Modeling And Analysis Of Rainwater Harvesting Systems Under Different Climates

Modeling And Analysis Of Rainwater Harvesting Systems Under Different Climates

By

Ahmed H.E. El Ganzouri, B.Eng.

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AUTHOR: El Ganzouri, A.

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Abstract

There is a strong interest in rainwater harvesting (RWH) solutions as the global demand for water increases and water sources face contamination and depletion. Despite the extensive research conducted on the impact of RWH on watersheds, there is significant research to be completed to determine the relationship between the collection tank volume, roof size, and water demand satisfied by the RWH system. This thesis aims to further the understanding of the behaviour of RWH systems through a quantitative assessment of the water provided by these systems. Calculating the reliability of RWH systems in various Canadian regions allows for an evaluation of the capacity of RWH in meeting various residential water needs in Canada's diverse climates. The results are obtained through hourly continuous simulation to provide the most accurate results and are presented in a user-friendly format through simple equations and graphs. RWH modeling through analytical equations do not require long-term historical data and are easier to use than conducting computer-aided continuous simulations. A better understating of the analytical equations' application is developed through a comparison between the analytical and continuous simulations methods. The comparison is held for different regions within Canada, and the analysis confirms a lack of accuracy for the analytical method in some climatic conditions. Daily continuous simulations conduced for Ugandan and Canadian regions provide a perspective on the feasibility of RWH systems to meet the human right to drinking water in the two countries. A comparison of the reliability of RWH tanks in Ugandan and Canadian regions is conducted to provide insight into the impact of rainfall patterns on the reliability of RWH systems. The evaluation of RWH performance in the RRM context in Canada and Uganda is aimed to address the lack of adequate water sources in rural, remote, and otherwise marginalized (RRM) communities globally. Examining the most accurate and appropriate modeling tools and assessing the actual yield of RWH systems provides information critical to water-sensitive communities and provides a foundation for future research to further explore the most effective application of RWH in urban and water-sensitive communities.

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Nomenclature

Abbreviations

EPA	U.S. Environmental Protection Agency
HLY	Hourly Weather
IET	Inter-Event Time
IETD	Inter-Event Time Definition
LID	Low-Impact-Development
LPCD	Litres per Capita per Day
RRM	Rural, Remote, and otherwise Marginalized
PURRS	Probabilistic Urban Rainwater and Wastewater Reuse Simulator
RWH	Rainwater Harvesting
SWMM	Storm Water Management Model
TSM	Tank Simulation Model
UNEP	United Nations Environmental Programme
UNICEF	United Nations International Children's Emergency Fund
WHO	World Health Organization

Symbols

A	roof size (m^2),
Acc	accuracy of the analytical method (%)
B	size of the residential tank (L)
B_c	size of the shared community tank (L)
b	storm event interevent time (hr)
$\bar{b}$	average inter-event time (days)
C_c	water consumed from the community tank on a given day (L/day)
C_i	water consumed from the RWH tank on a given day (L/day)
C_{i-1}	water consumed from the RWH tank on the previous day (L)

C_h	volume of water provided by the integrated RWH system to each household (per day)
Co	RWH system coefficient
D	total demand (L/day)
$E[p]$	expected value of the spill volume per cycle
$E(v_r)$	expected value of the volume of runoff (v_r) generated from a roof per rainfall event
G	water use rate (L/day)
G_{max}	maximum water use rate
$G_p(0)$	probability per cycle that some spill occurs (i.e. $P > 0$ where P is the volume of spill)
H_i	cumulative deficiency of the residential system per day
N	Manning Coefficient
N_f	number of families sharing the community tank
P	maximum potential daily rainwater harvest volume (per day)
Pr	daily precipitation value (mm)
R_e	Tank reliability
R^2	goodness of fit
R_A	tank reliability obtained through the analytical equation
R_a	annual total volume of runoff collected from the roof with diversion of first flush
R_c	annual total volume collected into the storage unit and utilized
R_{CS}	tank reliability obtained through continuous simulation
R_e	reliability of a stand-alone RWH system
$R_{e,c}$	reliability of the integrated RWH system
$R_{e\,max}$	maximum tank reliability
S	surface area of the roof connected to the residential collection tank (m^2)
S_c	surface area of the roof connected to the shared community tank (m^2)

v	storm event rainfall depth (mm)
V_c	volume of water in the shared community tank (L)
V_i	volume of water in the tank on a given day (L)
V_{i-1}	volume of water in the tank on the previous day (L)
v_r	volume of runoff (mm)
$\bar{v}$	average event depth (mm)
v_{ff}	volume of first flush (mm)
t	storm event duration (hr)
$\bar{t}$	average event duration (days)
ζ	rainfall event volume distribution parameter
Θ	average number of rainfall events per year.
λ	rainfall event duration distribution parameter
ϕ	runoff coefficient
ψ	rainfall event interevent time distribution parameter

Declaration of Academic Achievement

The author, Ahmed H.E. El Ganzouri, with the supervision and guidance by Dr. Sarah Dickson, Dr. Yiping Guo, and Dr. Corinne Schuster-Wallace, conducted the research presented in this Thesis. Chapter 2 has been submitted for publication on June 4th to the Canadian Water Resources Journal. Chapters 3 and 4 will be submitted to suitable peer-reviewed journals as well.

Chapter 1: Introduction

1.1 Background

With changing trends in human populations and global climate, water management has been a significant concern for many communities worldwide. The growing human population, predicted to increase by over 1 billion over the next 10 years, is triggering a rise in urbanization across the globe (Frederiksen, 1996). The number of large cities with populations over 10 million is rapidly increasing, especially in developing countries (Saeijs and can Berkel, 1995). This upsurge of large cities and global climate changes, in both developing and developed countries, are causing an increase in water demand which is significantly exceeding water supply (Frederiksen, 1996); the United Nations Environmental Programme UNEP predicts that this water crisis will affect two thirds of nations by 2025 and 4 billion people by 2050 (Thomas and Durham, 2003). Water access in rural communities is expected to continue declining in developing and developed countries due to the same causes of changing population and climatic conditions (Ivey et al., 2004).

Despite Canada holding 7% of the global renewable water supply (Bakker and Cook, 2011), some areas in the country are extremely dry such as the Prairie Provinces, which lie in the rain shadow of the Rocky Mountains (Schindler and Donahue, 2006). That being said, the entire country has been facing disconcerting water concerns (Bakker and Cook, 2011), proving that even water-rich countries are not immune from the global water crisis. Between 1994 and 1999, 25% of Canadian municipalities experienced water shortages; these water scarcities were contributed to the same factors impacting countries worldwide: increased consumption, changing climatic conditions, and infrastructure constraints (Environment Canada, 2002). With Canada's federal government overseeing fisheries, navigation, and international waters, the provincial government overseeing water resources, and municipal government managing water supply, there is a series of governance gaps, overlaps and challenges in providing adequate water, especially to RRM communities (Ecojustice, 2010). Due to these various layers of jurisdictions, Canadian rural and aboriginal communities are more at risk of water shortages and contamination. In 2008, drinking water advisories were in place for over 1700, mostly rural, remote, and otherwise marginalized (RRM) communities (Ecojustice, 2010). A report conducted by the Health Canada (Bakker and Cook, 2009) indicates that between 2000-2001 nearly one quarter of on-reserve homes occupied by First Nations families had an inadequate supply of quality water. Residential RWH systems can provide RRM communities with a water source to supplement existing water sources. RWH systems are ideal for RRM communities as they provide accessible water of acceptable quality and minimize mismanagement concerns as the RWH tanks are managed at the household/community level. Canada, with its considerable resources and technical infrastructure already in-place, diverse demographics, different climatic conditions throughout the country, in addition to its mix of water issues arising from its water-rich and water-sensitive areas, is an ideal country to be a global leader in addressing the various universal water troubles (Schindler and Donahue, 2006).

Africa too is burdened with severe water concerns, which have consequently impacted its food-security, heath, and social wellbeing (World Water Council, 2002).

Sub-Saharan Africa's rain has not resolved the region's water shortages due to the temporal and spatial variability of rainfall and its unpredictability. The rainfall's high intensity and short duration provides no opportunity for effective natural collection, leading to high runoff and soil losses (Gichuki, 2000). The continent has more than 20% of the world's land area, but only 10% of the world's freshwater resources, The shortage and uneven distribution of water resources leaves 40% of the continent's population without access to safe drinking water (Van Koppen, 2003), with only 75% of Ugandans having access to improved drinking water and only 5% having a household water connection (WHO and UNICEF, 2014). As populations migrate to urban centers, the country's already overstressed residential water supply pipes and infrastructure will face even more severe overexploitation (Nakanjakko and Karungi, 2003). Similarly to Canada, Uganda's rural and low-income households are more at risk of water issues; these households rely on unreliable and inaccessible communal water sources, often untreated and contaminated, raising the community's vulnerability to sickness and decline in social wellbeing (Howard et al., 2002; Ford, 1999).

Rainwater Harvesting (RWH) has been proving to be an adept solution assisting in the alleviation of some of the global water crises where water scarcity is due to lack of infrastructure or access. A RWH system typically consists of a rain barrel or collection tank accumulating runoff from the roof of a building (Guo and Baetz, 2007). Today, RWH projects exist globally, with a strong presence in Brazil, USA, Australia, UK, Sweden, Jordan, South Africa, Taiwan, India, Israel, Bangladesh, Malaysia, and India (Lu et al., 2013). This surge of RWH in arid, semi-arid, and even wet climates rarely facing water shortages, is attributed to its ease of implementation and a user-defined scale (Petrucci et al., 2012). In Canada, RWH systems are popularly used for gardening and watering lawns (Farahbaksh et al., 2008); while in Uganda, they are used to satisfy domestic needs, including drinking water. RWH is believed to be apart of a continuum of solutions to have the potential to fill the void created by the lack of reliable water supply in many parts of the world, and seen as a practical solution as African nations and others reduce the proportion of its population without sustainable access to drinking water (Helmreich and Horn, 2008).

There is a growing interest in RWH among all stakeholders, especially in urban areas, as water conservation practices gain momentum and to meet basic domestic water needs. Communities worldwide, including in Canada and Uganda, are turning to RWH as a new source of water and to offset water costs. In Canada, RWH can reduce residential intake of municipal water and provide significant municipal savings, e.g., $3 million of operational savings for the City of Guelph due to an 18% reduction in residential water demand with all new residential developments implementing RWH programs (Farahbakhsh et al., 2008). Due to the lack of water supply infrastructure in Uganda, RWH may act as the only on-site residential water source, offsetting a household's reliance on contaminated water sources, including distant boreholes (wells), surface waters and expensive vendors (Keener et al., 2010). Further studies are needed to accurately determine the quantity of water made available from RWH systems in both Canada and Uganda. While the two countries encompass vastly different infrastructure sophistications, they both share similar societal benefits of RWH, covered RWH tanks curb the spread of insects and disease due to reduced flow to urban ponds (Helmreich and Horn, 2008). Precipitation patterns for the two countries differ, with Uganda undergoing bimodal rainfall seasons and Canada experiencing a more temperate rainfall pattern during its non-winter months. The differences in precipitation strongly impacts the behaviour of a RWH system and hence its application. A dependable model is needed to accurately estimate a collection tank's reliability in meeting a residential water demand. An effective model can support design of a RWH system that minimizes water overflow during the wet season while extending rainwater supply during the dry period, a goal that both Canada and Uganda can benefit from (Farahbakhsh et al., 2008). Currently, there is a significant need for innovative product development for RWH tanks, to push RWH into being a technically relevant and applicable tool for a wide range of household needs in the world's different climatic conditions.

While RWH has proven to be an effective storm water management system, little research has been conducted to assess the reliability of RWH and means to optimize the system as a dependable source of water. There is a distinct lack of knowledge regarding proper design of RWH to meet its most optimum use; current reliance on 'rule-of-thumb' or simple mass balance approaches can result in calculations of unrealistic payback periods or overly optimistic quantity of water provided (Roebuck and Ashley, 2006). Effective modeling of RWH is needed to recommend most optimum tank volume for its specified use along with the tank's reliability, defined as the percentage of time when demands are satisfied by the water collected in the storage unit. Sizing RWH tanks is a miniature hydrologic engineering design problem and can be solved in an ad-hoc way due to its small scale, that being said the design should be as accurate as possible. A poor design can result in significant economic and environmental losses on a communal or larger scale (Guo and Baetz, 2007). Such losses can have severe implications in RRM communities, as they would rely on the implemented RWH system due to lack of other water sources. There has been a number of models developed to simulate RWH performance, such as: DRHM (Dixon et al., 1999), Rewaput (Vaes and Berlamont, 2001), RWIN (Herrmann and Schmida, 1999), PURRS (Coombes and Kuczera, 2001), and Aquacycle (Mitchell, 2005). However, there has been a general trend of communities rarely using these tools due to their apparent complexity and lack of availability (Ward et al., 2013). A new approach to modeling RWH is needed to disseminate information to communities regarding the capabilities and optimum design and management of a RWH system and their capacity in meeting a household's minimum water requirements (Imteaz et al., 2011).

An accurate approach to sizing rainwater tanks is through the use of models, i.e., continuous simulation models or through the use analytical equations to simulate hydrologic operations under local conditions. A popular continuous simulation model is the EPA's (U. S. Environmental Protection Agency) SWMM (Storm Water Management Model) software. The software is flexible and is well suited for representing rainwater collection with its built-in LID-Rain-Barrel feature (Elliott and Trowsdale, 2007). SWMM utilizes long-term historical rainfall data to mimic roof runoff generation and resulting tank behaviour. SWMM continuous simulations have been widely used to model the reliability of rainwater harvesting systems, e.g., Australia (Jenkins, 2007), USA (Abi

Aad et al., 2000), China (Jia et al., 2012), France (Petrucci et al., 2012), and Kuwait (Zaghloul and Al-Mutairi, 2007).

The second approach, i.e., the analytical method, can be completed through two means. The first is through conducting simulation modeling and regression analysis, eg. Lee et al. (2000). Each set of simulation and analysis is only applicable to the one geographic location studied; similar sets of simulation modeling and regression analysis is repeated for each geographical location of interest (Guo and Baetz, 2007); desired regression equations are then obtained which can be used for the proper sizing of storage tanks. The second approach, applied in this study, is to stochastically analyze the hydrologic operation of the systems; local climatic conditions are accounted for by incorporating probabilistic rainfall models; analytical equations are then derived which can be used for the sizing of storage tanks. In using this second analytical approach, rainfall statistics are obtained from long-term historical rainfall data; and these statistics are used to provide the basic information needed to represent local climate conditions, particularly rainfall event and dry period patterns. The statistical parameters entered into the analytical equations perform similar roles that the long-term historical rainfall data perform when they are inputted into continuous simulation models. Similar stochastic approaches have been used to develop analytical equations for various storm water management applications: the sizing of cisterns to collect rainwater from agricultural fields for crop use during dry periods (Lee et al., 2000), storage and overflow of sewage treatment plants (Howard, 1976), stream runoff (Di Toro, 1984), storm water detention storage (Loganathan and Delleur, 1984), design of sewage lagoons (Cruise and Singh, 1988), wash-off of pollutants on urban watersheds (Barbe et al., 1996), storm water treatment systems (Small and Di Toro, 1979), and urban storm water management (Adams and Papa, 2000; Guo and Adams, 1999).

An in-depth comparison of the continuous simulation and analytical methods is needed to determine how to maintain an accurate representation of the tank’s behaviour while still in an easy and accessible manner. Investigating the accuracy of the analytical method can provide the foundation in which further research can continue to develop accurate RWH models that are easily accessible and useable by all stakeholders, including marginalized communities. The use of both continuous simulation and analytical methods provides vital information to designers/engineers, decision and policy makers, and community members. The two methods, when used in the appropriate setting and pending on the data available, are useful tools in determining optimum tank volumes and withdrawal rates. It is critical to assess the accuracy and scope of application of the analytical method prior to application, especially in rural, remote and otherwise margianlized communities that are water-sensitive. A much-needed realistic depiction of a rainwater tank’s performance based on the household’s factors and climate conditions, is needed to provide an accurate portrayal of the RWH system’s capacity in meeting household demands in RRM communities across the world.

1.2 Objectives

The goal of this thesis is to provide a better understanding of rainwater tank behaviour and reliability in different climates. This is done through meeting the following objectives:

1. Providing an overview of the reliability of RWH in meeting various residential demands in different Canadian climates, calculated through continuous simulations.
2. Comparing RWH reliabilities obtained from continuous simulations and previously derived analytical equations.
3. Recommending the most appropriate modeling method for the different Canadian climates examined.
4. Investigating the reliability of RWH systems in meeting a Ugandan household's minimum water requirements for domestic uses and/or hygiene purposes.
5. Comparing a rainwater tank's behaviour in regions with bimodal and unimodal rainfall patterns.

1.3 Thesis Organization

This thesis contains three chapters in addition to this introductory chapter:

Chapter 2, which has been submitted for publication to the Canadian Water Resources Journal, is dedicated to modeling through continuous simulation of RWH systems in seven Canadian cities within different climatic regions. Chapter 3 provides a comparison of the use of the analytical and continuous simulation methods in calculating RWH reliability for the seven Canadian cities. Chapter 4 uses continuous simulations to investigate the role of RWH in meeting residential water needs in Uganda, and compares the behaviour of RWH tanks in Uganda and Canada.

Chapter 2: Reliability of Residential Rainwater Harvesting at Representative Canadian Locations

Keywords: Rainwater harvesting, Canadian Climate, Continuous Simulations, Storm-Water Management, Storage Reliability

Abstract

Rainwater harvesting has the potential to alleviate some of the stress on the current water supply infrastructure. A deeper understanding and communication of how to best manage rainwater harvesting tanks to maximize its reliability is needed. This study uses continuous simulations and statistical analyses to model the behaviour of rainwater harvesting tanks for seven selected cities throughout Canada. Historical hourly precipitation data was used to estimate the reliability of rainwater harvesting. A graph and a set of equations were developed in order to estimate tank reliability in each of these seven cities for a wide range of tank volumes. The graphs offer an immediate overview of the general trends, while the equations aim to provide an accurate reliability estimate for a specific house size, tank volume, and household water consumption rate. These graphs and equations can serve as a useful tool for various stakeholders, including policy makers, developers, tank manufactures, and homeowners, in selecting the most effective tanks for their specific communities.

2.1 Introduction

Increasing populations and changing climates are adding stress to already overwhelmed water supply systems (Imteaz et al., 2011). Municipalities face challenges in meeting water demands and collecting and treating storm water in sprawling urban communities. An effective method for solving part of the problem is the small-scale point-of-source management systems; e.g., rainwater harvesting (RWH). Rainwater harvesting has been in use for over 4,000 years (Fulton et al., 2012) and recently there has been a growing need for RWH to address the adverse hydrologic effects of urbanization (Zhang and Guo, 2013).

