A Novel Approach for Communal Rainwater Harvesting for Single-Family Housing: A study of Tank Size, Reliability, and Costs

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ABSTRACT

An emerging field in rainwater harvesting (RWH) is the application of communal rainwater harvesting system. This system's main advantage compared to individual RWH is the centralization of water treatment, which some users of individual RWH find difficult to maintain. Despite alleviating one concern, this communal approach does not increase the RHW system's (RWHS) reliability nor necessarily satisfy all water demands, and hence is not a major improvement in terms of system performance.

This research tackles this challenge with a novel approach to communal RWH for single-family houses. Instead of the traditional communal approach to RWH which uses only one storage location, we propose connecting multiple single-family homes' RWHSs to a communal backup tank, i.e., capturing overflow from multiple RWHS, which will increase reliability and water demand met in a way that will significantly improve the current performance of communal RWH. The proposed system will potentially maximize the availability of potable water while limiting spillage and overflow.

We simulated the performance of the system in two cities, Houston and Jacksonville, for multiple private and communal storage combination. Results show that volumetric reliability gains, of 1.5% - 6% and 1.5% - 4%, can be achieved for seven to ten and six to seven connected households, respectively, for Houston and Jacksonville if

the emphasis is on volumetric reliability (VR). As per total storage capacity, the system achieves higher VR gains for lower total storage capacity in Houston while the system achieves higher VR gains for higher total storage capacities in Jacksonville.

With regards to the total cost of ownership per household for the individual system and for the communal storage system, the lifecycle cost of the system was performed using the Net Present Value (NPV) method, with an interest rate of 7% over 30 years. The NPV of the total system costs per household in the city of Houston is lowest for nine to ten connected households, as well as comparable to the base case of a rainwater harvesting system that is not connected to a communal tank for seven and eight connected households.

This communal system is more resilient and can be a worthy addition to water and stormwater infrastructures, especially in the face of climate change.

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GENERAL AUDIENCE ABSTRACT

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Dedication

In memory of Rosette El Durr

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CHAPTER ONE: INTRODUCTION

General Background

The aging water infrastructure in the U.S. is becoming a critical issue and investment has not been keeping up with the needs. According to the ASCE, there will be an estimated $84.4 billion annual capital gap for water infrastructure by 2020 (Economic Development Research Group of the American Society of Civil Engineering 2016). Water demand is growing (Sabol 2011) and the rate of urbanization is increasing. The latest census of 2010 shows that urban areas are outgrowing the national growth by 2.4% (United States Census Bureau 2012)and water utility bills are on the rise (Walton 2015). City and town managers of growing urban areas are facing increasingly difficult choices with regards to water infrastructure management: should the status quo be maintained, which is investing in the existing infrastructure, or should there be funding investments at the parcel scale, or some mix thereof, which will ultimately affect water, wastewater and stormwater networks. A “soft” water management approach (Gleick 2003) considers the water system from a holistic point of view: instead of investing in the water, wastewater, and stormwater infrastructure on the town, city, or county scale, a different way to approach the challenge is to invest in interventions on the parcel scale, undertaken by individual owners or developers, which would ultimately reduce loads on the entire system.

At the center of decentralized water schemes lies rainwater harvesting systems (RWHS). RWHS act as a containment measure for stormwater runoff by storing rainwater which can be used for irrigation, car washing, non-potable domestic functions (laundry, toilet flushing, etc.) and when treated, as a potable water source. Rainwater harvesting is not a new concept; the practice has been available for centuries and multiple countries currently depend solely on harvested rainwater for day to day life. The vital importance of RWHS is the effect they have on the three water networks (potable, stomwater, and wastewater) in terms of decreasing water demand on the potable water network, decreasing stormwater runoff, and, if coupled with greywater recycling systems, decreasing the wastewater generated (Ghisi and Ferreira 2007).

RWH adoption is directly and indirectly tied to the adoption of Green Infrastructure (GI). They are directly related when a there is use of RWH in addition to green roofs in one building. A study done in Porto, Portugal (Monteiro et al. 2016) assessed the quality of the rainwater going into the RWHS from a green roof and it was found to be adequate for non-potable uses like toilet flushing and irrigation. In this case, such a combination of GI would affect the demand portion of the model per capita per day. The indirect relationship between GI and RWH exists when there's an addition of a rain garden. In individual RWHS, the rain garden would be constructed near the outflow pipe of a rainwater tank so that is absorbs the excess during rain events. This does not affect the water calculations.

In essence, understanding how RWHS perform could lead increased adoption of those systems, especially given that the direction of water infrastructure management is shifting towards the inclusion of more decentralized systems (Makropoulos and Butler 2010).

