumulative community deficiency from all household systems on any given day;
N_f = Number of households connected to community RWH system;
h = Household systems;
c = Community system;
C_{tot} = Total volume of water provided on any given day;
R_{tot} = Reliability of the RWH system on any given day

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