In a simple RWH system, storm water runoff from rooftops is directed through gutters and downspouts to rain-barrels, storing it for future residential use. RWH systems designed with appropriate tank volumes have been proven to be an effective storm water management tool; however, further research is needed to estimate the functions of tank volumes in order to estimate the reliability of rain-barrels for household use (Kellagher, 2011). The research presented in this paper aims to address this need, to further investigate the behaviour of rainwater tanks for residential water consumption, and to provide the tools for the determination of the appropriate rainwater tank volumes according to home sizes and water demand rates.

An effective rain-barrel design is one that considers both catchment-scale and parcel-scale impacts. Catchment-scale analysis examines the role of RWH on storm water runoff and the watershed, of which a solid understanding has already been developed (Guilon et al., 2008). Parcel-scale analysis is concerned with the ratios between tank collection volume, roof area, and rainwater demand (Petrucci et al., 2012). Currently, there is a strong need for detailed parcel-scale modeling (Aad et al., 2010); particularly the means to maximize RWH reliability through tank size optimization (Farahbakhsh et al., 2008). This study focuses on the parcel level design of a residential RWH system through a quantitative analysis of water collected through RWH, and presents overall trends of reliability for various tank volumes. Reliability is defined as the fraction (or percentage) of time, per house, when needs are satisfied by water collected in the storage unit (Guo and Baetz, 2007). An easy-to-understand visual demonstration of the tanks' reliability is necessary for the practical implementation of RWH at the residential level (Marsalek et al., 2009).

The quality of harvested rainwater has been confirmed to be acceptable for toilet flushing, laundry, and outdoor uses (Coombes et al., 2007). RWH has an untapped potential in meeting household needs due to the lack of information available at the community-level. Currently, a significant portion of homeowners has no knowledge of the optimum storage volume required for their specific site conditions (Imteaz et al., 2012). This paper aims to better the understanding of household-specific RWH and storm water collection capacities; encouraging Canadian homeowners to install RWH systems and providing the information to best manage it (Ward et al., 2013). The objective of this paper is to equip stakeholders with the tools needed to make well-informed decisions regarding RWH implementation.

2.2 Methodology

RWH tank sizing requires significant data integration, as the collection tank behaviour is dependent on water demand and supply of rainwater. The input of rainwater is predicted based on previous precipitation data and trends. The size of rain-barrels needs to be relative to the area of the roof and the desired water demand rate. These parameters vary depending on rainfall characteristics and water use behaviour within the household. Continuous simulations of modeled RWH system operations for seven Canadian cities were conducted in this study. The simulation model utilizes long-term rainfall data, excluding the winter months. Unlike previous models and research conducted, an hourly time-step rather than a daily time-step was used in this study. The hourly time step minimizes inaccuracies and improves the reliability of the model’s results (Coombes and Barry, 2007).

The model was developed using the EPA’s (U.S. Environmental Protection Agency) SWMM (Storm Water Management Model) 5.0 software. SWMM has been used across the world for hydrologic modeling. The software is a flexible tool and is well suited for representing rainwater collection with its built-in LID-Rain-Barrel feature (Elliott et al., 2007). Hourly rainfall data for the 7 selected cities were obtained from the Digital Archive of Canadian Climatological Data. The data is presented in an HLY (Hourly Weather) format, which SWMM 5.0 is readily capable of interpreting. More information regarding the 7 rain gauge stations is available in Table 1. Precipitation data of non-winter months were inputted into the model; all durations exceed the 30-year threshold needed to minimize modeling inaccuracies (Mitchell et al., 2008).

Table 1- Rain Gauge Stations

City	Station Name	Station ID	Time period	Duration (years)
Shearwater, NS	Shearwater A	8205090	1955-1999	45
Quebec, QC	Quebec/Jean Lesage Intl A	7016294	1961-1995	35
Toronto, ON	Toronto Lester B. Pearson Int'l A	6158733	1960-2003	44
Windsor, ON	Windsor A	6139525	1960-2003	44
Saskatoon, SK	Saskatoon A	4057120	1960-1993	33
Calgary, AB	Calgary Int'l A	3031093	1960-1999	40
Vancouver, BC	Vancouver Int'l A	1108447	1960-1999	40

The SWMM model was set up to include 10 catchment areas, each representing a residential roof collecting the rainfall and diverting it to the SWMM LID-Rain-Barrel function. Table 2 outlines the properties of the catchment areas. It is noted that changes in the catchment slope and the Manning roughness coefficients do not alter the simulation results. During a simulation, each of the 10 catchment areas represented a roof of the same size but attached to a different RWH tank of the following volumes: 200, 600, 1000, 3000, 6500, 8000, 11000, 15000, 20000, and 25000 L. The simulation was repeated for the following roof sizes: 60, 80, 100, 120, 140, and 160 m^2. The roof sizes chosen reflect typical residential homes across Canada; encompassing townhouses to 5-bedroom homes. The 20 m^2 increments allows the model to be accurately interpolated for different roof sizes, and extrapolated to provide a general indication of tank volume reliability for smaller and larger homes.

Table 2-SWMM Catchment Properties

Property	Definition	Value
% Slope	Average surface slope (%)	50
% Imperv	Impervious area (%)	100
N-Imperv	Manning for impervious area	0.0115
N-Perv	Manning for pervious area	0.1
D store-Imperv	Depression storage for impervious area (in)	0
D Store – Perv	Depression storage for impervious area (in)	0
%Zero-Imperv	Impervious area with no depression storage (%)	100
% Routed	Runoff routed between sub areas (%)	100

The water use rates are based on a 3-person household, as shown in Table 3. All 5 water use rates do not require extensive treatment or infrastructure changes (Farakhakhsh et al., 2008), making them ideal for existing and new homes. Previous RWH tank sizing modeling was based on continuous simulations using daily time steps (Fulton et al., 2012). In this study, an hourly time step is used to increase the model's precision and provide a more accurate representation of a rainwater tank's water flow rates to meet household needs (Coombes et al., 2007).

Table 3-Rainwater Demands

Demand Name	Demand Type	Daily Demand (L/Day)
D1	Toilet Flushing	93
D2	Toilet and Outdoor Use	171
D3	Toilet, Outdoor Use, and water-saving Laundry	363
D4	Toilet, Outdoor use, and Laundry	420
D5	All Indoor and Outdoor use, except drinking water	516

2.3 Results and Discussion

To best communicate the simulation results to the potential users, each city is provided with a standard graph outlining the trends of reliability of the various tank volumes (Figures 1 through 7) along with a series of equations (Tables 4 through 10). The graphs display the reliability for the various demand studies (Table 3) for a fixed roof size of 100 m^2 and a range of collection tank volumes (200-25,000 L). Changes in roof size do not cause any significant changes to the general trend of the graphs. Thus, regardless of roof size, the user gains an immediate understanding of the correlation between tank volume and demand satisfied from the graphs provided. The graphs offer homeowners within each region an overview of the reliability of all reasonable tank volumes for various water use rates; this allows homeowners to quickly narrow the range of tank volumes to meet a desired reliability rate and their household feature and location.

A more precise estimate of the reliability is provided by a series of equations obtained through regression analysis. The equations are used to provide a factor (F) with (x) representing roof area in m^2. Reliability obtained from the graph is multiplied with the calculated factor to give a precise reliability for the given roof size, tank volume, and demand type. The equations allow the user to choose which type of rainwater use best fits their household and the results are customized to their specific circumstances. The R-Squared values of the regression equations are included in Tables 4-10 to validate the accuracy and goodness-of-fit of the equations.

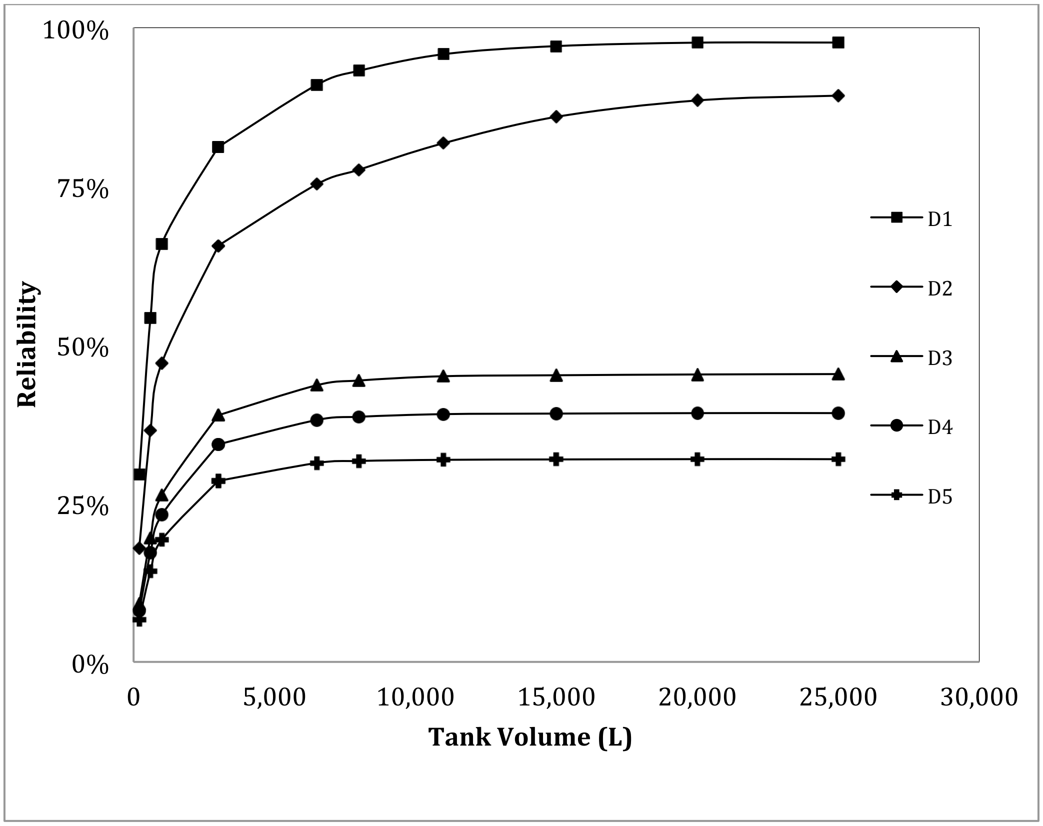

Figure 1- Toronto Rainwater Tank Reliability

Table 4- Toronto Factor Equations

Toronto, Ontario		
Small tanks (< 3,000 L)		
Demand	**Equation**	**R^2**
1	$F = -1^{-0.5\,x^2} + 0.0034x + 0.7774$	0.99
2	$F = -2^{-0.5x^2} + 0.0063\,x + 0.5742$	1.0
3,4,5	$F = 0.1891\,x^{0.3594}$	0.99
Large Tanks (> 3,000 L)		
Demand	**Equation**	**R^2**
1	$F = -1^{-0.5\,x^2} + 0.003x + 0.8172$	0.87
2	$F = -5^{-0.5\,x^2} + 0.0153\,x - 0.0081$	0.99
3,4,5	$F = 0.0089x + 0.0935$	1.00

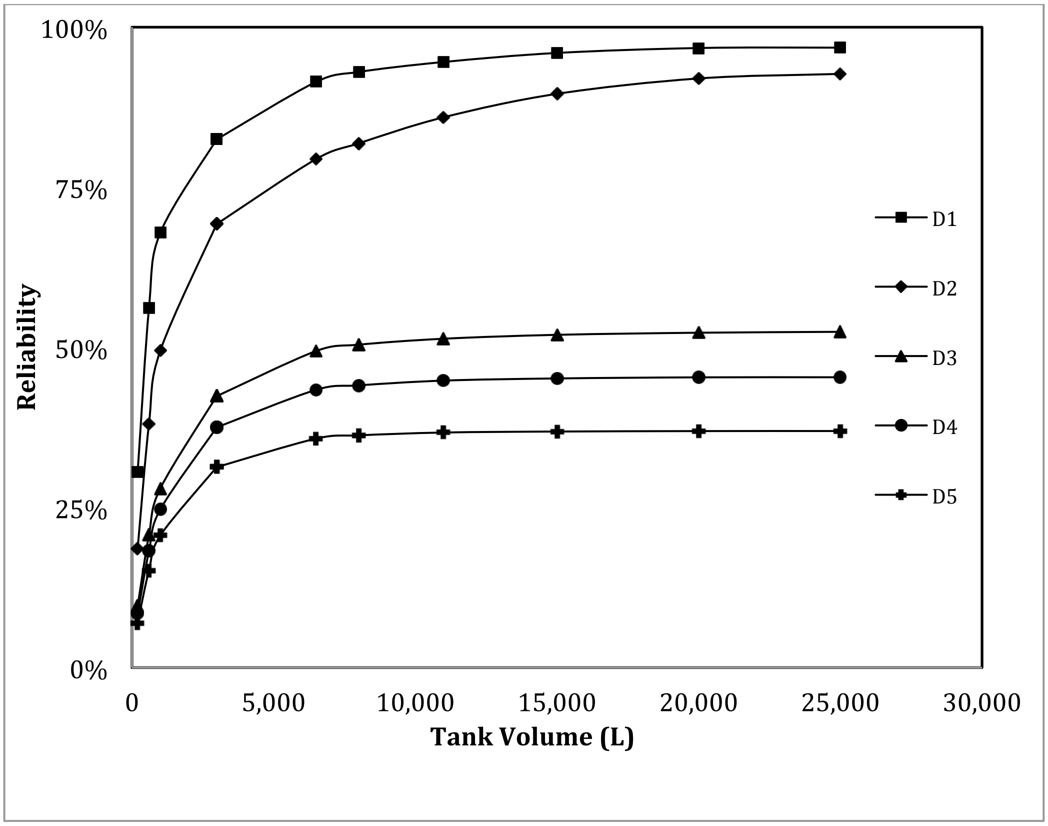

Figure 2- Windsor Rainwater Tank Reliability

Table 5- Windsor Factor Equations

Windsor, Ontario		
Small tanks (< 3,000 L)		
Demand	**Equation**	**R^2**
1	$F = 1$	1.00
2	$F = -8^{-6x^2} + 0.003\,x + 0.7849$	1.00
3,4,5	$F = -2^{-5x^2} + 0.0076\,x + 0.4569$	1.00
Large Tanks (> 3,000 L)		
Demand	**Equation**	**R^2**
1	$F = 1$	1.00
2	$F = -5^{-5x^2} + 0.0126\,x + 0.1893$	0.97
3,4,5	$F = -3^{-5x^2} + 0.0.0139\,x - 0.1191$	1.00

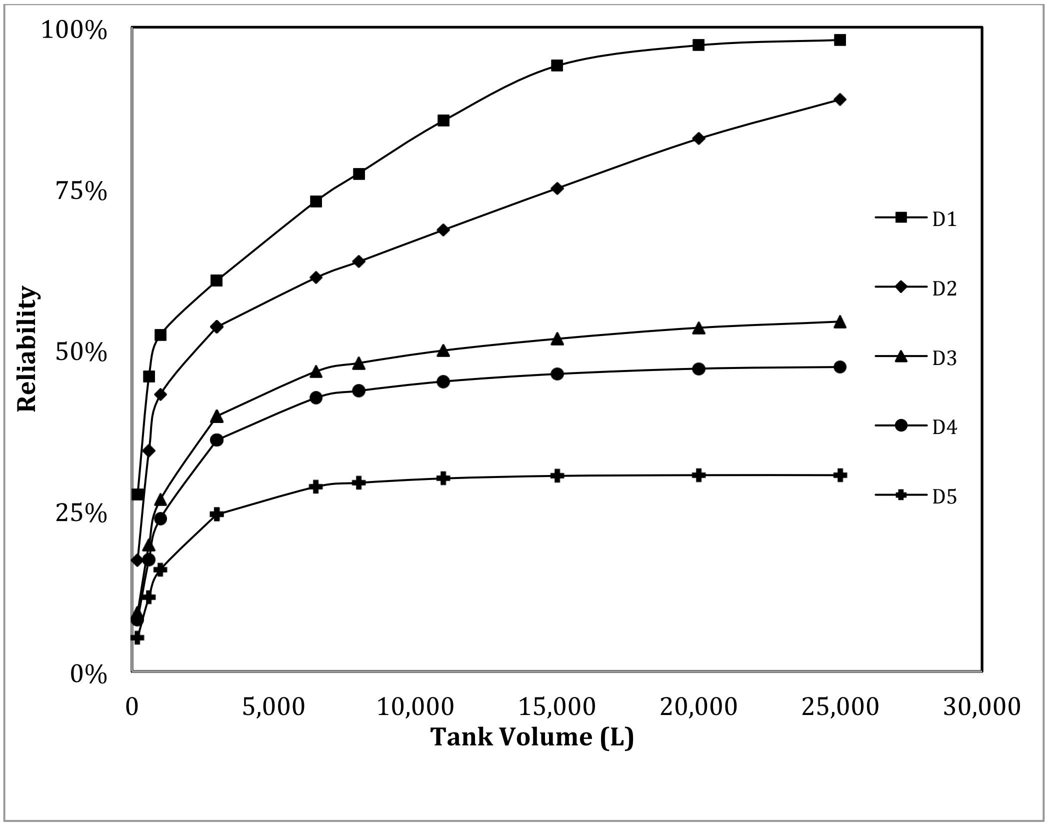

Figure 3 - Quebec City Rainwater Tank Reliability

Table 6- Quebec City Factor Equations

Quebec City, Quebec		
Small tanks (< 3,000 L)		
Demand	**Equation**	R^2
1	$F = 1$	1.00
2	$F = -1^{-5x^2} + 0.0031\,x + 0.8052$	0.98
3,4,5	$F = -2^{-5x^2} + 0.0067\,x + 0.5413$	1.00
Large Tanks (> 3,000 L)		
Demand	**Equation**	R^2
1	$F = 1$	1.00
2	$F = -2^{-5x^2} + 0.0062\,x + 0.6062$	0.95
3,4,5	$F = -5^{-5x^2} + 0.0169\,x - 0.1845$	1.00