Communal RWHS is a new trend within the RWHS sphere. Communal RWHS for single-family houses presently consists of collecting rainwater from multiple roofs, transporting the rainwater to a common central location where water is treated, and then sending back the treated water to the houses in the network. However, the reliability and the cost of communal RWHS to individual users does not differ much from owning individual RWHS. Hence, the question becomes: how can we improve communal RWHS for single-family houses by increasing reliability and decreasing costs? This research will focus on the relationship between communal RWHS for single-family houses, the reliability and the total cost per household. Storing stormwater runoff is not a novel concept. In fact, earlier uses of rainwater cisterns have been traced back to the Neolithic Age (Mays et al. 2013) during which time humans learned to raise crops and keep domestic livestock which would have prompted the habit of storing rainwater for later usage. The cisterns consisted of carved holes in rock where rainwater pooled during storm events, which could be later used during dry spells. In fact, in some small island communities, rainwater harvesting is still the major supply of domestic water (Bailey et al. 2018).

Current rainwater harvesting processes vary from simple cisterns (as above-ground rain barrels) to more complex systems (above- or below-ground cisterns) such as the rainwater harvesting systems. Angrill et al. investigated the different RWHS configurations (tank above roof, below roof, distributed under roof and underground) in a dense neighborhood in Spain (Angrill et al. 2011). Melville- Shreeve et al. conducted the same analysis for systems in the UK (Melville-Shreeve et al. 2016). Cisterns are usually the most expensive component in the system, typically made from cinderblock, reinforced concrete, precast concrete, fiberglass, or steel. Rain barrels and cisterns capture water from the roof that can be later used on lawns, gardens and indoor plants. RWHS typically consist of a catchment area (roof), conveyance (screened gutters), roof washer (first flush system), storage (tank), distribution (pump), and purification (a combination of filters + disinfection), as shown in Figure 1.

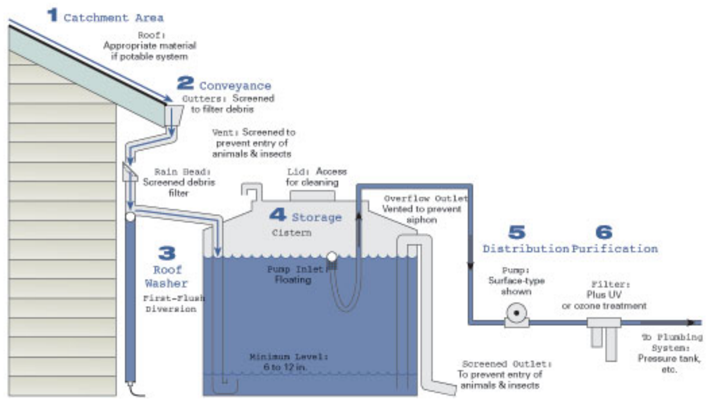


Figure 1 - A rainwater harvesting system (HomePower 2008)

RWHS have been used in households (Campisano et al. 2017; Eroksuz and Rahman 2010; Petrucci et al. 2012; Shadeed and Lange 2010), in multi-unit buildings (Eroksuz and Rahman 2010), schools (Imteaz et al. 2011c), commercial buildings (Imteaz et al. 2011c; Matos et al. 2013; Ward et al. 2012), communities (Cook et al. 2013) and even airports (Neto et al. 2012). Ennenbach et al. even considered the county scale for rainwater harvesting feasibility in the US (Ennenbach et al. 2018).

Rationale for the Study

One of the main obstacles to a more widespread adoption of residential RWHS is the difficulty of reliable maintenance for some owners to maintain the system, potentially compromising water quality (Gurung and Sharma 2014). One way of alleviating the pressure of adequately maintaining the system by individual users would be by adopting a communal rainwater harvesting approach.

Communal rainwater harvesting at the individual residential scale preserves excess runoff from multiple roofs, stores it in a communal tank, then treats and redistributes it as potable water to the community as shown in Figure 2 (Cook et al. 2013; Gurung and Sharma 2014; Gurung et al. 2012; Seo et al. 2012; Seo et al. 2015). Other types of communal RWH currently exist in multi-residential buildings (Agudelo-Vera et al. 2013; Eroksuz and Rahman 2010; Ghisi and Ferreira 2007; Marinoski et al. 2018; Silva and Ghisi 2016). A communal RWHS for single-family houses works best in off-grid locations, where access to the municipal water supply is difficult (Cook et al. 2013; Gurung and Sharma 2014). The main advantage of a communal RWHS over individual RWHS is that it provides a centralized means for adequate maintenance for individual users who could have difficulties maintaining their own system properly. This centralized approach ensures better water quality (Gurung and Sharma 2014) and economies of scale for capital costs, reduced land footprint, centralized disinfection, and flexibility in matching supply and demand for different households (Cook et al. 2013).