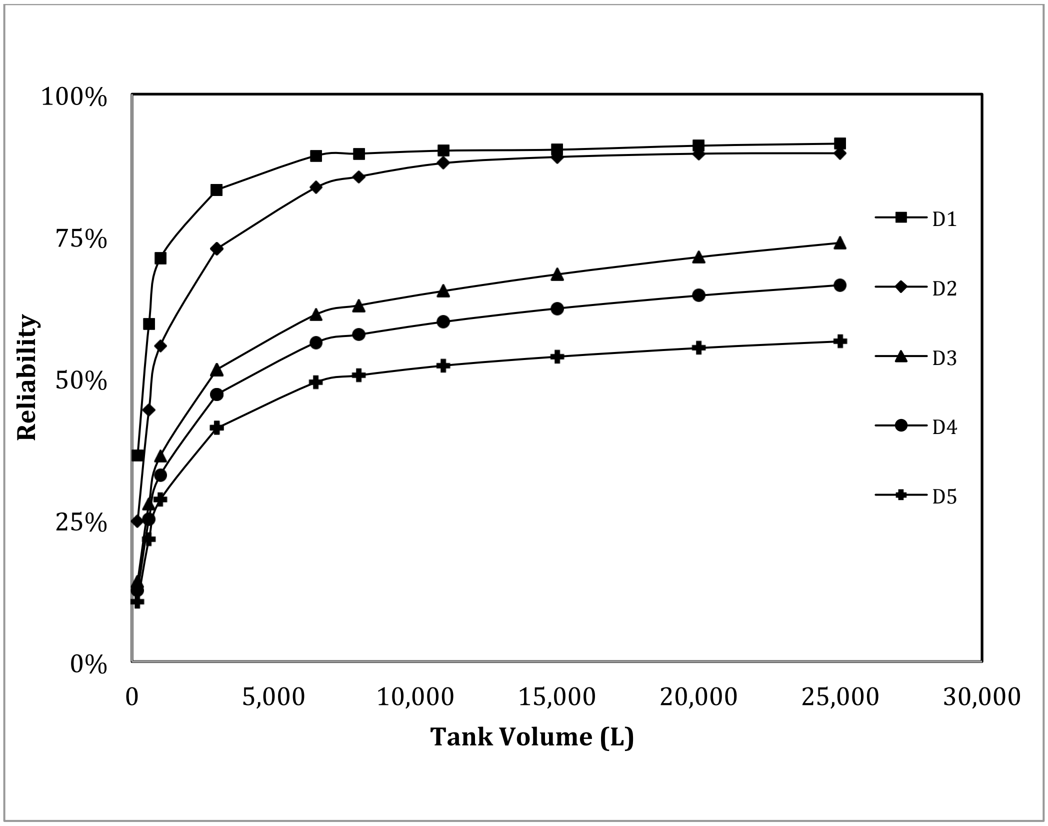

Figure 4- Vancouver Rainwater Tank Reliability

Table 7- Vancouver Factor Equations

Vancouver, British Columbia		
Small tanks (< 3,000 L)		
Demand	**Equation**	**R^2**
1,2	$F = 1$	1.00
3,4,5	$F = -2^{-5x^2} + 0.0054\,x + 0.6464$	0.99
Large Tanks (> 3,000 L)		
Demand	**Equation**	**R^2**
1,2	$F = 1$	0.95
3,4,5	$F = -4^{-5x^2} + 0.0133\,x + 0.0579$	1.00

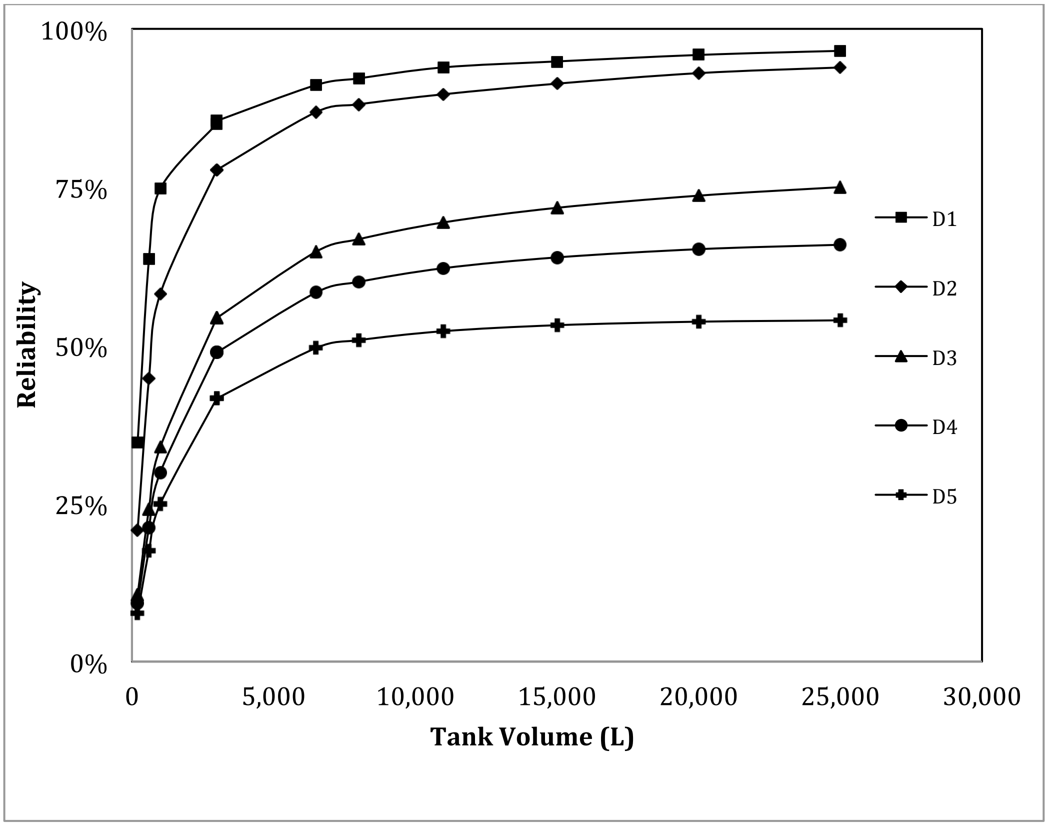

Figure 5- Shearwater Rainwater Tank Reliability

Table 8-Shearwater Factor Equations

Shearwater, Nova Scotia		
Small tanks (< 3,000 L)		
Demand	**Equation**	**R^2**
1	$F = 1$	1.00
2	$F = -1^{-5x^2} + 0.0036\,x + 0.7656$	0.99
3,4,5	$F = -2^{-5x^2} + 0.0064\,x + 0.5477$	1.00
Large Tanks (> 3,000 L)		
Demand	**Equation**	**R^2**
1	$F = 1$	1.00
2	$F = -2^{-5x^2} + 0.0048\,x + 0.706$	0.90
3,4,5	$F = -5^{-5x^2} + 0.0161\,x - 0.1464$	1.00

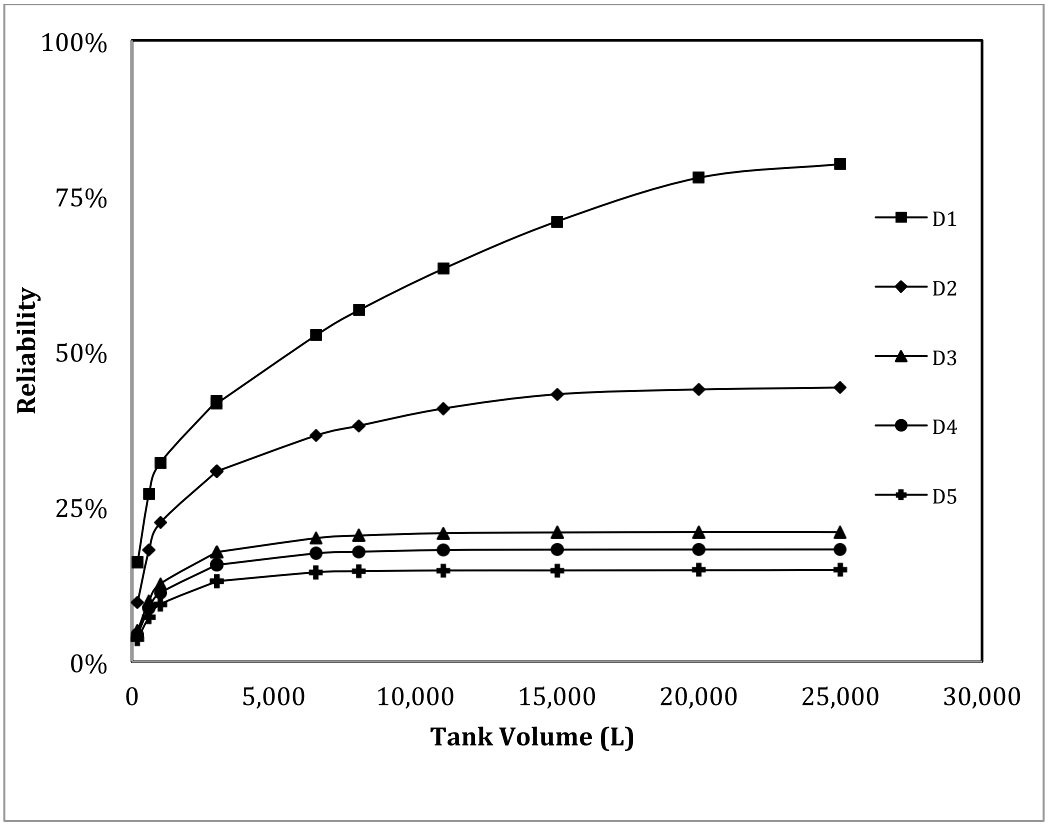

Figure 6- Calgary Rainwater Tank Reliability

Table 9- Calgary Factor Equations

Calgary, Alberta		
Small tanks (< 3,000 L)		
Demand	**Equation**	**R^2**
1	$F = -8^{-6x^2} + 0.003\,x + 0.7849$	1.0
2	$F = -2^{-5x^2} + 0.0072\,x + 0.4992$	1.0
3,4,5	$F = -2^{-5x^2} + 0.0089x + 0.3509$	1.0
Large Tanks (> 3,000 L)		
Demand	**Equation**	**R^2**
1	$F = -4^{-5x^2} + 0.0126\,x + 0.1404$	1.0
2	$F = -4^{-5x^2} + 0.0149\,x - 0.0796$	1.0
3,4,5	$F = -2^{-5x^2} + 0.0125x - 0.0677$	1.00

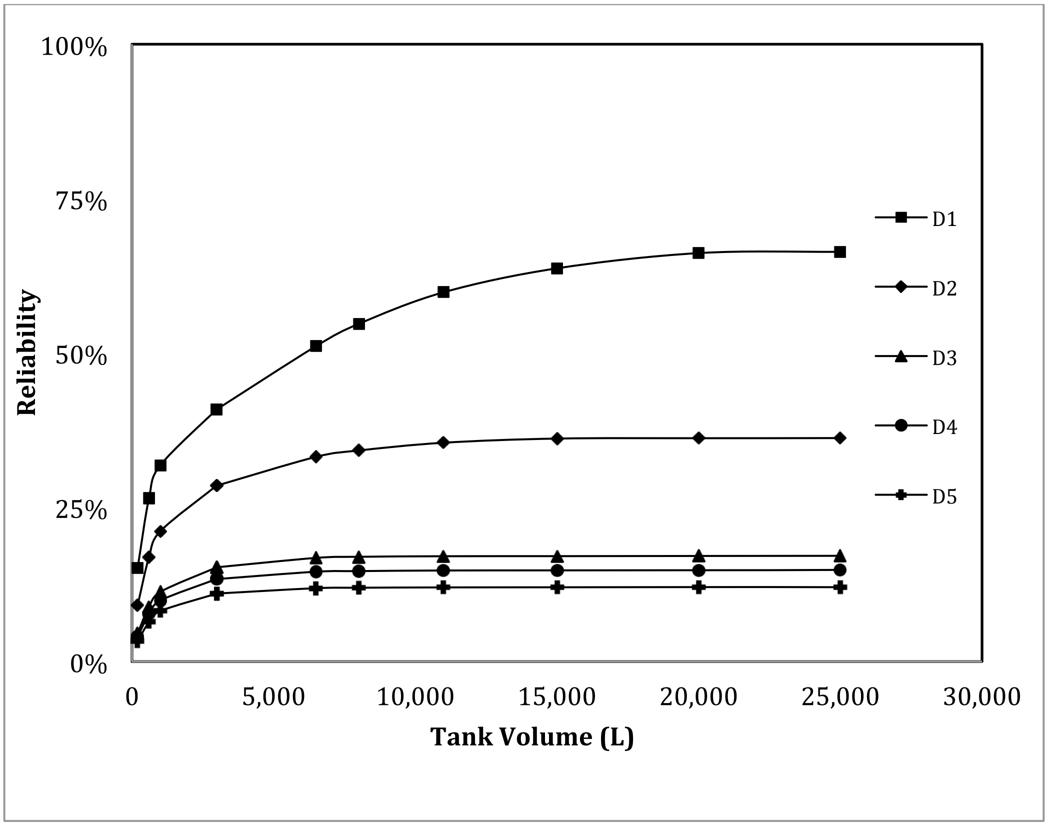

Figure 7- Saskatoon Rainwater Tank Reliability

Table 10- Saskatoon Factor Equations

Saskatoon, Saskatchewan		
Small tanks (< 3,000 L)		
Demand	**Equation**	**R^2**
1	$F = -2^{-5x^2} + 0.0063\,x + 0.5573$	1.00
2	$F = -2^{-5x^2} + 0.0086\,x + 0.3907$	0.99
3,4,5	$F = -4^{-5x^2} + 0.0126\,x + 0.0952$	1.00
Large Tanks (> 3,000 L)		
Demand	**Equation**	**R^2**
1	$F = -4^{-5x^2} + 0.0145\,x - 0.026$	1.00
2	$F = -2^{-5x^2} + 0.0125\,x - 0.0017$	0.90
3,4,5	$F = -8^{-6x^2} + 0.011\,x - 0.0228$	1.00

There is a significant reduction in reliability when the daily use rate is increased from 171 to 363 L/Day in Toronto, Windsor, and Quebec City. Large tanks, greater than 20,000 L, in the Ontario and Quebec region can only meet 30-50% of water demands greater than 360 L/Day. Large tanks in water-rich areas in Canada, such as Vancouver and Shearwater, can meet 60-70% of these demands. Vancouver and Shearwater, due to their excessive precipitation, show significant increases in demand satisfaction as tank volumes increase up to 25,000 L; unlike Ontario and Quebec whose efficiencies plateau at the 7,000 L tank volume. Water-poor areas in Canada, such as the Prairies, have different trends; with significant drops in reliability between the 93 L/Day to the 171 L/Day and further to the 363 L/Day water demand levels. Despite being on the eastern and western coasts, Shearwater and Vancouver share similar rainwater harvesting reliability trends. Toronto and Windsor, and Calgary and Saskatoon also share similar trends; these similarities were expected as each couple of cities share similar geographic characteristics.

Continuous simulations using a daily time step were also conducted and compared with hourly time steps' results. Graph 8 exemplifies the difference in results obtained from using a daily or hourly time step in continuous simulations. The results are obtained for a 100 m^2 roof in Toronto using a D5 water demand. It is evident that the daily time-step overestimates the reliability by 35-45% for all tank volumes.

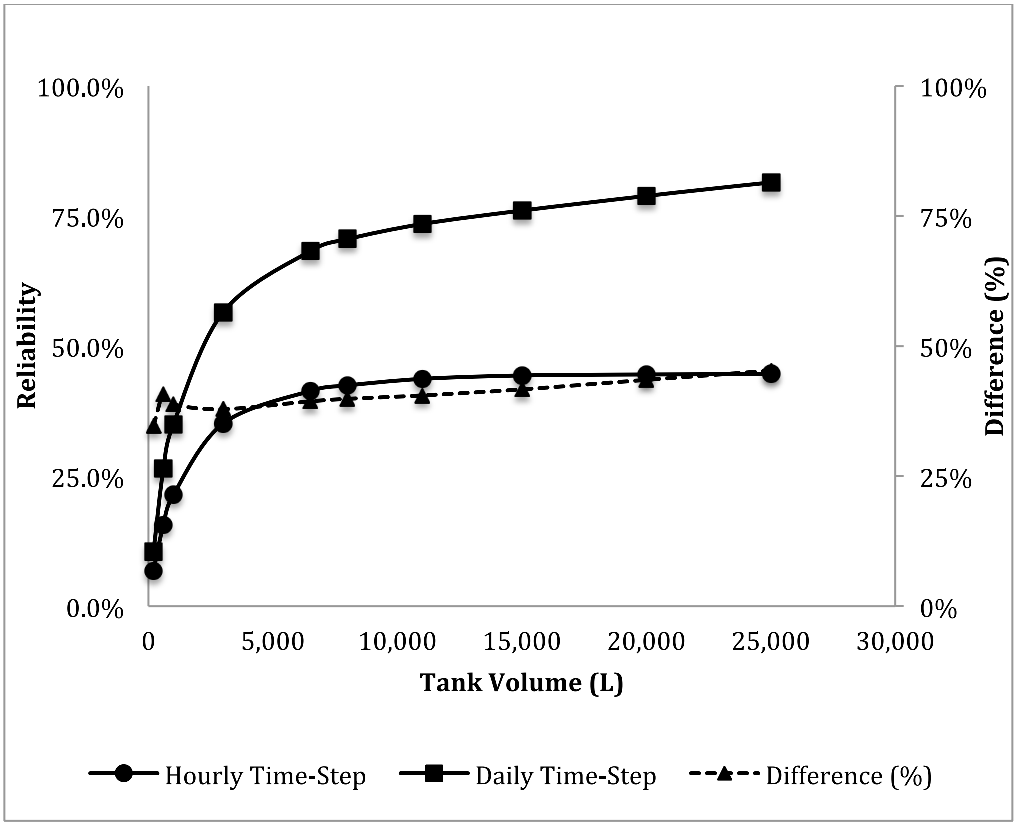

Figure 8- Comparison of hourly and daily steps for RWH continuous simulations, for a 100 m^2 home with a 516 L/day demand

2.4 Application of Results

Providing the proficiency information for all tank volumes, rather than just the most effective volume, empower the users to make a decision that best suits their needs. The resulting wide range of information allows for all stakeholders to be engaged in the tank volume selection process. The combination of the graphs and equations offers a new approach to tank volume optimization. The visual representation provides an immediate perspective of tank efficiencies and the simple equations can be used to calculate a more precise estimate of reliability in order to forecast water savings for homeowners. The tools provided in this paper are versatile and compatible for almost any possible house sizes and tank volumes.

Homeowners can now easily estimate RWH reliability for the various water uses and the various household variables. The user-inputted roof size in addition to the hourly time-step allows for a more precise estimate than what are provided by earlier studies. The distinction in water use rates between efficient and traditional laundry machines encompasses all homes and provides an outlook on the significant water savings due to water-efficient appliances. The tools provide Canadian homeowners with the resources to decide on the tank volume size along with how to best use the collected rainwater.

Various other stakeholders can also use the tools provided. For example, municipalities and policy-makers can forecast the decline in water consumption trends due to the implementation of large-scale residential RWH systems. A comparison of the various tanks' behaviours for different rainwater uses can support decisions regarding appropriate incentives for RWH projects. The model's flexibility allows a municipality to estimate reduction in municipal water supplied for the majority of home sizes within its district. Policy makers and municipal engineers can more precisely forecast the impact on water treatment plants and wastewater treatment plants.

Developers can incorporate RWH tanks in new homes as a selling advantage for buyers. The five demand types discussed in this paper do not require extensive water treatment, making integration of RWH infrastructure into new or existing homes a cost-effective method that yields long-term environmental and financial incentives.

Communicating to potential homebuyers the water savings and reduction in water bills due to the RWH system adds an incentive for customers.

Tank manufacturers can design tank sizes for different cities and markets based on the reliability rates and rainwater uses. Knowing the reliability of the different tank volumes, manufactures can produce the most cost-effective tanks. The graphs and equations are capable of providing information catered to the specific needs of the buyers, allowing retailers to advertise their reliability to increase sales. The tools provided in this paper allow the various players to better understand the behaviour of RWH collection tanks; consequently, advancing RWH initiatives and strategies.

2.5 Conclusions

This study provides application-oriented results that encourage homeowners to make a well-informed decision regarding rainwater harvesting tank volumes. The graphs provide an overview of tank reliability in a user-friendly manner. The flexibility of the tools provided in this paper makes them ideal for various participants, providing specific statistics useful for forecasting the RWH tank behaviour in meeting residential water demands. The graphs and equations empower the various beneficiaries to better understand the linkage between rainwater collection and reduction in municipal water consumption.

The mix of graphs and equations best communicate the tanks' reliability in meeting various rainwater use rates for various tank sizes in a concise form that still lets the user visually see the trends. Despite Canada's climatic and geographic diversity, there are common trends within regions. The accessibility and ease of interpretation of the graphs raise awareness of the water savings associated with RWH tanks, motivating homeowners to implement rainwater-harvesting technologies at the residential level. The use of hourly time-steps minimizes inaccuracies and provides a more representative model.

Acknowledgements

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Chapter 3: Comparison of Two Methods for the Analysis and Design of Rainwater Harvesting Systems

Keyword: Rainwater Harvesting, Continuous Simulations, Probabilistic methods, Canadian Climate, Rainfall Characteristics

Abstract

Computer simulations or use of analytical equations can be used to model the performance of rainwater harvesting (RWH) systems. The analysis and comparison of RWH systems of seven Canadian cities with different rainfall patterns provide a representative foundation for cities across Canada. Results obtained from the analytical method are compared to those from computer simulations. The accuracy of the analytically derived equations can thus be determined. The paper also investigates the goodness-of-fit of the theoretical exponential distributions to the observed relative frequencies of the rainfall event volume, duration and inter-event time, as the analytically derived equations are only valid when these rainfall event characteristics follow approximately exponential distributions.

3.1 Introduction

The global water shortages caused by increasing water demands and urban flooding caused by the increase in severe rainstorms are two main concerns in sustainable urban development (Villarreal and Dixon, 2005). Rainwater harvesting (RWH) has proven to have the ability to reduce urban flooding and increase potable water savings (Cheng et al., 2009; Angrill et al., 2012). The design of RWH systems is largely dependent upon the ability to model supply, storage, and demand effectively. It is because of the dynamic relationships between these three factors that challenges arise when planning for and design the details of residential RWH systems (Fulton et al., 2012). This paper aims to compare two methods for the modeling of the operation of RWH systems: computer simulation and the use of analytical equations. The analytical equations are derived by Guo and Baetz (2007). This paper determines the accuracy and the most suitable scope of the analytical equations for typical Canadian climates.

Computer simulations use historical daily or hourly rainfall as input to replicate continuously time step-by-step the processes of runoff generation from a residential roof, collection of runoff into a rainwater tank, and consumption of rainwater from the tank for a long period of time. That is why this method is commonly referred to as continuous simulation. Continuous simulations have been widely used to model the reliability of rainwater harvesting systems: e.g., Australia (Jenkins, 2007), USA (Abi Aad et al., 2000), China (Jia et al., 2012), France (Petrucci et al., 2011), and Kuwait (Zaghloul and Al-Mutairi, 2007).

The analytical method is based upon rainfall statistics obtained from the analysis of the long-term historical rainfall data; these statistics provide the basic information needed to represent local climate conditions, particularly rainfall event and dry period patterns. Statistics are used in the analytical equations as if the long-term historical rainfall data are inputted into the computer simulation models. The analytical equations are simpler to use because much less information is required to operate them in comparison to the years of rainfall data and software needed for continuous simulations. Similar analytical equations have also been derived for various storm water management applications: the sizing of cisterns to collect rainwater from agricultural fields for crop use during dry periods (Lee et al., 2000), storage and overflow of sewage treatment plants (Howard, 1976), stream runoff (Di Toro and Small, 1984), storm water detention storage (Loganathan and Delleur, 1984), design of sewage lagoons (Cruise and Singh, 1988), wash-off of pollutants on urban watersheds (Barbe et al., 1996), storm water treatment systems (Small and Di Toro, 1979), and urban storm water management (Adams and Papa, 2000; Guo and Adams, 1999).

A comparison of the results from the two methods for seven Canadian cities provides the evidence to determine in which climatic conditions the analytical method is appropriate and delivers accurate results. This paper first provides the analysis and results of the continuous simulation method for determining RWH reliability in the seven Canadian cities studied. Secondly, the paper examines the goodness-of-fit of the exponential distributions of the seven cities' rainfall event characteristics (storm duration, volume, and inter-event time) to determine which cities are suitable for the use of the analytical method, since exponentially distributed sets of rainfall events and inter-event dry periods are required so that the analytical method can provide accurate results. The analytical equations derived by Guo and Baetz (2007) are then used to calculate the reliability obtained from a specific rainwater collection system, the minimum tank volume needed to achieve a required reliability, and the maximum reliability obtainable for a specified water demand. A comparison is conducted between the results obtained from the analytical and continuous simulation methods to determine the validity of the analytical method. The comparison and conclusions made provide users with the tools to determine which method is best suited for their environment. All the comparisons were conducted for tanks less than 2,000 L as smaller tanks are more popular among consumers and are readily available at retailers.

3.2 Continuous Simulations

Continuous simulations are conducted using the EPA’s (U.S. Environmental Protection Agency) SWMM (Storm Water Management Model) 5.0 software. The software is a flexible tool and is well suited for representing rainwater collection and usage with its built-in LID-Rain-Barrel feature (Elliott et al., 2007). An hourly time-step is used to ensure a precise estimate of the tank’s behaviour and capacity to meet residential demands (Coombes et al., 2002). Hourly rainfall data for the 7 selected cities were obtained from the Digital Archive of Canadian Climatological Data. The data were presented in an HLY (Hourly Weather) format, which SWMM 5.0 is readily capable of interpreting. Precipitation data of non-winter months were inputted into simulation models; the lengths of data all exceed the 30-year threshold needed to minimize modeling inaccuracies (Mitchell et al., 2008). More information regarding the 7 rain gauge stations is available in Table 1.

Table 1- Rain Gauge Stations

City, Province	Station Name	Station ID	Time period	Duration (years)
Calgary, AB	Calgary Int’l A	3031093	1960-1999	40
Quebec, QC	Quebec Int’l A	7016294	1961-1995	35
Toronto, ON	Toronto Int'l A	6158733	1960-2003	44
Saskatoon, SK	Saskatoon A	4057120	1960-1993	33
Shearwater, NS	Shearwater A	8205090	1955-1999	45
Vancouver, BC	Vancouver Int’l A	1108447	1960-1999	40
Windsor, ON	Windsor A	6139525	1960-2003	44

The SWMM model contains 5 catchment areas, each representing a 100 m^2 residential roof collecting rainfall and diverting it to the SWMM LID-Rain-Barrel function. Table 2 outlines the properties of the catchment areas. During a simulation, each of the 5 catchment areas is attached to a different RWH tank volume: 200, 600, 1000, 2000, or 3,000 L.

Table 2- SWMM Catchment properties

Property	Definition	Value
% Slope	Average surface slope (%)	50
% Imperv	Impervious area (%)	100
N-Imperv	Manning for impervious area	0.0115
N-Perv	Manning for pervious area	0.1
D store-Imperv	Depression storage for impervious area (in)	0
D Store – Perv	Depression storage for impervious area (in)	0
%Zero-Imperv	Impervious area with no depression storage (%)	100
% Routed	Runoff routed between sub areas (%)	100

The water use rates are based on a 3-person household, as shown in Table 3. All 5 water use rates do not require extensive treatment or infrastructure changes (Farakhakhsh et al., 2008), making them ideal for existing and new homes.

Table 3- Rainwater Demands

Demand Name	Demand Type	Daily Demand (L/Day)
D1	Toilet Flushing	93
D2	Toilet and Outdoor Uses	171
D3	Toilet, Outdoor Uses, and water-saving Laundry	363
D4	Toilet, Outdoor use, and Laundry	420
D5	All Indoor & Outdoor uses except drinking water	516

The reliability of a RWH system is defined as the fraction (or percentage) of time when demands are satisfied by water collected in the storage unit (Guo and Baetz, 2007). The SWMM simulations provide the total volume of water consumed from the rainwater collection tanks; and based on the required demand rate, the reliability was calculated from the continuous simulations as the ratio between the volume of water consumed from the rainwater tank and the total demand volume. The minimum tank volume required to achieve a desired reliability was calculated based on the reliability obtained from the continuous simulations conducted and through trial-and-error of different tank volumes. The maximum reliability obtainable is calculated through modeling tanks large enough to hold 40 years of precipitation of any of the seven cities.

3.3 Exponential Distributions

The Guo and Baetz (2007) analytical equations for calculating RWH reliabilities were derived following similar approaches pioneered by Howard's (1976) for calculating the frequency and volume of sewage spills. Howard's equations were developed using the derived probability distribution theory and assumed that storm parameters (i.e. intensity or volume of rainfall, duration, and dry time between storms) are independent and exponentially distributed random variables. Hence, prior to utilizing the Guo and Baetz (2007) equations, verification is needed to ensure that the storm characteristics of the seven Canadian cities in this study follow exponential distributions.

Developing a probabilistic model of storm characteristics requires historical rainfall records to be divided into discrete rainfall events. The criterion for distinguishing between events is the chosen minimum duration of time without rainfall, referred to as the inter-event time definition (IETD) (Guo and Baetz, 2007). The IETD chosen for an urban catchment should be greater than the catchment's response time, but not too large to merge consecutive rainfall events into one. An objective IETD is one which when increased further does not result in significant changes to the number of annual rainfall events (Guo and Adams, 1998). A comparative analysis was conducted to observe the impact of IETD on number of annual events and the most appropriate minimum IETDs were selected as shown in Table 4.

Table 4-Rainfall Event Statistics

City	IETD (hrs)	$\bar{v}$ (mm)	$\bar{t}$ (hrs)	$\bar{b}$ (hrs) (Modified)	$\bar{b}$ (hrs) (Unmodified)
Calgary	7	8.3	9	228.8	172.0
Quebec City	7	11.7	10.6	140.2	121.2
Toronto	6	9.3	8	128.0	104.9
Saskatoon	7	7.3	7.6	236.3	180.6
Shearwater	7	14.5	10.7	123.1	108.5
Vancouver	9	12.32	16.63	95.3	80.3
Windsor	7	8.13	7.03	131.4	110.0

Rainfall periods separated by a dry time interval less than the selected IETD are included in the same storm event; rainfalls separated by a dry time interval longer than the selected IETD are categorized as separate events. Each separate rainfall event is characterized by its duration (t), rainfall depth (v) and inter-event time (b, i.e., the dry time preceding the current event). After running a SWMM simulation, the SWMM program provides a table listing all storms with respective duration, volume of rainfall, and duration of dry periods between storms. These SWMM outputs are used in our event-based rainfall frequency analysis. Rainfall events of a depth less than 1 mm were excluded from the analysis to ensure that moderate and large storms are properly represented in the histograms and fitted exponential distributions. This omission of extremely small storms can be justified as rainfall volume of 1.0 mm or less results in a negligible amount of runoff. A frequency analysis of the events' characteristics (i.e., *t, v,* and *b*) was conducted to construct histograms and fit probability density functions. Histograms with fitted exponential distribution functions were prepared to determine the goodness-of-fit of the exponential distributions. The distribution parameters and functions are provided in Table 5. The values of the three distribution parameters, ζ, λ, and ψ, are estimated from $\bar{v}$, $\bar{t}$, and $\bar{b}$; where $\bar{v}$ = average event depth (mm), $\bar{t}$ = average event duration (days), and $\bar{b}$ = average inter-event time (days). For locations throughout Canada, the values of the distribution parameters can be found in Adams and Papa (2000); for locations throughout the United States, they can be found in Wanielista and Yousef (1993), Driscoll et al. (1989), or USEPA (1986). The values reported in these references are based on rainfall data that are not up to date.

Table 5-Probabilistic Model of Local Rainfall Characteristics

Rainfall event characteristic	Exponential probability density function	Distribution parameter
Depth, *v* (mm)	$f_V(v) = \zeta e^{-\zeta v}$	$\zeta = \frac{1}{\bar{v}}$
Duration, *t* (days)	$f_T(t) = \lambda e^{-\lambda t}$	$\lambda = \frac{1}{\bar{t}}$
Interevent time, *b* (days)	$f_B(b) = \psi e^{-\psi b}$	$\psi = \frac{1}{\bar{b}}$

To maintain the continuity of this paper and ensure an effective comparison between the continuous simulation and analytical methods, the distribution parameters for the seven cities were calculated from the results obtained from SWMM continuous simulations. As mentioned earlier, the SWMM Statistics feature provides the event volume, duration and inter-event time of all storms. The statistics software program R was used to remove all storms below the 1.0 mm event volume threshold. The duration of an omitted storm and its inter-event time are added to the subsequent storm's inter-event time, hereinafter this is referred to as the modified inter-event time. Unmodified inter-event times are simply the original values with storms less than 1 mm still treated as separate storms. The analytical method was tested using both the modified and unmodified parameter values for inter-event times. The R software was used to calculate the average event volume, duration, and inter-event time, as provided in Table 4, and also provided the histograms and fitted exponential distribution functions. The coefficients of determination, R^2, values of the exponential distribution functions of all 7 cities for all 3 rainfall event characteristics were high enough demonstrating a satisfactory goodness-of-fit, as shown in Table 6. This goodness-of-fit obtained agree in general with tests conducted previously (Eagleson, 1972, 1978; Howard, 1976; Adams and Bontje, 1984; Adams et al., 1986).

Table 6- R^2 values for the exponential distribution functions

City	R^2 Inter-event time	R^2 Duration	R^2 Volume
Calgary	0.93	0.95	0.91
Quebec City	0.89	0.94	0.96
Toronto	0.94	0.93	0.96
Saskatoon	0.95	0.95	0.90
Shearwater	0.92	0.88	0.95
Vancouver	0.91	0.91	0.96
Windsor	0.94	0.94	0.96

The histograms and fitted exponential distributions for Calgary, Quebec City, and Vancouver are provided in Figure 1-9. The Saskatoon histograms and fitted exponential distributions are not provided as they follow the same trends as the Calgary's. The Shearwater histograms followed the same trends as Halifax's histograms reported by Li (2007) and Windsor's frequency distribution followed that of Detroit (Zhang and Guo, 2013). The Toronto graphs were also similar to previous researchers' graphs (Guo and Adams, 1998).

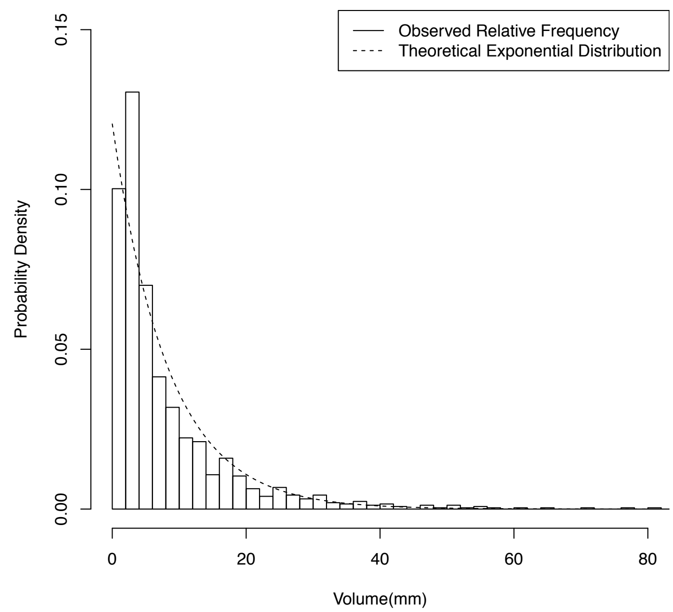

Figure 1-Histogram and PDF of rainfall event volume (Calgary, rainfall events >1mm)

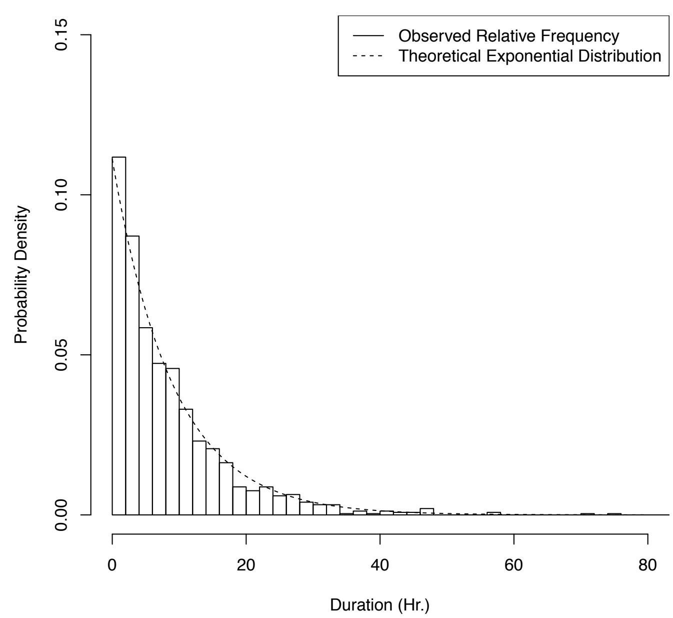

Figure 2-Histogram and PDF of rainfall event Duration (Calgary, rainfall events >1mm)