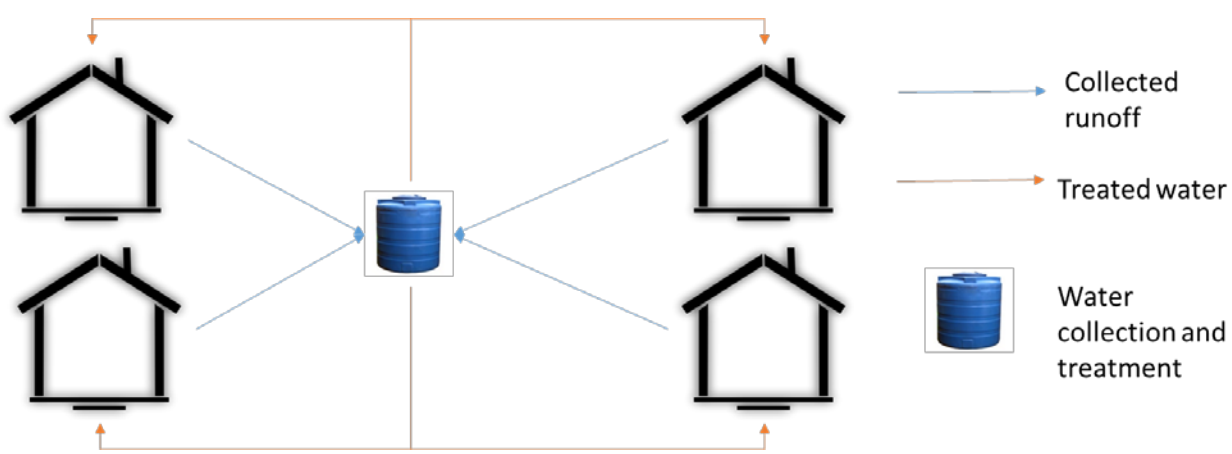


Figure 2 - A conventional single-family house communal RWHS scheme

Only six peer-reviewed publications were found in the literature that dealt with communal RWH for single-family houses. The papers are summarized in Table 1.

Table 1 - Summary of communal RWH for individual homes in the literature

Paper	**System**	**Study type**	**Range of rainfall data**	**Type of connection**	**Water use**	**Number of households**	**Location**	**Reliability**	**Cost**	**Conclusion**
Ward et al. (2010)	Communal RWH	Simulation and experimental	Historical	Physical	Non-potable	173	U.K.	36%	-	Appropriately sizing storage tank is important
Seo et al. (2012)	Rain barrels sharing (water not treated)	Simulation	Historical	Physical or non-physical (community sharing of rainwater)	Non-potable	4	USA (6 cities)	-	-	Reduction in storage size by 37% for heterogeneous users
Cook et al. (2013)	Communal RWH	Monitoring and simulation	Historical	Physical	Potable (excludes flushing, laundry)	46	Australia	90%	-	Successful for mid-sized community
Hashim et al. (2013)	Communal RWH	Simulation	Historical	Physical	Non-potable	200	Malaysia	60%	443,861 USD	Significant water savings
Gurung and Sharma (2014)	Communal RWH	Simulation	Historical	Physical	Only potable (hot water usage)	Optimal between 192 and 288	Australia	94%	$ 10,150 AUD	Optimal development sizes occurred between 192 and 288 households

Seo et al. (2015)	Rain barrels sharing (water not treated)	Simulation	Historical	Physical or non-physical	Non-potable	4	Korea (4 locations)	80%	-	Reduced storage by 61%

Key points observed in a synthesis of the literature shown in Table 1 include:

a. Only one prior work discussed the cost of the system per household (Gurung and Sharma 2014), which can be quite significant in terms of feasibility but could become lower with the economies of scale.

b. In the Gurung and Sharma study, the communal system met 94% of the potable water demand, which excluded flushing and laundry and none of the non-potable water demand (Gurung and Sharma 2014). The system studied by Cook et al. (Cook et al. 2013) attempted to meet some potable water demand, but the remaining three works only sought to meet non-potable water demand (Hashim et al. 2013; Seo et al. 2012; Seo et al. 2015; Ward et al. 2010).

c. The communal tank proposed by Gurung and Sharma (Gurung and Sharma 2014) was sized for individual use then multiplied by the total number of users of the communal system, which does not improve on the reliability of the system since the total quantity of available water is the same. Hashim et al. (2013)'s system determined the size of the tank for the minimum total cost.

d. The rainfall data considered in sizing the systems is only historical data; hence, climate change was not considered. Climate change affects the tank size and the reliability of the system: in locations where more rainfall is expected, the tanks should be sized smaller whereas in locations where more dry spells are expected, tanks should be sized bigger (Haque et al. 2016; Lash et al. 2014; Youn et al. 2012). In other words, the tank size that is considered to reliably meet expected water demands could become undersized in the presence of longer dry periods and oversized if more rainfall is expected.

It is especially important to design a communal RWH that can: a) accommodate climate change by sizing the system accurately, therefore minimizing cost and reducing potential problems of water age from oversizing, b) meet more water demand, and c) increase reliability. For that purpose, we ask a fundamental question: can we improve on the existing communal RWHS for single-family houses where reliability and water demand met is increased while the cost to individual owners does not increase greatly?

Increasing the reliability of a communal RWHS for single-family houses and meeting an increase in water demand can be effective if we consider connecting several RWH systems to a backup communal tank as shown in Figure 3. In the proposed novel communal system, the overflow from these multiple individual RWHS will be stored in a backup communal tank, which can then be returned to the users when needed. This scheme is comparable to how the smart grid returns back to the grid the excess energy harvested for other users' consumption, thus minimizing the load on the energy grid.