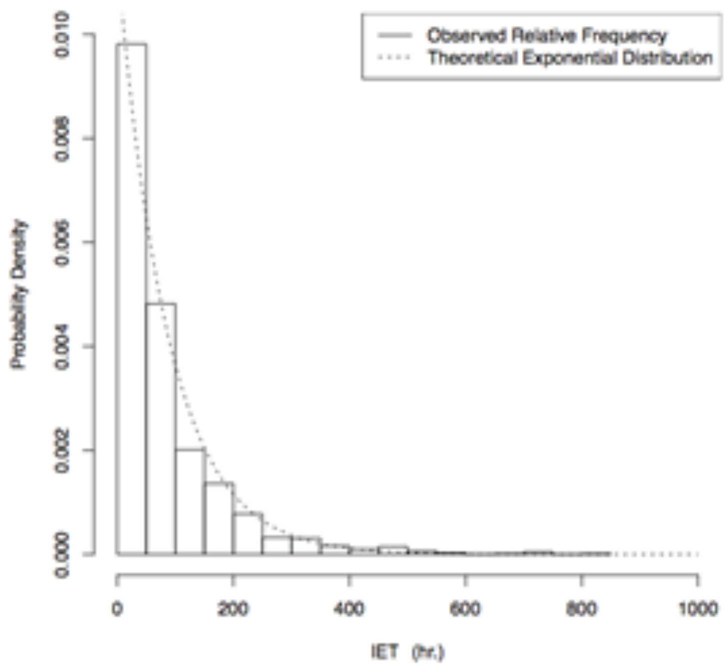

Figure 3- Histogram and PDF of rainfall event interevent time (Calgary, events volume>1mm)

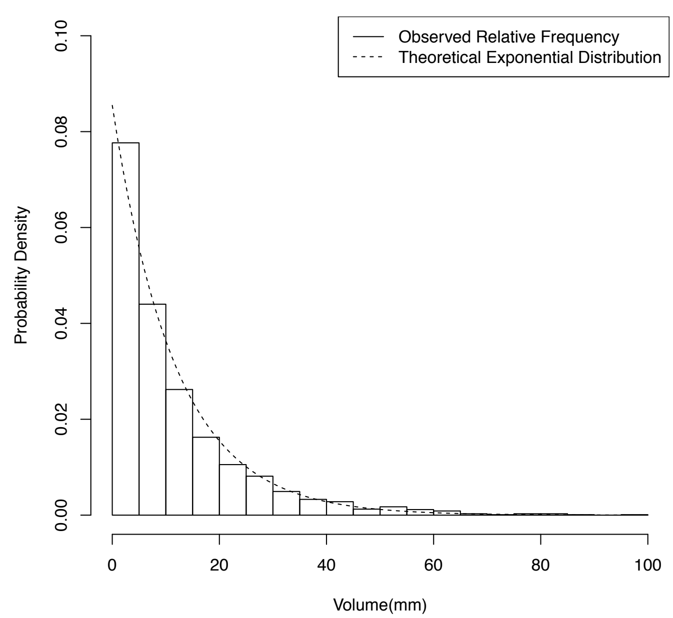

Figure 4-Histogram and PDF of rainfall event volume (Quebec City, rainfall events volume >1 mm)

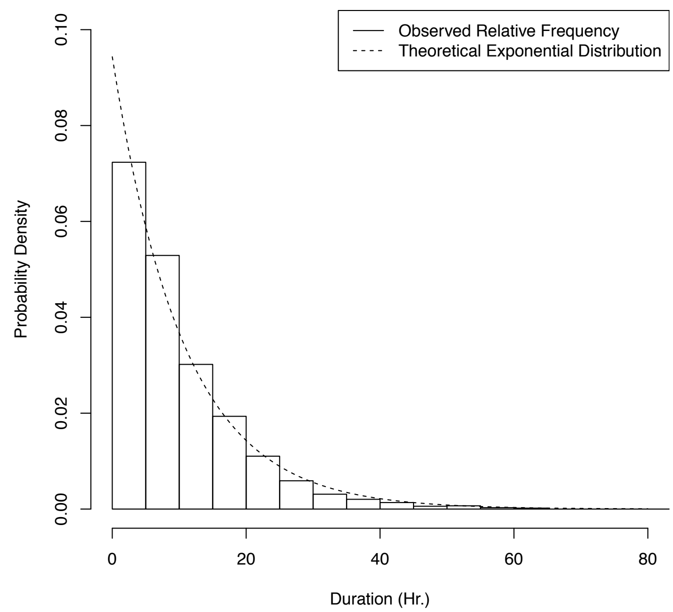

Figure 5- Histogram and PDF of rainfall event duration (Quebec City, rainfall events volume >1 mm)

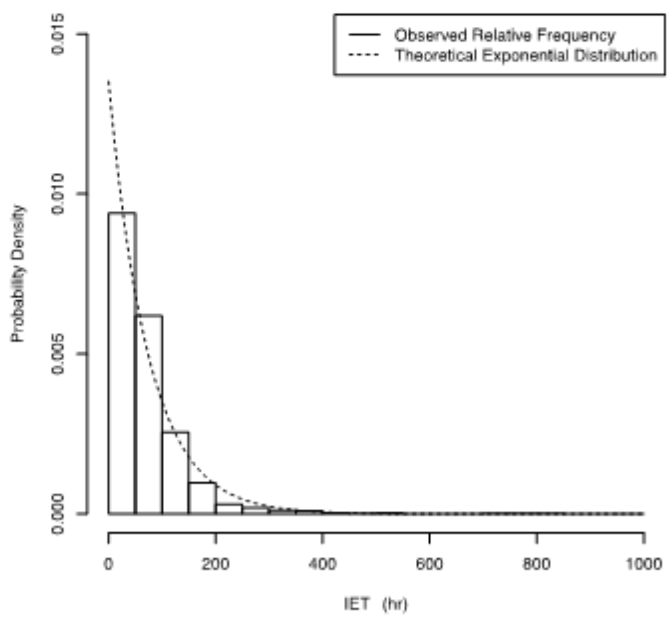

Figure 6- Histogram and PDF of rainfall even interevent time (Quebec City, rainfall events >1mm)

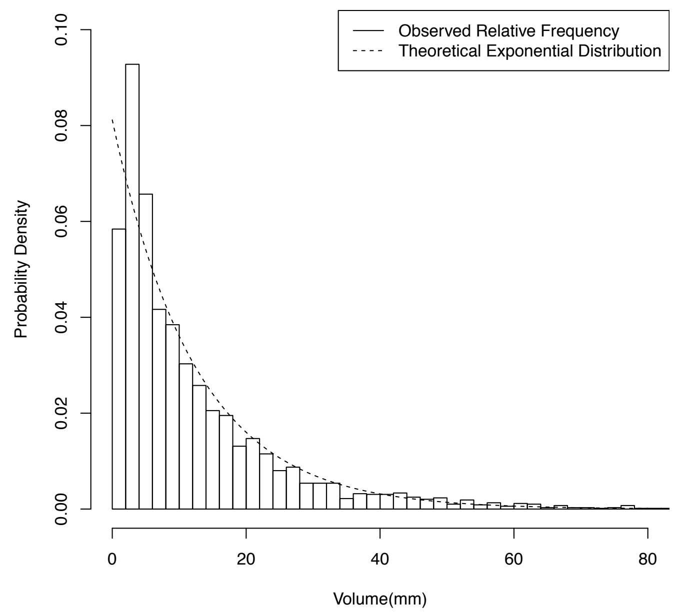

Figure 7- Histogram and PDF of rainfall event volume, Vancouver, rainfall events > 1mm)

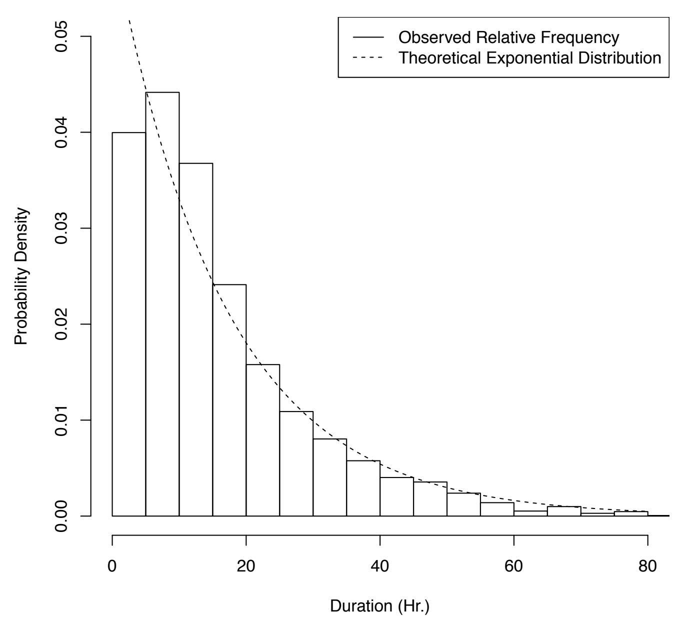

Figure 8- Histogram and PDF of rainfall event duration (Vancouver, rainfall events >1mm)

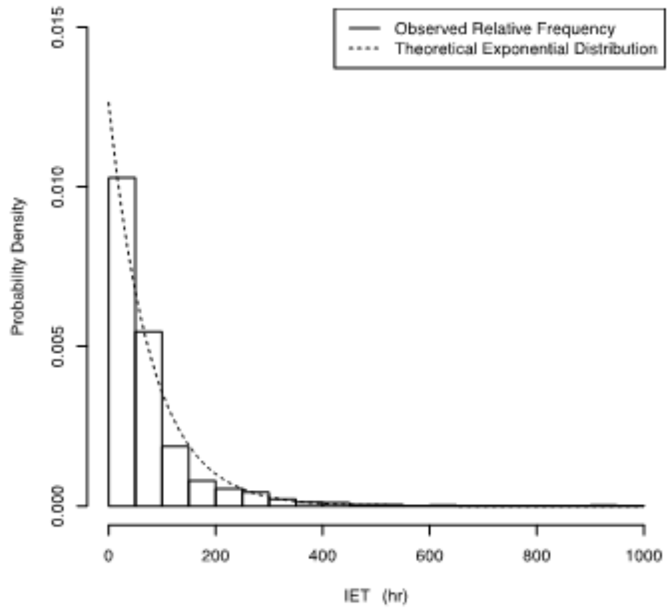

Figure 9- Histogram and PDF of rainfall event interevent time (Vancouver, rainfall events >1mm

3.4 Analytical Equations

The Guo and Baetz (2007) reliability equations focus on the use/load cycles starting from the beginning of a dry period of duration *b*, followed by a rainfall event with duration *t* and depth *v*. For each individual cycle, the exact *b, t,* and *v* values are treated as random realizations from their respective probability distributions. The expected value of a variable of interest for a random cycle is derived by considering the functional relationships between related variables and incorporating the probability density functions listed in Table 5**.** From the expected values, the annual totals are determined as the product of the average number of cycles contained in a year and the expected values per cycle. Guo and Baetz (2007) derived the expected value of the volume of runoff (v_r) generated from a roof per rainfall event (denoted as $E(v_r)$).

$$E(v_r) = \frac{\phi}{\zeta} e^{-\zeta v_{ff}} \tag{1}$$

Where v_r = volume of runoff (mm), v_{ff} = volume of first flush (mm), ϕ = runoff coefficient, ζ = rainfall event volume distribution parameter.

With further derivations, Guo and Baetz (2007) determined that the maximum use rate G_{max} that may be provided by a storage unit of infinite size for a reliability of R_e is:

$$G_{max} = \frac{A\phi\psi}{\zeta R_e} e^{-\zeta v_{ff}} \tag{2}$$

Where A = roof size (m^2), ψ = inter-event time distribution parameter

The quantity of rainwater that can be actually collected and subsequently used needs to be determined in order to estimate the required storage volume for a desired use rate and reliability. To do so, the total volume that is spilled from the storage unit, due to excess rain and the limited size of a storage unit, needs to be determined first. The estimation of the annual total spill volume is solved as an urban storm water management problem. The roof area corresponds to an urban catchment and the storage unit corresponds to an urban runoff storage reservoir. There are two main differences between the two systems that need to be accounted for. Firstly, no use of water from the rainwater storage unit is necessary during rainfall events; there are only withdrawals during dry periods. Secondly, the rainwater storage units may be designed to bypass the initial volume of runoff, known as first flush, while urban reservoirs are designed to capture and detain the more polluted first flush. Guo and Baetz (2007) modified previous procedures for estimating spill volumes from runoff control reservoirs developed by Adams and Papa (2000), Howard (1976), Di Toro and Small (1979), and Guo and Adams (1999) to adequately meet the constraints of a RWH system.

The use/load cycle starting from the beginning of a dry period and the end of the following rainfall event was analyzed to determine the annual total spill volume. The inter-event times, durations, and depths comprising each use/load cycle were treated as statistically independent and exponentially distributed random variables. The aim is to determine the probability per cycle of a spill volume equalling or exceeding a given value using the derived probability distribution theory (Benjamin and Cornell 1970). Guo and Baetz (2007) derived that the probability per cycle that some spill occurs (i.e. $P > 0$ where P is the volume of spill), denoted as $G_p(0)$, is given by

$$G_p\ (O) = \left(\frac{A\phi\psi}{A\phi\psi+\zeta G} + \frac{\zeta G}{A\phi\psi+\zeta G} e^{-\frac{\zeta B}{A\phi}-\frac{\psi B}{G}}\right) e^{-\zeta v_{ff}} \tag{3}$$

where G = water use rate (L/Day), B = tank volume (L)

Further derivations by Guo and Baetz (2007) yielded the expected value of the spill volume per cycle as:

$$E[p] = \frac{A\phi}{\zeta}\ G_p(0) \tag{4}$$

The annual total volume collected into the storage unit and utilized subsequently is denoted as R_c and it is calculated based on the annual total volume of runoff collected from the roof with diversion of first flush (R_a) minus the annual total spill volume:

$$R_c = R_a - \theta\ E[P] = \frac{A\phi\theta}{\zeta}\left[e^{-\zeta v_{ff}} - G_p(0)\right] \tag{5}$$

Where θ = average number of rainfall events per year.

Guo and Baetz (2007) also developed equations for calculating various measurements needed for designing rainwater collection systems. For the purpose of this paper, the following three equations were used to compare analytical results with those from continuous simulations. The first equation to be analyzed calculates the storage tank's reliability based on a given tank volume and the desired water demand rate:

$$R_e = \frac{A\phi\psi}{A\phi\psi+\zeta G}\, e^{-\zeta v_{ff}}[1 - e^{-\frac{\zeta B}{A\phi}-\frac{\psi B}{G}}] \quad (6)$$

Where B = the tank volume (L). The second equation analyzed calculates the required tank volume based on the desired reliability and water demand rate:

$$B = \frac{A\phi G}{A\phi\psi+\zeta G}\ln[\frac{A\phi\psi e^{-\zeta v_{ff}}}{A\phi\psi e^{-\zeta v_{ff}} - R_e(A\phi\psi+\zeta G)}] \quad (7)$$

The third equation calculates the maximum reliability for a given demand with a limitless tank volume:

$$R_{e\,max} = \frac{A\phi\psi}{A\phi\psi+\zeta G}\, e^{-\zeta v_{ff}} \quad (8)$$

These 3 equations are used to calculate the reliability and tank volumes for the five water demand rates in Table 3, and the distribution parameters in Table 5, obtained from the averages in Table 4. For the purpose of replicating continuous simulation results, a roof size of 100 m^2 is used, with a runoff coefficient (ϕ) of 1, and a v_{ff} value of 0 (no first flush).

3.5 Comparisons

The results obtained from Equations 6-8 were compared to the corresponding results obtained from the SWMM continuous simulations. The accuracy of the analytical method (A_{cc}) is defined as how close the analytical results are to the continuous simulation results; which is calculated as:

$$Acc = 1 - \frac{(R_A - R_{CS})}{R_{CS}} \tag{9}$$

Where R_A is the analytical result and R_{CS} is the corresponding continuous simulation result.

Comparison of the two methods was conducted using the five daily water demand rates. Table 7 shows the average accuracy of each city, this average accuracy is calculated as the average for the five daily water demand rates and for water collection tank volumes from 200 to 2,000 L connected to a 100 m^2 roof.

Table 7- Average accuracy of the analytical equations in comparison to continuous simulation results

	Equation 6		Equation 7		Equation 8	
City	Modified IET	Unmodifie d IET	Modifie d IET	Unmodifie d IET	Modifie d IET	Unmodifie d IET
Calgary	81%	52%	71%	50%	68%	60%
Quebec City	90%	81%	81%	69%	89%	79%
Saskatoon	81%	52%	67%	50%	75%	48%
Shearwater	89%	92%	78%	99%	85%	92%
Toronto	97%	88%	88%	71%	93%	87%
Vancouver	93%	89%	85%	71%	96%	88%
Windsor	93%	94%	61%	91%	83%	92%

For all three equations, distribution parameters based on the modified inter-event time (IET) dataset provide more accurate analytical results, with the exception of Shearwater and Windsor. Equation 6 is the most accurate, followed by equation 8, with equation 7 providing unsatisfactory results for some cities. Modified IETs provide satisfactory accuracy for all seven cities utilizing Equation 6. The prairie cities (Saskatoon and Calgary) have the lowest accuracies of 81%, the remaining five cities have an accuracy of 89% or higher. Windsor and Shearwater have more accurate results with unmodified IETs. The accuracy of these two cities while utilizing modified IETs with Equation 7 drops to 78% for Shearwater and 61% for Windsor; yet, the unmodified IETs provide very acceptable results with an accuracy of 99%. Once again, the prairie cities have the lowest accuracy while utilizing Equation 7, with an accuracy of 71% for Calgary and 67% for Saskatoon with modified IET. The remaining three cities, Vancouver, Toronto, and Quebec City, have an acceptable average accuracy above 80%.

Equation 8, calculating the highest reliability achieved for a specified demand rate for an unlimited tank volume, provides the same trends as Equations 6 and 7 in terms of average accuracies. The prairie cities have the lowest average accuracies, and Shearwater and Windsor have more accurate results while utilizing the unmodified IET dataset (92% average accuracy), but still acceptable average accuracies of 83% for Windsor and 85% for Shearwater with the modified IETs. The remaining cities have an accuracy of 89% to 96% while utilizing the modified IET dataset. The accuracy of the seven cities studied provides evidence that there may be no direct correlation between the R^2 value measuring the goodness-of-fit of the exponential distribution and the accuracy of the analytical equations. Despite Saskatoon having the highest R^2 value, as shown in Table 6, it has one of the lowest accuracies. Saskatoon's average accuracy for Equation 7 is only 67%, while Toronto, which has a lower R^2 value, has a significantly higher accuracy of 88% for Equation 7.

The analytical equations were derived based on the assumption that the tank is full at the end of a rainfall event, this full content of the tank would likely be used up if the demand rates are relatively high, as a result, this assumption would not have any effect on the operation of the tank from the beginning of the next rainfall event (referred to as the current event in the derivation process) which was analyzed in detail in the derivation of the analytical equations. Consequently, relatively lower water demand rates would result in relatively lower accuracy of the analytical equations. To get an idea of the lowest accuracy of the analytical equations, Figure 18 provides the average accuracy for Equation 6 for the lowest demand rate of 93 L/day and for tank volumes ranging from

200-2,000 L. Modified IET parameters were used for all seven cities, as the accuracy difference between the modified and unmodified IETs for Windsor and Shearwater was negligible. Figure 10 confirms that the analytical method provides inaccurate results for Calgary and Saskatoon, with average accuracies reduced to 60% and 70% respectively for 1,000 L tanks. The remaining five cities maintain acceptable accuracies of above 80%.

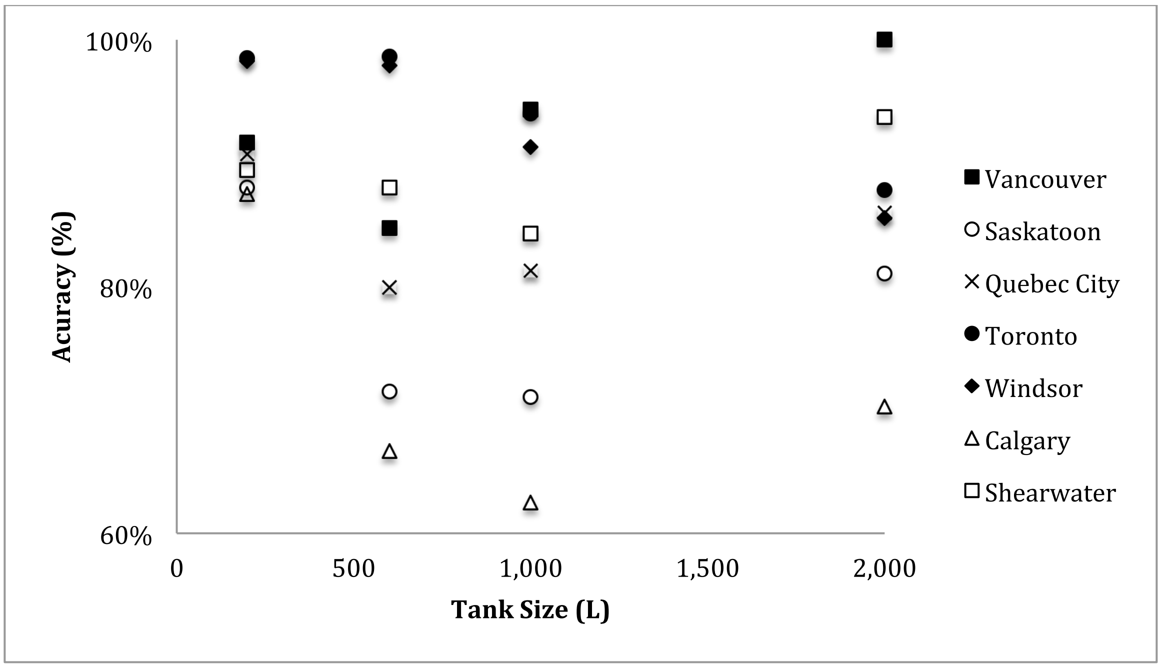

Figure 10- Accuracy of Equation 6 for a Demand of 93 L/Day

Figure 11 provides an overview of the accuracy of Equation 7 for a demand rate of 93 L/Day. Figure 11 shows the tank volumes recommended for a residence in Vancouver or Windsor to achieve a specified reliability obtained from the continuous simulation method and the analytical equations (using modified IET values). Despite having an average accuracy of 85% for Equation 7, the analytical method fails to provide accurate tank volumes required for lower demand rates for Vancouver; this holds true for

Toronto, Quebec City, Saskatoon, and Calgary. Surprisingly different to the other five cities, the analytical method using unmodified IET values delivers appropriate tank volumes to meet the specified reliability for Windsor and Shearwater.

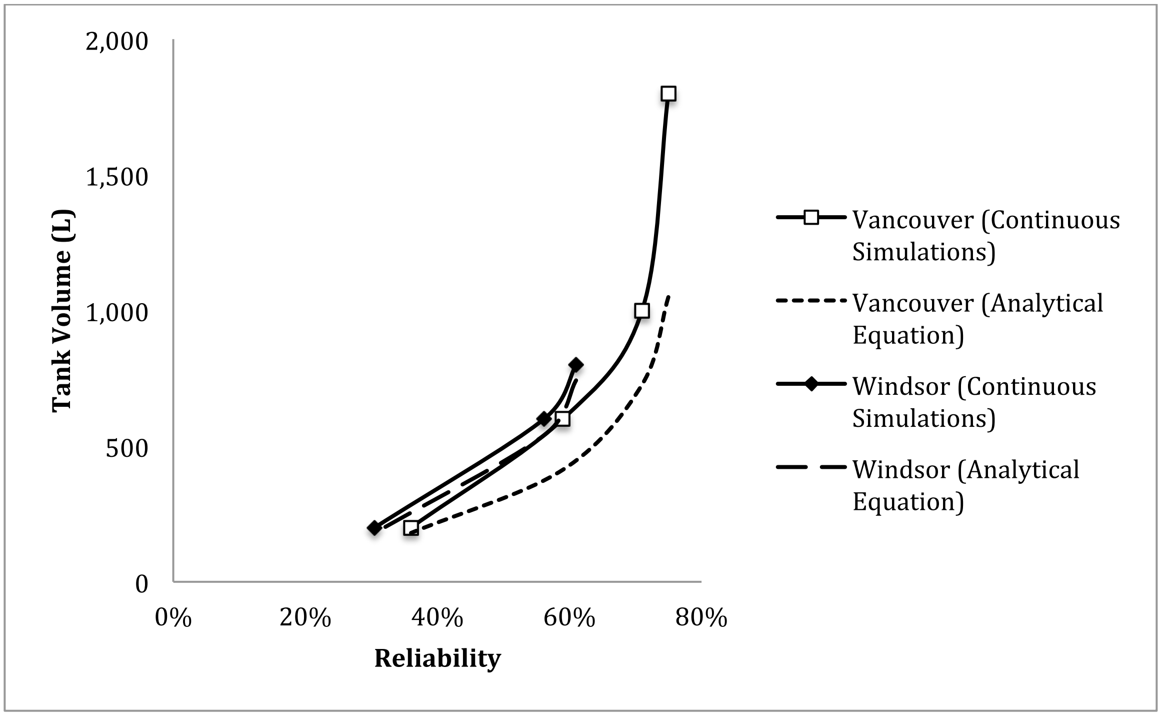

Figure 11- Minimum tank volume required to fulfill a specified reliability for a demand of 93 L/Day

Table 8 provides the maximum reliability obtainable for a demand rate of 93 L/day for an unlimited tank volume using continuous simulation and analytical methods (Equation 8). The maximum reliabilities provided by the analytical equation, either with the modified or unmodified IET, are too conservative. This conservative nature is expected from the derivation of the equations, since the assumption of full content of the tank at the end of the previous rainfall event results in more spills from the tank and thus less water collected by the tank (and later on utilized) during the current rainfall event.

The unlimited tank volume and the lowest demand rate make the full content assumption unacceptable. That is why the analytical equation predicts maximum reliabilities lower than the continuous simulations' by 20% to 35%; these low estimates do not provide a true representation of a RWH system's potential in meeting a specified demand.

Table 8 - Maximum Reliability Obtainable for a 93 L/Day Demand

	Continuous Simulation	Analytical Method (Modified IET)	Analytical Method (Unmodified IET)
Calgary	81%	48%	55%
Quebec City	100%	68%	71%
Saskatoon	66%	44%	50%
Shearwater	100%	75%	77%
Toronto	97%	65%	70%
Vancouver	100%	76%	80%
Windsor	95%	62%	65%

3.6 Conclusion

Despite the generally acceptable goodness-of-fit of exponential distributions for the three rainfall event characteristics of all seven cities, the accuracy of the analytical method varied for different cities. In this paper, a focused examination of the accuracy of the analytical method for lower water demand rates provides a better evaluation for the operation of small residential tanks. Based on the accuracy of the three equations for lower water demand rates, it is observed that the analytical method does not yield very accurate results for Saskatoon and Calgary if unmodified inter-event times (IETs) are used in estimating the mean of inter-event times. Overall, it can be seen that modified IETs should be used for the majority of cities. The most obvious improvement resulting from the use of modified IETs is for Calgary and Saskatoon.

Other than Equation 8, the accuracies of the analytical equations are generally acceptable for the purpose of planning level decision-making, more detailed comparisons show that Equation 6 provides accurate results for cities other than Calgary and Saskatoon for all tank volumes of 2,000 L and less and withdrawal rates less than 516 L/Day. Equation 7 only provides very accurate results for Shearwater and Windsor, while underestimating tank volumes needed for the remaining five cities. Equation 8 failed to provide accurate maximum reliabilities obtainable by an infinite tank volume, the results from Equation 8 may only be used for inter-city comparison and cannot be used for the purpose of decision-making for any specific city.

It is recommended that Equation 6 be used with a high degree of confidence with the acquired rainfall statistics for Shearwater, Vancouver, Toronto, Windsor, and Quebec City. Because of the way the analytical equations were derived (Guo and Baetz, 2007), Equations 6 provided conservative results, within an acceptable accuracy, for Shearwater, Vancouver, Toronto, and Windsor, allowing users to implement systems to meet the desired specifications. For Calgary and Saskatoon, the lowest accuracy was provided by the analytical equations as compared to the other cities. That is why extra caution should be used when use the analytical equations for these two cities. For Quebec, Saskatoon, and Calgary, however, Equations 6 did not provide conservative results. The unique climate characteristics of these locations may contribute to these unusual results. Further research may look into that. For Shearwater and Windsor, future research may investigate as to why the use of modified IETs does not result in more accurate analytical results.

Future research may also look into why the use of modified IETs resulted in so significant improvement of analytical results for Calgary and Saskatoon.

Acknowledgements

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Chapter 4: Rainwater Harvesting: A Necessary But Insufficient Solution To Meeting The Human Right To Drinking Water

Keywords: Rainwater Harvesting, Reliability, Rainfall patterns, Uganda, Canada

Abstract

It is widely believed that Rainwater harvesting (RWH) is an important tool in improving water access across the world. This paper develops a tool to investigate the impact of tank volumes and roof sizes on a tank's ability to satisfy the human right to drinking water in several regions with diverse climates and rainfall patterns. The modeling of RWH tanks for three Ugandan and three Canadian regions through the *Tank Simulation Model* provides insight into the performance of RWH tanks and the most efficient methods of optimizing the reliability of RWH. The six regions are home to rural, remote and otherwise marginalized (RRM) communities that lack adequate access to water. Various water withdrawal rates are compared to recommend the daily water consumption per capita that a RWH system can consistently provide year-round. A system of larger tanks connected to public infrastructure (i.e. school or hospital) within the community and shared by several households is also examined. Comparison of RWH reliability in the two countries provides insight into the impact rainfall patterns has on RWH systems and the reliability of RWH tanks in different global regions. The findings of this work demonstrate that RWH can help provide access to safe drinking water, however it is insufficient as the sole source of water for the RRM communities in both countries considered in this study.

4.1 Introduction

Rainwater Harvesting (RWH) has seen a global surge in exposure and usage over the past 20 years with tens of millions of RWH systems constructed in Africa and South-Asia alone. Developing countries, such as Kenya and Thailand, are harnessing this emerging technology to address the human right to water (Gould and Niessen-Petersen, 1999). This surge of RWH in arid, semi-arid, and even wet climates that rarely face water shortages, is attributed to its ease of implementation and adaptable scale (Petrucci et al., 2012). The potential for RWH to meet residential water demands in RRM communities in warrants investigation. Further, there is a growing interest in residential RWH in many developed countries, by non-RRM homeowners and municipal policy-makers, due to its potential to lessen the stress on water treatment plants and its financial benefits for all stakeholders.

As of 2012, only 75% of Ugandans had access to improved drinking water, with only 5% having a piped connection on premises (WHO and UNICEF, 2014). In rural and low-income communities, households often rely on communal water sources, often contaminated, raising the community's vulnerability to sickness and resulting in a decline in social wellbeing (Howard, et al., 2002; Ford, 1999). Rainwater collected from rooftops has typically met the minimum WHO drinking water quality standards, especially that collected in rural communities (Kahinda et al., 2007; Thomas and Greene, 1993). An assessment of the quality of water sources in North-East Uganda found that rainwater harvesting provided water of higher quality than covered hand dug wells, open hand dug wells, and open water (Howard et al., 2002; Parker et al., 2010). In Uganda, the lack of access to safe drinking water is not due to an insufficient supply (water scarcity), but to a lack of economic means and water management systems (water poverty) (Van Koppen, 2003). With 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. However, the country's bimodal rainfall distribution pattern and changing climatic conditions have been barriers to adequately predicting RWH capacity in meeting residential demand (De Wit and Stankiewicz, 2006). A better understanding of how to harvest and manage rainwater is needed to determine the capacity of a RWH system in fully meeting residential water demands year-round.

Domestic RWH requires minimal infrastructure, especially when compared to other water supply systems. Anywhere from 28% to 95% of roofs in any Ugandan community can be suitable for RWH (Ntale et al., 2005). This indicates the existence of communities with immediate capacity for RWH systems, while others will require structural improvements prior to implementation of RWH. The addition of roofs compatible with RWH systems improves the quality of living for the residents within these households beyond access to water; the enhanced roofs strengthen the home's resilience to storms, and offer better protection to the inhabitants.

Canada, despite holding seven percent of the world's accessible fresh water supply, is not immune to the global water crisis, especially its rural, remote and aboriginal communities (Bakker and Cook, 2011). Between 2000-2001, nearly one in four on-reserves homes had an inadequate supply of quality water (Bakker and Cook, 2009). As of August 2014, there were over 75 First Nation communities in Ontario alone with a drinking water advisory (Health Canada, 2014). For Canada's RRM communities, RWH can be a vital source of water. As of August 2014, Canada's coastal region has six First Nations communities with a water advisory, the Prairies have 53, and Canada's Central region has 77 (Health Canada, 2014). These communities, similarly to RRM communities in Uganda, are in need of a reliable source of high-quality water. Rainwater harvesting is an ideal solution in these RRM communities as it provides an accessible water supply. Improving access to water at the household level is a necessity not only to increase access to clean water (Kahina, Taigbenu, and Boroto, 2007), but also to reduce other social distresses common to these regions, such as poverty and hunger (Baguma et al., 2010).

Rainwater harvesting has proven to be an effective tool in reducing residential water shortage in the Oruchinga Valley, south of Mbarara, Uganda, since 1993 (Sturm et al., 2009). The success of the Oruchinga implementation is due to an initial deep understanding of the tanks' effectiveness and behaviour achieved through demonstration tanks in Kenya. However, trial studies are not an ideal method of determining the effectiveness of RWH, as the trial's scope is narrow in the geographic area it serves and the parameters it has tested (i.e. roof sizes, tank volumes, and withdrawal rates). The trials are also time consuming, requiring a minimum of one year to cover the full rainfall cycle. Further, analyses based on only one year of data will not provide a true depiction of the variance in rainfall trends.

Continuous simulations conducted in this study aim to achieve an improved understanding of a RWH tanks' reliability through software models, saving the time and cost of establishing trial studies while providing more representative results. A software tool, The Tank Simulation Model (TSM), is developed in this paper and utilizes a continuous simulation method of analysis. TSM's objective is to provide communities with the means to better understand the performance of RWH tanks within their regions. TSM is a flexible program allowing users to calculate the reliability of RWH systems based on a user-input tank volume, roof size, and water withdrawal rates; reliability is defined as the percentage of demand satisfied by water provided from the RWH tank (Guo and Baetz, 2007). The statistics and information provided by TSM empowers a community to self-reliantly design and manage the most effective RWH systems for their environment and water needs.

TSM is used in this paper to investigate the reliability of rainwater tanks, connected to both residential and larger roofs within a community, to meet a minimum household demand. There has been much debate about the minimum water requirements to facilitate social and economic development. The most common standard is 20 LPCD (Litres Per Capita Per Day), recommended by the World Health Organization and UNICEF (Chenoweth, 2008), and therefore this paper uses 20 LPCD as the minimum water requirement for human consumption.

This paper investigates the reliability of RWH within three Ugandan regions: Buikwe, Jinja, and Rakai and three Canadian Regions: Central Canada, The Prairie

Provinces, and Coastal Canada. With Uganda's bimodal and Canada' unimodal precipitation patterns, the comparison of the tanks' reliability between the two countries provides insight between the relationship of rainwater volume, precipitation patterns and RWH reliability. Despite the socio-economic and cultural differences between Canada and Uganda, the two countries are home to RRM communities with inadequate access to water. Examining the reliability of RWH tanks provides an understanding of the capacity of RWH to meet the human right to drinking water. The TSM is intended to be used by community members and policy-makers in designing customized RWH strategies and providing an understanding of the performance of RWH systems year-around.

4.2 Methodology

The Excel-based TSM developed for this study was utilized to calculate the reliability for various household and community scenarios in three Ugandan regions (Rakai, Buikwe, and Jinja) and three Canadian regions (costal, prairie and central). The program uses a daily continuous simulation process, for which the equations, method, and model-setup are provided below.

The TSM was developed using raw daily precipitation obtained from the Uganda Meteorological Agency and Environment Canada. The 10 most recent years of daily rainfall data for which no values were missing were selected (Table 1) and input into TSM. As discussed above, the three Ugandan regions investigated in this work are Buikwe, Jinja, and Rakai. For the Canadian simulations, Toronto, Calgary and Vancouver were selected to represent the central, prairie, and coastal regions respectively.

Table 1- Rain Gauge Stations

City	Time period considered
Buikwe, Uganda	1998-2002, 2008-2012
Jinja, Uganda	2003-2006, 2008-2013
Rakai, Uganda	2000-2002, 2005-2011
Toronto, Canada	2003-2012
Calgary, Canada	2001-2010
Vancouver, Canada	2002-2011

Three different RWH systems are assessed by the TSM: stand-alone residential tanks, stand-alone shared community tanks, and a integrated system with both residential and shared community tanks. The stand-alone residential tank system assumes a RWH tank connected to a residential roof providing water for one family. The stand-alone shared community tank system assumes a RWH tank connected to a public roof providing water to a number of families. The integrated RWH system assumes that shared community tanks exist but are only used to complement the residential tanks when they cannot meet the water demand on their own. Therefore, the water withdrawal rate from the community tank is dependent on the residential tanks' capacity to meet the specified water demand. The same methodology and equations was used for the stand-alone residential and shared community tanks, as described below.