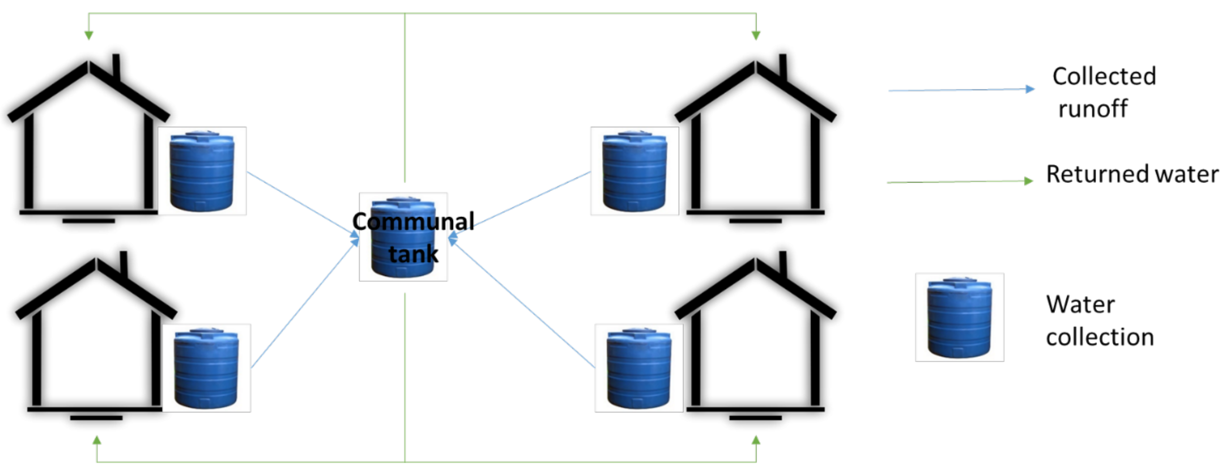


Figure 3 - Connected RWHS to a communal backup tank

The advantages of such a communal approach are as follows:

1. Owners have the freedom in using the disinfection method they choose instead of being forced to use the “central” disinfection method. They could also opt out of using water treatment.
2. A smaller amount of rainwater will be wasted compared to using individual RWHS, and less runoff will go into stormwater systems, thus reducing load on wastewater infrastructure.
3. Increasing the amount of storage available will increase water demand met as well as reliability of service.
4. By adding a backup communal tank, individual household storage tank size could be reduced (Seo et al. 2012), which would balance the cost of all the extra components needed for the communal system especially given that the bigger the tanks, the more expensive they get as shown in Figure 4.
5. This communal system will be more resilient in the face of climate change because its design can take into consideration expected changes in the climate.

Even though connecting several rainwater harvesting systems to a backup communal tank offers potential advantages such as a higher reliability of meeting water demands, the effect on cost has not been studied and in fact costs per user might increase. Some of those costs will include additional piping, pumps and tanks. So the question becomes:

Can connecting multiple single-family’s rainwater harvesting systems to a backup communal tank balance cost and reliability in a way to better satisfy water demand than a single traditional RWH system? We will examine in detail a) how the performance of such a system can be modeled, b) its optimal tank sizes, reliability and connected number of individual systems and c) the total cost of ownership.

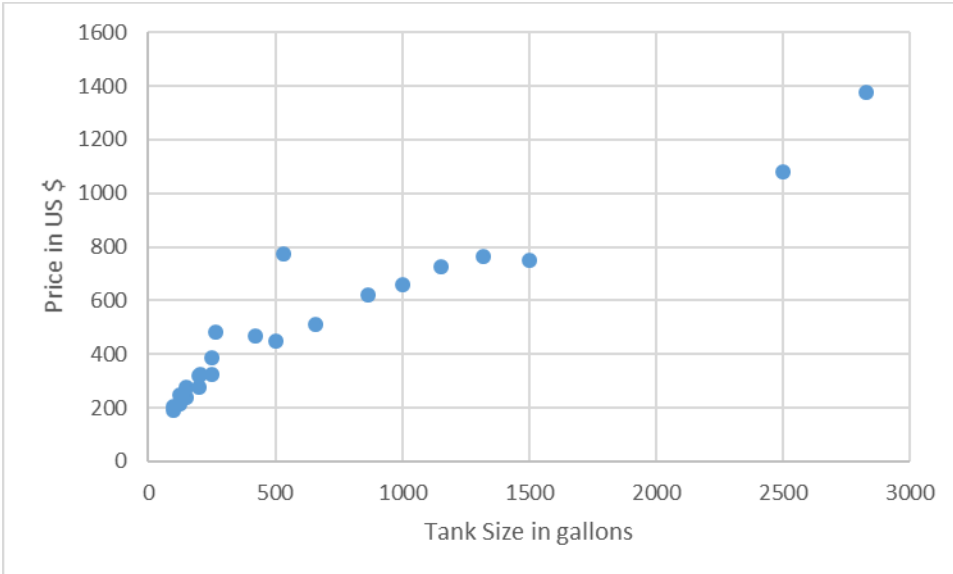


Figure 4 - Price of tanks in proportion to tank size; only polyethylene tanks were selected because they are most commonly used in rainwater tanks at a residential scale across the US for the year 2018 (data from *(Tank Depot 2018; Thomas et al. 2014)*