First, the maximum potential daily rainwater harvest volume, *P* (per day)*,* was calculated. This is the volume of runoff from the roof entering the tank. The RWH system coefficient is selected as 0.85 to account for any water loss due to evaporation and system leakage (Ward et al., 2010):

$$P=pr^{*}\ S\ ^{*}1000^{*}Co \qquad (1)$$

where Co is the RWH system coefficient=0.85, pr represents the daily precipitation value (mm), and S is the surface area of the roof connected to the water collection tank (m^2).

Second, the volumes of water in the tank (*V)* and water consumed from the tank *(C)* on a given day are calculated. The two values 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. The volume of the water in the tank also cannot exceed the tank volume itself. Therefore the following constraints were implemented:

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

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

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

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

where V_i is the volume of water in the tank on a given day (L), V_{i-1} is the volume of water in the tank on the previous day (L), P is the maximum daily potential harvest volume (L), C_{i-1} is the water consumed on the previous day (L), B is the size of the water collection tank (L), C_i is the water consumed on a given day (L/day), D is the total water demand per day (L/day), and V_i is the volume of water in the collection tank on a given day (L).

The reliability of the tank (R_e) on each day is calculated as:

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

Equations 1-5 were modified for the integrated RWH system model. The first step in determining the reliability of an integrated RWH system is to calculate the cumulative deficiency of the residential system per day, H_i, which is based on the number of families sharing the community tank and the water deficiency per household. The household deficiency is assumed to be constant for all households as it is assumed they share the same roof sizes, tank volumes, and daily water withdrawal rates. Thus, the shared community tanks provide each family with an equivalent volume of water to support the residential tanks in meeting the water demand specified.

$$H_i = (D - C_i) * N_f \tag{7}$$

where N_f represents the number of families sharing the community tank.

In the integrated model, the volume of water consumed from the community tank (C_c) and the volume of water in the tank (V_c) are dependent on one another. Therefore, the following constrains were implemented:

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

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

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

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

where B_c is the size of the shared community tank (L).

The potential rainwater harvested by the community tank (P_c) is calculated as follows:

$$P_c = pr * S_c * 1000 * Co \tag{12}$$

where Co is the RWH system coefficient= 0.85, pr is the daily precipitation value (mm), and S_c is the surface area of the roof connected to the shared community tank (m^2).

The water provided by the residential tanks (C_i) is added to the household's share of the water provided from the community tanks to calculate the total volume of water provided by the integrated RWH system to each household each day (C_h):

$$C_h = C_i + (C_c)/N_F \tag{13}$$

The reliability of the integrated RWH system ($R_{e,c}$) on each day is calculated as:

$$R_{e,c} = \frac{C_h}{D} \tag{14}$$

where D is the total household demand (L/day).

The Ugandan and Canadian simulations were conducted using the same daily per capita demand, family size, roof area and tank volume to enable a fair assessment and comparison of the capacity of RWH to satisfy the 20 LCD demand in RRM communities. The simulations were conducted for a household with six members, as it accommodated the average household size of five in Uganda (Baguma and Loiskandl, 2010) and six in Canada's aboriginal communities (O'Donnell and Wallace, 2014). The simulations were conducted for roof sizes from 20 m^2 to 65 m^2 to accommodate for Ugandan and aboriginal Canadian households, and for tank volumes from 200 - 10,000 L to provide the user with a clear depiction of the behaviour of tanks typically available at retailers.

4.3 Results

The three Ugandan regions investigated provide insight into the impact of rainfall patterns on a RWH collection tank's reliability together with the number of days the tank is empty and the number of days the tank provides 100% of the specified water demand. The rainfall pattern in the three Ugandan regions is bimodal and Canada's three regions experience a unimodal rainfall pattern, as shown in Figure 1. The annual average rainfall volumes during the study period for the six regions are included in Table 2. The different rainfall patterns in each region result in different RWH reliabilities in each of these regions. However, the six regions investigated do share some overall RWH reliability trends and patterns.

Table 2- Rainfall Summary

City	Yearly Average (mm)
Rakai, Uganda	1,084
Buikwe, Uganda	1,547
Jinja, Uganda	1,369
Toronto, Canada	700
Vancouver, Canada	1,094
Calgary, Canada	345

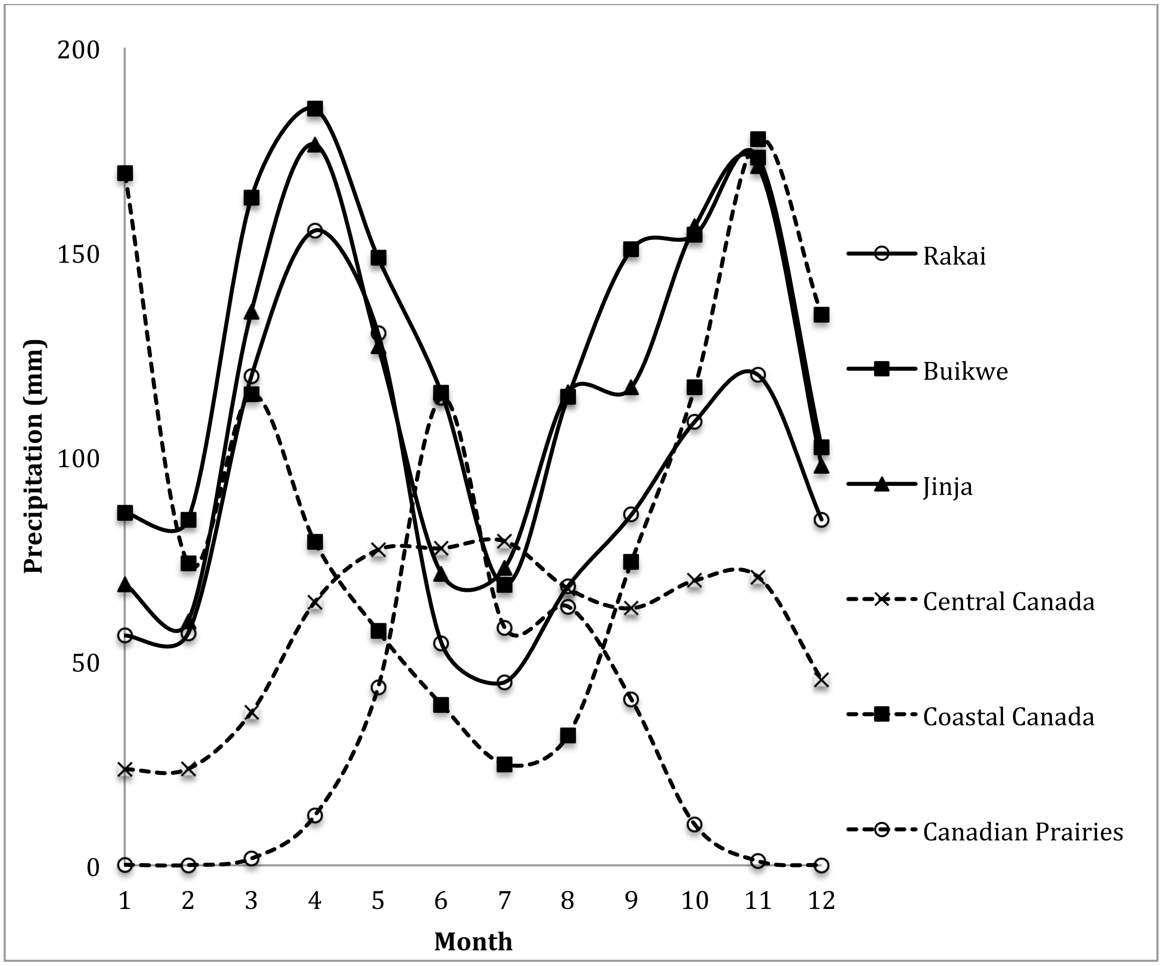

Figure 1- Average monthly rainfall (mm) in Rakai, Buikwe, Jinja, central Canada, costal Canada and the Canadian praries.

Figure 2 shows shows the relationship between reliability and tank volume for a 20 LPCD water demand for six individuals in a 20 m^2 residence. It is clear that increasing tank volume improves reliability to a point; however, a maximum reliability is reached at tank volumes of 1,500 L – 2,000 L for all six regions. Increasing tank volumes beyond this size will not improve the reliability of a RWH system in any of the six regions investigated. Figure 3 shows the relationship between the size of the RWH tank and the number of days it meets 0% and 100% of the demand. Similar to the pattern for reliability, the number of days with 0% of demand met decreases with increasing tank size to a maximum size of 1,500 L, at which point the number of days with 0% of demand met remains constant. Similarly, the number of days that 100% of demand is met increases with increasing tank size to a maximum size of 1500 L. This trend is illustrated in Figure 3 for Ugandan the three Ugandan regions investigated; the same trend emerged for the three Canadian regions, however it is not shown here. A 1,500 L tank in Buikwe can only deliver the full 20 LPCD demand an average15 days a month and is empty 10 days a month. The reliability is significantly lower for Jinja and Rakai, which achieved maximum reliabilities of 50% and 30% respectively (Figure 2). The RWH tanks in Rakai will be empty an average of 18 days per month (Figure 3), compelling users to rely on other water resources more than half of the time. RWH systems in Canada's Prairie and Central regions can only provide a maximum reliability of 12% and 25% respectively for a 20 LPCD demand. Despite the fact that costal Canada and Rakai receive approximately the same volume of rain per year, Rakai's maximum RWH reliability is 6% lower than that of Coastal Canada's. The reduction in reliability can be attributed to the difference in rainfall patterns, and the fact that Uganda experiences longer dry periods between its wet months. The incapacity of residential RWH tanks to meet the 20 LPCD demand in all six regions investigated here illustrates that with the current housing infrastructure, stand-alone residential RWH tanks cannot independently fulfill a household's human right to drinking water.

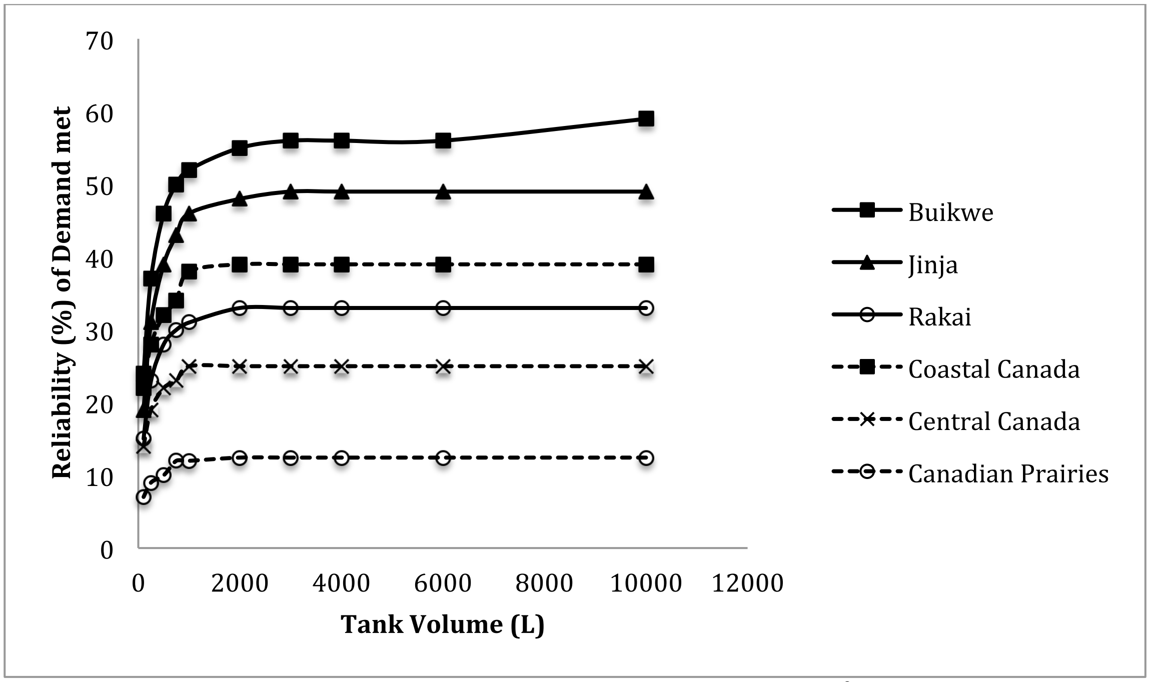

Figure 2- Reliability of a residential tank connected to a 20 m^2 residence housing six individuals, with a water demand of 20 LPCD

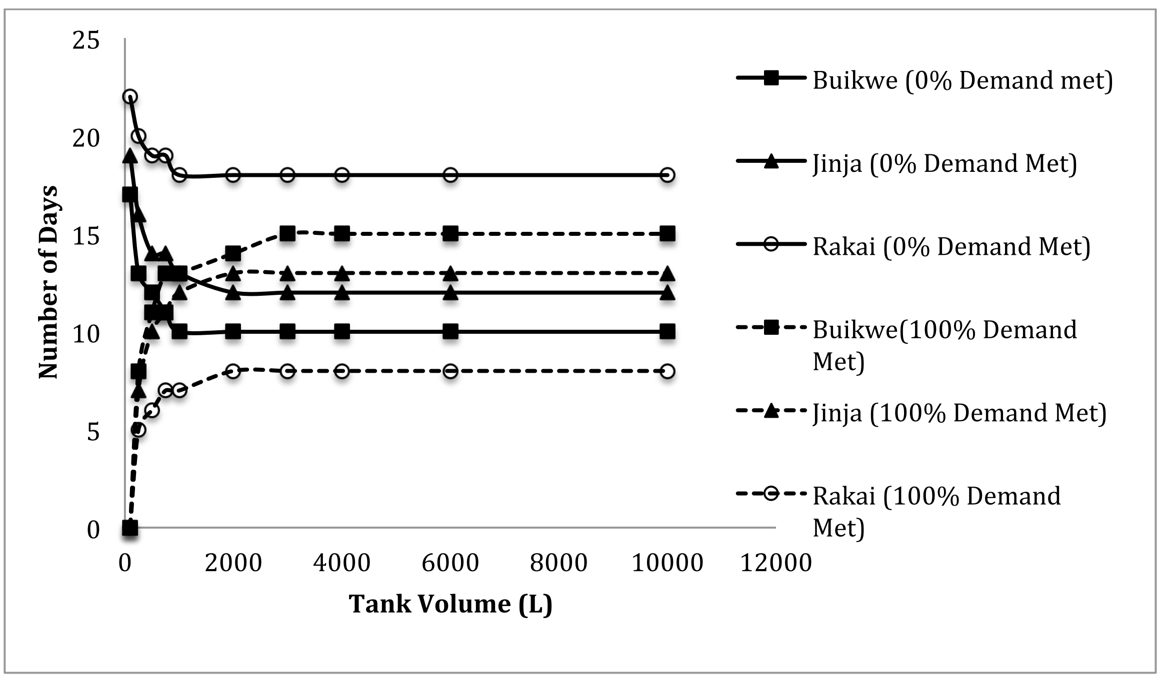

Figure 3- Average number of days per month in Buikwe, Jinja and Rakai with: a) 0% demand met and b) 100% water demand met, for a residential tank connected to a 20m^2 residence housing six individuals with a water demand of 20 LPCD

Figures 4 and 5 illustrate the influence of roof size on reliability, and the number of days that 0% and 100% of demand is met, respectively. A 1,000 L RWH tank in Buikwe can provide up to 85% of a 20 LPCD demand, although it takes an exceptionally large roof size to achieve this degree of reliability. Minor increases to roof size decrease the number of days per month that 0% of demand is met, and adds more days that 100% of demand is met. For example, increasing a roof size from 20 m^2 to 25 m^2 with a 1,000 L tank in Jinja provides the homeowner with an average of two extra days a month that 100% of demand is met, one less day that 0% of demand is met, and a 5% increase in reliability. However, even roof sizes up to 65 m^2 (housing six family members) do not render the RWH system 100% reliable for a 20 LPCD demand in any of the six regions investigated. Similar to the analysis for tank size, increasing roof size improves coastal Canada's reliability beyond that of Rakai's, and as roof sizes become larger the gap between RWH reliability for the two regions widens. The tank reliability of Canada's central region reaches that of Rakai's as roof size extends to 60 m^2, despite the Central region receiving significantly less rain than Rakai. It is evident that rainfall patterns strongly impact tank reliability due to increasing tank volume and roof size.

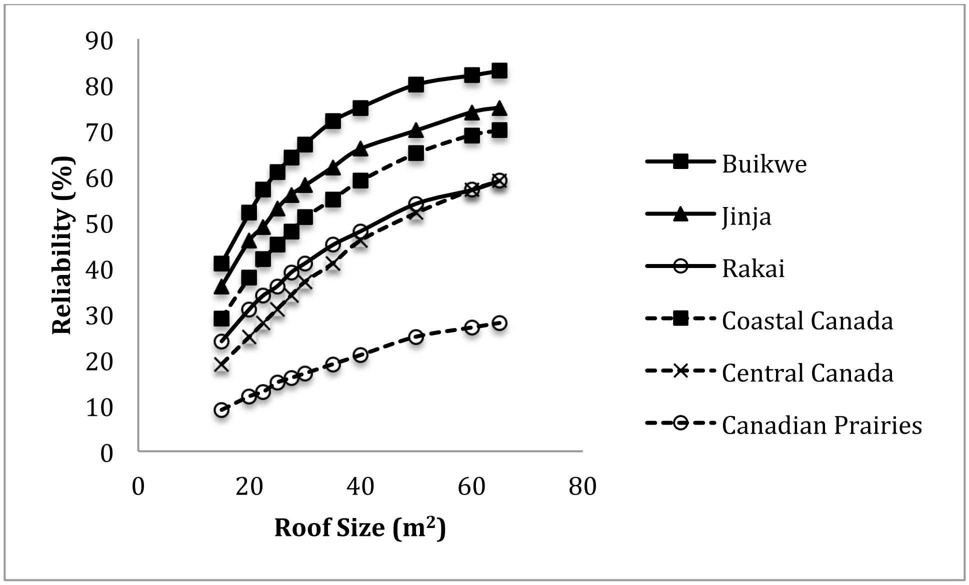

Figure 4- Reliability of a 1,000 L residential tank for a household of six, with a water demand of 20 LPCD

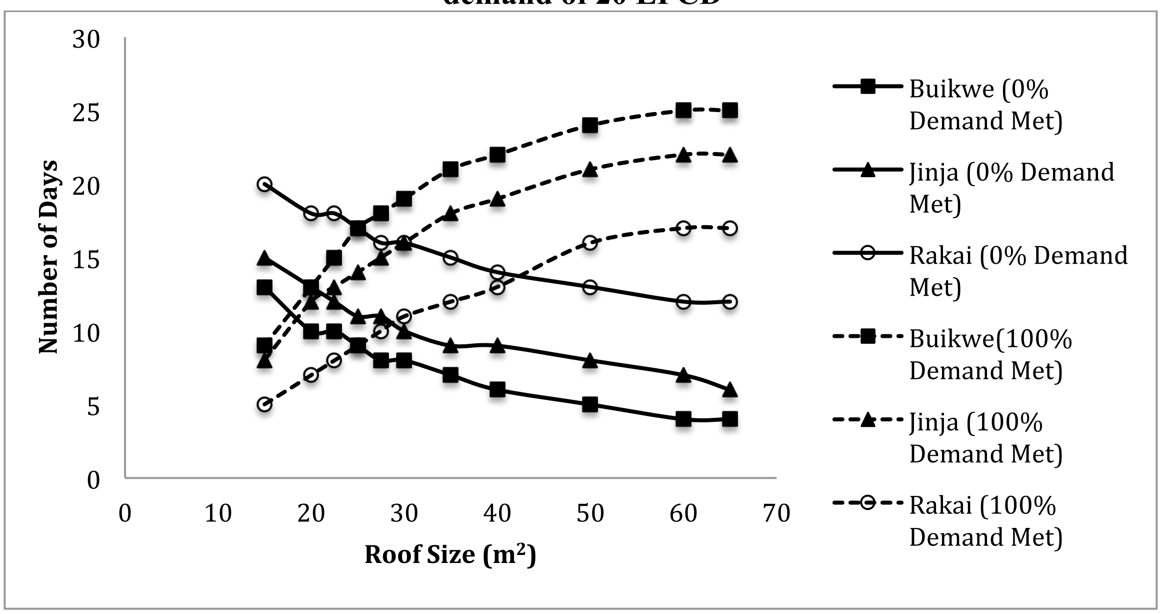

Figure 5- Average number of days per month with a) 0% demand met and b) 100% water demand met, for a 1,000 L residential tank for a household of six, with a water demand of 20 LPCD

The stand-alone shared community tank option is explored to assess the reliability of a system incorporating a bigger tank connected to a large public roof shared by several families in the community (Figures 6 and 7). This system assumes there are no residential tanks present. Figure 6 shows the reliability for an 18,000 L tank (or two 9,000 L tanks) connected to a 75 m^2 roof shared by 15 families. In all six regions investigated, the shared tank can provide 20 LPCD with a reliability of less than 20%; thus, this system cannot consistently provide the desired minimum water need of 20 LPCD. In Canada's prairie region, even the 2 LPCD demand was only met with a 30% reliability. Clearly the stand-alone shared system is significantly less efficient than the stand-alone household systems under the conditions investigated here.

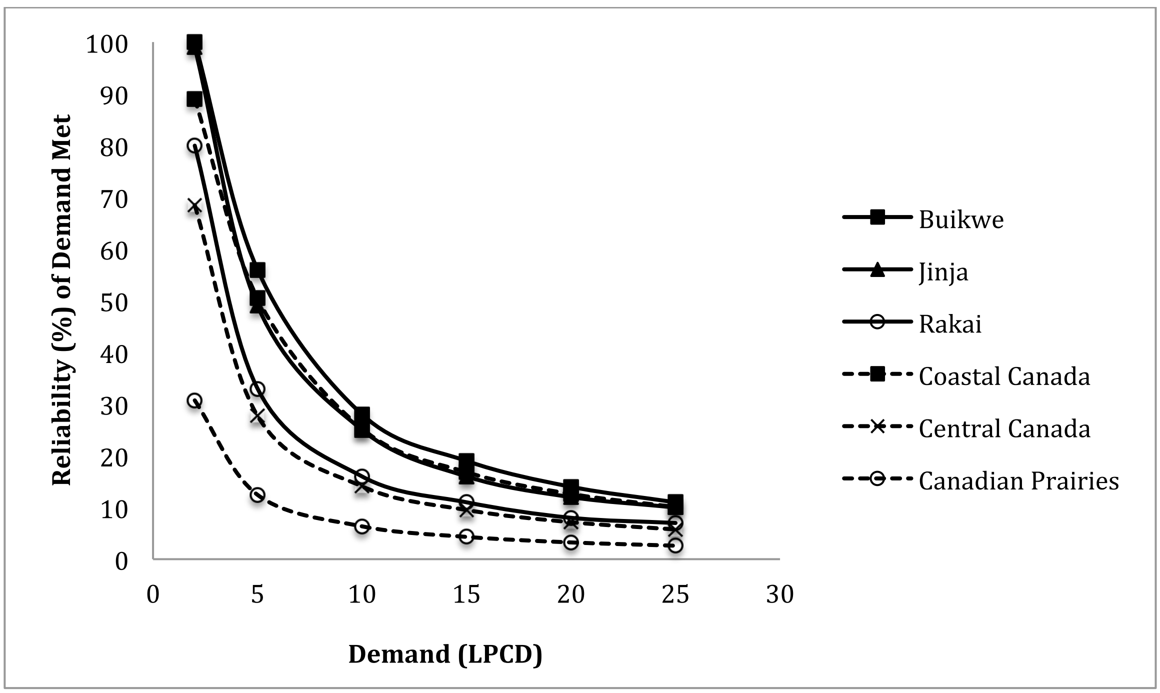

Figure 6- Reliability of an 18,000 L shared community tank connected to a 75 m^2 roof, providing water for 15 households (six members per household)

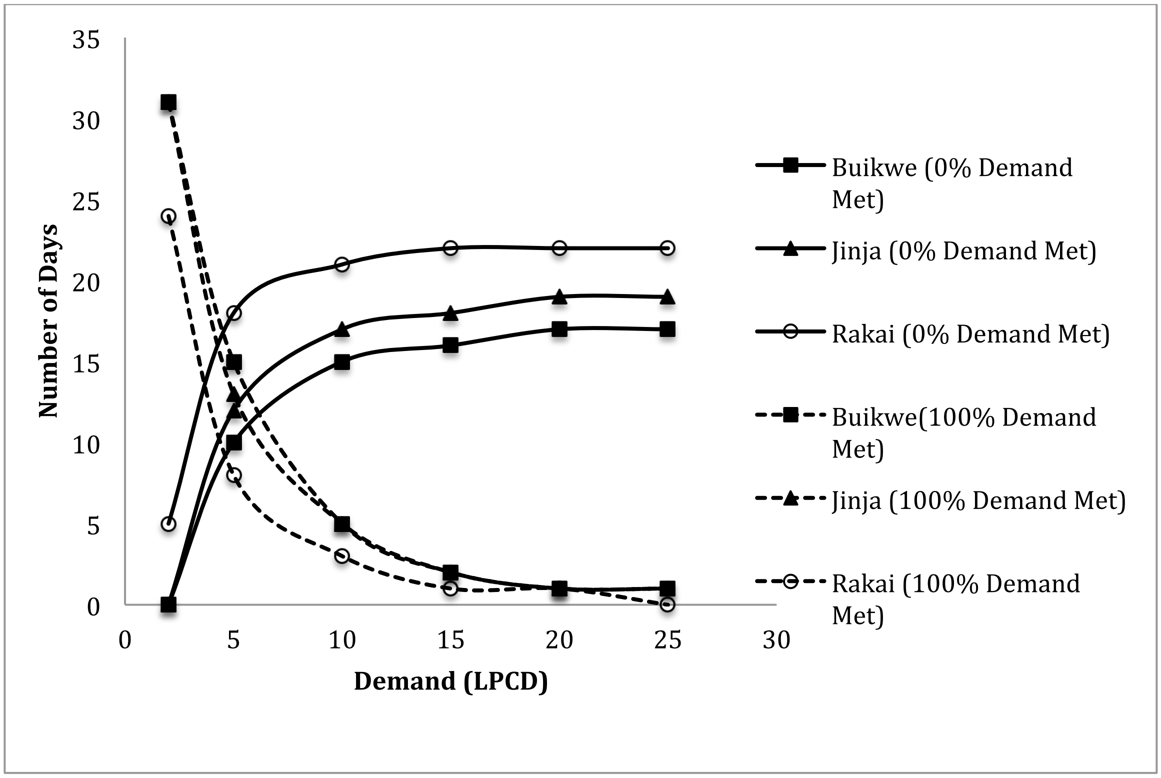

Figure 7 - Average number of days per month with a) 0% demand met and b) 100% water demand met, for a 18,000 L shared community tank connected to a 75 m^2 roof, providing water for 15 households (six members per household)

Similar to the residential tanks, a roof size has a stronger influence on the reliability of the shared community tank system than tank volume does. As shown in Table 3, for a 10 LPCD demand, tank volume has minimal impact on reliability while larger roof sizes are able to provide a higher reliability for all three Ugandan regions investigated. Increasing the size of the collection roof beyond 75 m^2 can significantly decrease the number of days that 0% of the demand is met, and increase the number of days it meets 100% of the demand. It is critical to note that regardless of tank volume (up to 24,000 L) and roof size (up to 350 m^2), 100% reliability cannot be achieved for any of the six regions in meeting a 20 LPCD through either of the stand-alone RWH systems, residential or shared community tanks. Further, it is evident that the shared community tanks are a completely inadequate water source in all six regions.

Table 3- Reliability of shared community tanks providing water to 15 households (six members per household) with a water demand of 10 LPCD

	Tank Volume (L)		
	9,000	**18,000**	**24,000**
Roof Size (m^2)		**Buikwe**	
50	19%	19%	19%
75	28%	28%	28%
200	65%	70%	71%
350	81%	90%	93%
		Jinja	
50	16%	16%	16%
75	25%	25%	25%
200	57%	62%	64%
350	72%	83%	87%
		Rakai	
50	11%	11%	11%
75	16%	16%	16%
200	39%	42%	43%
350	54%	62%	65%

Table 4 shows the reliability of an integrated RWH system for a 2,000 L residential tank connected to a 20 m^2 roof with an 18,000 L shared community tank connected to a 200 m^2 roof. Fifteen households, with six people per household, share the community tank. Table 4 clearly shows that an integrated RWH system is more effective in meeting a community's water needs than either of the stand-alone systems. All six regions benefit from the integrated RWH system. The shared community tanks are accessed as needed on days that the residential tanks are insufficient in meeting the specified household demand. With the integrated RWH system, Buikwe and Jinja can achieve a water withdrawal rate of 20 LPCD with reliabilities of 79% and 71% respectively, while Rakai’s reliability is 50%.

Due to less annual rainfall, the integrated RWH systems in Canada are not capable of providing the same reliability as the regions investigated in Uganda. The maximum demand that can be met in central and coastal Canada, with an acceptable reliability, is 5 LPCD; this decreased to 2 LPCD in the prairie region. As observed in previous comparisons, coastal Canada’s reliabilities are higher than Rakai’s. Despite the integrated RWH system providing a higher reliability rate than the stand alone systems, the integrated system is still inadequate in meeting the daily minimum water requirement of 20 LPCD in all six regions.

Table 4- Reliability of integrated RWH systems for a 2,000 L residential tank connected to a 20 m^2 roof with an 18,000 L shared community tank connected to a 200 m^2 roof. Fifteen households, with 6 people per household, share the community tank.

	Buikwe		Jinja		Rakai	
Demand (LPCD)	**Residential System**	**Integrated System**	**Residential System**	**Integrated System**	**Residential System**	**Integrated System**
2	100%	100%	100%	100%	100%	100%
5	100%	100%	100%	100%	96%	100%
10	91%	99%	92%	97%	67%	81%
15	70%	91%	71%	84%	48%	63%
20	55%	79%	55%	71%	37%	50%

	Central Canada		Canada's Prairies		Coastal Canada	
Demand (LPCD)	**Residential System**	**Integrated System**	**Residential System**	**Integrated System**	**Residential System**	**Integrated System**
2	99%	99%	86%	98%	100%	100%
5	89%	98%	47%	61%	97%	100%
10	50%	75%	25%	37%	70%	84%
15	33%	54%	16%	27%	51%	70%
20	25%	41%	12%	20%	39%	59%

4.4 Conclusion

The continuous simulations demonstrated that even regions in Canada and Uganda that receive the most rainfall (i.e. Vancouver and Buikwe) cannot fully rely on RWH systems to satisfy the minimum water requirement of 20 LPCD with the current housing infrastructure and average number of household members in their RRM communities. The TSM demonstrated that roof size has a significant impact on RWH reliability; increasing roof size provides more substantial increases to a RWH system's reliability than increasing tank volume. Uganda's higher reliabilities for the same household structures and number of family members again demonstrates the impact that rainfall patterns have on RWH reliability. Due to Uganda's bimodal trends and more severe storms, larger roof sizes have a stronger impact on tank reliability than in Canadian cities. With homes in Canadian aboriginal communities are larger than those in Uganda, their roof sizes are also larger; however, it is apparent then even homes 60-65 m^2 are incapable of meeting the 20 LPCD demand.

The model further demonstrated that integrated RWH systems satisfy more demand reliably than either the residential or community stand alone systems. The integrated system can completely satisfy demands of up to 10 LPCD in some communities, and provide a significant contribution towards a 20 LPCD demand. However, an additional source of water would be need in all six communities investigated to meet the 20 LCPD demand to satisfy the human right to water. These results indicate that RWH is a necessary but insufficient source in supplying a community with adequate water to fully satisfy its minimum water needs. Implemented in conjunction with other water sources, RWH can be a vital tool in providing communities their fundamental human right to access to drinking water.

Chapter 5: Conclusions and Future Work

5.1 Conclusions

The series of equations and graphs provided in Chapter 2 best describe tank reliability in satisfying various rainwater use rates for various tank sizes in a concise form that still lets the user visually see the trends. The results were obtained using the continuous simulation method, and are presented through the graphs in a user-friendly manner. The versatility of the tools provided in this thesis makes them ideal for various users, providing specific statistics useful for estimating a RWH tank's behaviour in meeting residential water demands. Despite Canada's climatic and geographic diversity, there are some common trends apparent within regions: Central Canada (Windsor, Toronto, and Quebec City), Prairies (Calgary and Saskatoon) and Coastal (Vancouver and Shearwater). In the Central and Costal regions, a 2,000-3,000 L tank provides a reasonable reliability in meeting a 93 L/Day demand that suffices for watering lawns and outdoor water uses requiring no extensive water treatment. Attempting to fully meet water demands of 363 L/day and higher proved to be ineffective even in rainfall-rich cities, such as Vancouver and Shearwater. However, rainwater harvesting in Canada has a worthwhile capacity in providing a significant proportion of the 93 and 171 L/day demands with reasonable tank volumes. The graphs and equations provided in Chapter 2 allow the various stakeholders to better understand the behaviour of RWH collection tanks; consequently, designing and managing an effective RWH program.

Despite the generally acceptable goodness-of-fit of exponential distributions for the three rainfall event characteristics of all seven cities, the accuracy of the analytical method varied for different cities. The analytical equations provided the lowest accuracies for the prairie cities, Calgary and Saskatoon. Equation 6 accurately calculated reliability rates obtained for the various tank volumes for the five remaining cities; however Equation 7 only provided accurate tank volume calculations for Shearwater and Windsor. Equation 8 grossly underestimated maximum reliability obtainable for most cities. The analytical method is preferred as it allows users to perform RWH design calculations conveniently and not rely on previously conducted continuous simulation results. The analytical equations however, for the most part, lack a high enough degree of accuracy to be recommended for application in a region without comparison with continuous simulation results. Chapter 3 has confirmed the validity of using particular analytical equations in the Central and Coastal region of Canada.

Chapter 4 has investigated, through continuous simulations modelling by the TSM program, the reliability of RWH in meeting the minimum water requirements of 20 LPCD. That research confirmed that households in Uganda cannot fully reply on RWH as a sole water supply to meet the minimum water requirement. The current housing infrastructure coupled with the high number of occupants per residence decreases the amount of rainwater collected and increases the daily water withdrawal from a tank. Some Ugandan and Canadian cities share similar reliability curves, despite the fact that the Ugandan cities receiving more annual rainfall. This reduction in RWH reliability in Uganda is attributed to the country's bimodal rainfall pattern and drought periods. Integrated RWH systems of residential and shared community tanks are shown to have the capacity in providing a significant contribution to a household's water needs in

Uganda. While RWH may not be a sufficient water source, it is a necessary one and one that can provide a considerable relief to the global water crisis.

5.2 Future Work

Continuous simulation models should be conducted on more Canadian cities to better understand the relationship of RWH reliability among cities and within Canada's diverse climatic and geographic regions. Comparing the reliability curves of additional cities within each region allows for a better understanding of the relationship of rainfall patterns and RWH tank behaviour. An in-depth analysis of the coastal region can provide more insight on the similarities between coastal cities, despite their geographic distance apart. While this thesis briefly discussed potential municipal financial savings due to residential RWH, an exploration of the cost savings and the return of investment for a homeowner are recommended. As homeowners and developers are the stakeholders actually purchasing and placing RWH tanks in their homes, a better understanding of the savings for these participants due to RWH is needed. This exploration also provides government entities an understanding of the incentives needed to supplement these savings and motivate homeowners to introduce RWH tanks into their homes. These studies and their consequent findings will develop a strong foundation in which future policy and application of residential and large-scale RWH projects are implemented in Canada.

The analytical method is an influential tool in advancing RWH implementation in Canada, especially for rural and aboriginal communities in which continuous simulations have not been conducted. Future research is needed to increase the accuracy of the analytical method, and to better recognize the climate conditions in which it is suitable for. Research examining the behaviour of the analytical method in unique and dry climates, such as the Prairies, is recommended especially as these water-sensitive regions are in need of an integrated water supply management system to mitigate potential future water crises. An investigation into the role of IETs and goodness-of-fit of a city's rainfall parameter's probability distributions can provide a better understanding of the application of the analytical method and also of how to select the distribution parameter values used in the equations. This additional research will also provide a foundation with which modifications can be made to the analytical method to account for diverse climate conditions and also to increase the accuracy of the analytical method with larger tanks.

As research quantifying the reliability of RWH in Uganda and Eastern-Africa is still relatively new; there are numerous research opportunities in advancing RWH in the region. Chapter 4 provided insight into the significance of the home's roof size on the behaviour of a RWH system, it is apparent that roof size has a stronger influence on a tank's reliability than tank size. Further research is needed to determine the most optimum combination of roof size and tank volume for the various types of households within Uganda. The research can look into the impact of the number of residents within the household and the various community parameters that influence the withdrawal rates and tank reliability. Research on the ground is needed to better understand the current infrastructure conditions; this data of residential and public buildings will provide a sense of the roof sizes in which communities can harvest rainwater from. Similar to Canada, there is a need to better understand the financial savings a rainwater tank can provide to a

Ugandan household. An analysis of the current water sources and their cost, financial and time, can provide a basis for the better understanding of the subsequent impacts felt by introducing RWH systems into a community.

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