Sizing of RWHS

An apparent lack of economic benefits and the high first costs are often quoted as the major reasons for the lack of a more extensive implementation of RWHS (EPA 2013). However, recent increases in water bills might accelerate the adoption trend. Indeed, the price of residential water service in 30 cities across the US rose faster than all other household staples in 2015 (Walton 2015). The combined monthly charges for water, sewer and stormwater for a four-person family at the 100-gallon per person per day level in Atlanta was $325.52 and in Seattle $309.72.

Rainwater harvesting affects both the potable and stormwater infrastructures by reducing water demand and reducing stormwater runoff. In fact, several states and cities across the US are offering tax incentives, credits, and rebates to encourage the adoption of RWHS and consequently reduce demand on these infrastructure systems (Loper 2015).

The bulk of the cost of a typical RWHS lies with the choice of the cistern. Cisterns vary in price depending on the material, size, location, and shape but costs are typically between $1.50 and $3.00 per gallon of storage. This cost does not include the cost of pumps, controls, filtration and/or distribution, which could add $2 to $5 per gallon of harvesting capability (EPA 2013). Moreover, some systems require excavation, which can significantly add to the cost of the project.

Since tanks are the costliest individual component of the system (tanks account for 30% of the whole-of-life costs (Gurung et al. 2012), capital costs make up (80%-82%) the majority of the costs (Stewart 2011), and simulations have shown that installed tanks can be oversized with respect to demand (Ward et al. 2010), care should be taken to correctly size the system. In fact, modelling tools have been developed to simplify the evaluation and design of RWHS. Even though ultimately all tank sizing models rely on mass balances in order to size tanks, different types of models exist to optimize the tank design:

- Empirical relationship methods (Ghisi 2010; Palla et al. 2011): empirical relationships are used to describe the sizing of rainwater tanks. Some parameters used include rainfall, water demand, roof area, etc. The advantage of such methods is to, in fact, assess the effect of several parameters on tank sizing. For example, Ghisi (Ghisi 2010) determined that multiple parameters (rainfall, roof size, runoff, water demand) all equally impact tank sizing and are equally important when making tank size determinations.
- Stochastic non-parametric methods (Basinger et al. 2010; Cowden et al. 2008b): these methods use stochastic methods to simulate an important parameter in tank design, for

which data is missing or incomplete. For instance, Basinger et. al (Basinger et al. 2010) used a bootstrapped Markov chain to simulate rainfall data in NYC for the past 25 years.

- Stochastic parametric methods (Guo and Baetz 2007): stochastic parametric methods use both probabilistic methods in conjunction with an analytical approach to optimizing tank sizing. For instance, Guo and Baetz (Guo and Baetz 2007) used probabilistic methods of local rainfall characteristics to analyze the operation of a rainwater storage unit.
- Continuous mass balance simulation of the tank inflow and outflow (Campisano and Modica 2012; Fewkes 2000; Liaw and Tsai 2004b; Mitchell 2007; Sample and Liu 2014): mass balances typically represent the inflow, outflow, and losses of the tank in order to represent the optimal tank size. The model may use different time scales and algorithmic models (yield before spillage and yield after spillage) to estimate tank sizes (Jenkins and Pearson 1978). Campisano and Modica (Campisano and Modica 2012) used the daily water balance simulations for 17 rainfall gauging stations in Italy in conjunction with the yield-after-storage algorithm to estimate optimal tank design.

The performance of rainwater harvesting systems is generally expressed in terms of either the volumetric reliability or the time-based reliability (McMahon et al. 2006). The volumetric reliability, also known as water-saving efficiency, is defined as the total volume of rainwater supplied divided by the total demand during the entire simulation period. The time-based reliability requires taking into account the time steps when the demand is fully met and can be defined as the fraction of time when the demand is fully met.

Using the parallel example of energy storage, sizing for energy storage of photovoltaic cells (PV cells) uses historical solar radiation data, energy demand data, number of PV cells, seasonal impact on appliances and number of users in the case of sizing energy storage for a community

(Alharbi and Bhattacharya 2018; Hemmati 2018; Zhu et al. 2017). Water tank sizing, similarly to energy storage sizing, encompasses several parameters such as historical rainfall data and user water demand. Table 2 shows examples of the different models used for tank optimization, as well as the parameters used in the models.

Table 2 - Example of models and parameters used for tank sizing

Paper	**Model Type**	**Location**	**Parameters**	**Model used**
Fewkes (2000)	Mass balance	5 locations in the U.K.	Daily rainfall, Roof area, Volume in store, Yield from store, Store capacity, Demand fraction: D/AR, Storage fraction: S/AR	Yield After Spillage (YAS)
			Monthly rainfall, Volume in store, Yield from store, Store capacity, Demand fraction: D/AR, Storage fraction: S/AR	Yield Before Spillage (YBS)
Palla et al. (2011)	Mass balance	Italy	Historical precipitation, Runoff coefficient: 0.8, Roof area: 250 m^2, Water demand, Detention time (water spent in tank), Demand fraction, Storage fraction, Water saving efficiency, Rainwater overflow ratio	Yield After Spillage (YAS)

Paper	Model Type	Location	Parameters	Model used
Guo and Baetz (2007)	Stochastic, parametric	Chicago Phoenix	Roof area, Rainfall statistics, Runoff coefficient, First flush, Use rate	Synthetic rainfall generator, Poisson distribution
Cowden et al. (2008b)	Stochastic, Non-parametric	West Africa	Per capita roof area, Runoff coefficient, Daily rainfall	Synthetic rainfall generator, Markov
Basinger et al. (2010)	Stochastic, non-parametric	NYC		SARET: Storage and reliability estimation tool
Ghisi (2010)	Parametric	Brazil	Roof area, Potable water demand, Location, Number of residents, Daily rainfall, Daily rainwater demand as percentage of potable water demand, Rainwater tank capacity, Runoff coefficient (assumed 80%)	Neptune (Ghisi and Trés 2004): water balance Daily basis analysis

Sizing a rainwater harvesting tank accounts for at least 30% of the whole-of-life costs of RWHS and directly impacts its reliability (Gurung et al. 2012). Hence, correctly sizing the cistern for the needs of the users is important in terms of managing total cost of ownership while maintaining adequate

Several examples of optimal tank sizing are found in the literature. Those examples are summarized in Table 3 .

Table 3 - A summary of tank optimization peer-reviewed papers in the literature

Paper	Type of water	Type of Building	Time step	Tank size	Reliability (%)	Overflow	Cost	Simulation/ experimental
Fewkes (2000)	Non-potable	Not specified	Daily/ monthly	-	-	-	-	Simulation
Wung et al. (2006)	Non-potable	School	Monthly	190 m^3	100%	-	-	Simulation
Eroksuz and Rahman (2010)	Potable, non-potable	Residential (multifamily)	Daily	10 kL to 100 kL	10-52%	-	-	Simulation
Jones and Hunt (2010)	Non-potable	Other	15 minute to 1 hour intervals	208 L	14 - 53% volume captured	Overflow frequency between 46% and 80%	-	Simulation/ experimental
Belmeziti et al. (2013)	Non-potable	Residential, business	Average	Range	-	-	-	Simulation
Dallman et al. (2016)	Non-potable , irrigation	Residential	15 minute interval	208 L cistern most effective	-	0 to 24% reduction in annual volume	Yes	Simulation
Hajani and Rahman (2014)	Non-potable	Residential	Average	5 kL	96-99% 69-99% (during dry year)	-	Yes	Simulation
Khastagir and Jayasuriya (2010)	Non-potable	Residential	Daily	Between 1 kL and 9 kL	85 - 95%	-	-	Simulation
Ward et al. (2010)	Non-potable	Office building and communal development	Continuous	9 to 10 m^3 12 to 30 m^3	36 - 46%	-	-	Simulation

Paper	Type of water	Type of Building	Time step	Tank size	Reliability (%)	Overflow	Cost	Simulation/ experimental
Basinger et al. (2010)	Non-potable	Residential	Average	5 m^3	7 - 40%	Reduction of runoff by 28%	-	Simulation
Palla et al. (2011)	Non-potable	Residential	Daily	Range	Range	-	-	Simulation
Imteaz et al. (2011a)	Irrigation	Residential	Daily	110 m^3 and 185 m^3	-	-	-	Simulation
Palla et al. (2012)	Non-potable, toilet flushing	Residential	Average	0.4 – 150 m^3	30- 95% depending on storage	-	-	Simulation
Rahman et al. (2012)	Non-potable	Residential	Daily	2 kL, 3kL and 5kL	38 - 99%	-	-	Simulation
Umapathi et al. (2013)	Non-potable	Residential	Continuous/ Average	-	31%	-	-	Experimental
Matos et al. (2013)	Non-potable (pavement washing and irrigation)	Commercial building	Average	11 m^3	-	-	-	Simulation
Vialle et al. (2015)	Non-potable	Residential	Average	5 m^3	87%	-	-	Simulation
Notaro et al. (2016)	Non-potable	Residential	Daily	10,15,20 m^3	75-95%	-	-	Simulation
Silva and Ghisi (2016)	Potable and non-potable	Residential (multifamily)	Daily	Range up to 50,000 L	30-70%	-	-	Simulation
Ghimire et al. (2017)	Non-potable	Office building	Average	20,000 gallons	77%	-	-	Simulation

Synthesizing the papers in Table 3, we can summarize the following:

- Only Eroskuz and Rahman (Eroksuz and Rahman 2010) optimized tank design for potable and non-potable water demands, but for a multi-residential building, not for single-family dwellings.
- Even though several prior works propose models to optimally size residential RWHS, only a few do for all water demands (Eroksuz and Rahman 2010; Silva and Ghisi 2016) with a reliability of 70% at most. None of the designs discuss the costs associated with the system.
- The literature does not quantify the overflow from the tanks except for Jones and Hunt, Dallman et al. and Basinger et al. (Basinger et al. 2010; Dallman et al. 2016; Jones and Hunt 2010) where the reduction of outflow is expressed in percentage.

Research Problem and Purpose of the Study

Since this research deals with a novel approach to communal RWHS, none of the models described above are able to satisfy the modeling requirements of the proposed new system, given its cascading flows from multiple tanks to a communal storage tank. The outflow from the individual tanks is an important parameter in the new design which is not usually quantified in the optimal sizing of RWHS. Few prior works (Eroksuz and Rahman 2010; Silva and Ghisi 2016) design a RWHS for potable use with a higher reliability.

Hence, we propose building a new sizing model for the system, based on the models available in the literature, that can model single-family RWHS connected to a communal backup tank, evaluate the optimal/acceptable tank sizes, and reliability for connected systems, and evaluate the total cost of ownership of the system.

Research Questions

The *purpose* of this research is to evaluate the effects in terms of ***total cost of ownership*** and ***reliability*** of meeting potable and non-potable water demands in ***residential households*** using a system that connects several rainwater harvesting systems to a backup communal tank. A sizing model will be designed to simulate this new rainwater harvesting configuration. The outcome of this sizing model will be used to assess the total cost of ownership. The ***research questions*** of this research are as follows:

1- What sizing model can describe the new communal rainwater harvesting system?

2- How will this proposed storage by the new sizing model affect reliability of the system compared to the reliability of the original setup, and what is the optimal number of connected systems?

3- What is the total cost of ownership associated with this new communal system of connecting multiple RWHS to a communal backup tank?

Dissertation Organization

This dissertation is organized into five chapters. The first chapter provided a general overview and a literature review to understand the rationale behind conducting this research and introduced the perspective of the research problem, which introduced the research questions.

Chapter two introduces the research design, which is divided into three phases. On top of the research design, this chapter includes the limitations of the study in each phase. Chapter three discusses simulation validation for rainwater harvesting system performance. Chapters four, five and six mirror the three phases laid out in chapter two. Chapter four is a review of optimal sizing for rainwater harvesting. Chapter five is the simulation of this novel communal rainwater harvesting system. Chapter six is the total cost of ownership per household of the connected households to this communal harvesting system. Chapter seven discusses the impact of the communal system on water usages, the tragedy of the commons and its impact on the operation of the novel system. Chapter eight presents the conclusions for the overall research question and the sub-questions, the expected outcomes of these findings and the future impact of this research.

List of Publications

As a byproduct of the above contributions, thus far, this dissertation has made the following key contributions:

- **Mary Semaan**, Susan D. Day, Michael Garvin, Naren Ramakrishnan, and Annie Pearce. "A novel approach to rainwater harvesting systems for single-family households: distributed rainwater harvesting", *Journal of Water Resources Planning and Management*, planned for submission in March 2020.
- **Mary Semaan**, Susan D. Day, Michael Garvin, Naren Ramakrishnan, and Annie Pearce. "Optimal sizing of rainwater harvesting systems for domestic water usages: a systematic literature review", *Resources, Conservation and Recycling:X*. Accepted and to appear 2020.

CHAPTER 2: RESEARCH DESIGN

This research aims to make residential communal RWHS more reliable and less costly by connecting multiple RWHS to a backup tank which, we hypothesize, will increase the reliability of the system compared to the original individual system and decrease the associated costs to individual owners of such a system. The research will be conducted in several phases as described in Figure 5.

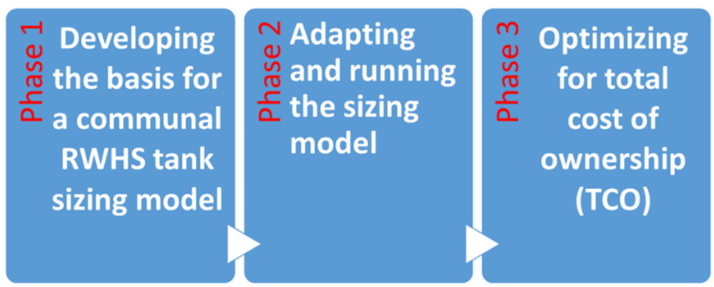


Figure 5 - Overall research design

Model limitations or constraints

This communal RWHS model is bounded by the following conditions:

1. The individual tanks for the communal system have to be smaller than the size they would have had without the communal backup: according to Seo et al. (Seo et al. 2012), sharing rain barrels reduced the total storage size depending on the target reliability.
2. In this research, we are assuming that all users have homogeneous water demands, hence all tanks for individual system are the same size.

3. The reliability of meeting water demands of the re-designed communal RWHS has to be an improvement over the configuration of stand-alone systems.
4. The cost of the communal tank and accessories have to be less or comparable than the marginal individual savings from downsizing individual storage.

Phase 1: Developing the basis for a communal RWHS tank sizing model

Objective: Select a tank sizing model that works for the novel communal system

Research approach: Rainwater tank sizing and reliability metrics will be required in order to address objective one. Those variables needed to build the sizing model will be assessed from a systematic literature review. The goal of the first phase is to select a model that will work for this novel communal RWHS.

Study population: The study population for the first objective is peer-reviewed journal articles that specifically address RWHS tank sizing and reliability.

Data collection/Analysis techniques: The systematic literature review will focus on peer-reviewed journals between 1999 and 2019 published in English. Preliminary search has narrowed the timeline to peer-reviewed journals published after 1999. The search terms will be: “rainwater harvesting”, “tank sizing”, “reliability”, “storage” and variations of “size”. The main search engines will be Google Scholar, Web of Science and the ASCE database. The snowball technique will also be used to identify relevant material for collection.

Implementation:

1. Inventory available peer-reviewed publications about optimal tank sizing

This task is important to inventory the different optimal models and parameters used in order to adapt the best-fitting approach to modelling connected RWHS with backup communal storage. This step is significant because Part II of the work will consist of a) sizing individual tanks before connecting them and, b) possibly re-sizing the tanks and the backup communal tank to take into account the new connections to the backup communal tank. A result of this task will be a list of the optimal sizing models that are used to estimate size and usage of RWHS in existing papers. Screening terms will include terms such as “optimal”, “optimize” and “rainwater harvesting”. The scope of the search will be limited to residential RWHS for potable and non-potable usage.

2. Evaluate the available sizing models for suitability to current objective

The vital question which will be answered in this task is the following: what makes an optimal sizing model for communal RWHS? The sizing model must satisfy the following conditions:

- Time-step: daily
- Geographic location: USA
- Input: average/variable water demand
- Building type: residential, single-family house
- Purpose: all water usage

3. Select and configure sizing model

After reviewing the available literature on optimal tank sizing, this task will focus on determining the optimal model for the new system based on the criteria listed in subtask 2. The parameters of the model have to also be chosen to satisfy the new constraints. For instance, parametric modelling has been used when crucial data needed for the sizing was missing. On the other hand, water mass balances were more effective when historic rainfall data was available.

Limitations: The scope of the literature review will be limited to publications published in English and focused on tank sizing and reliability for residential homes.

Outcomes: Phase 1 sets up the sizing model and parameters that will be used to run the modelling in Part II by performing a review of the literature available with regards to tank sizing and system reliability. The outcome of this phase will be a sizing model that can optimize connected residential RWHS to a communal tank in terms of size and reliability.

Phase 2: Adapting and running the sizing model: optimizing size and reliability

Objective: Optimize the new system's performance with regards to tank size, reliability and number of connected households using the sizing model

Research approach: In this phase, the emphasis of the research will be on adapting and running the RWHS sizing model developed in Phase 1, to find out the following:

- What will the optimal number of connected houses of the communal RWH system be?
- What reliability can this RWH system provide compared to stand-alone RWH?

For that purpose, an optimization model describing the communal RWHS will be derived and simulated in order to get the optimal system.

Study population: The study population, i.e., the population being modeled, for this objective will be the RWHS of single-family households, that will provide sufficient water to meet all water demands.

Data collection/Analysis techniques: In this analysis, regions that have access to historical rainfall data will be selected; thus, a continuous mass balance will be used to simulate tank performance to simulate the optimal tank size for individual tanks and a continuous mass balance simulation for the communal system.

Implementation: Unlike for an individual RWHS, connected multiple RWHS multiple tanks with a communal backup tank need to be optimized recursively in terms of size and reliability. The output of Phase 2 will be an optimized connected RWHS in terms of tank sizes, reliability, and number of connected systems.

1. Optimize tank size and reliability for an individual RWHS

After selecting a model in Phase 1, the sizing model selected will be adapted to the new communal system. Of the parameters that will differ from individual sizing systems is the recursive nature of the water demand and availability, which does not exist in individual systems.

a. Sizing individual tanks for a given reliability: this step will inform the maximum tank size and the minimum reliability that can be targeted in the connected system.

b. Connecting two systems and calculating overflow: measuring the overflow is critical to correctly size the communal backup tank.

c. Sizing the communal tank to capture the overflow: in typical communal RWHS, the communal tank is sized by sizing an individual tank and multiplying it by the number of connected households (Gurung and Sharma, 2014). In this study, the communal tank being the receptacle of overflows will be sized depending on the amount of overflow received and water demand from connected RWHS.

2. Adapt the selected tank sizing model to work with a communal RWHS with a connected backup tank

The first step is to solve for the individual tank size prior to connecting multiple RWHS to a communal backup tank. A point of reference for future analysis will be provided by optimizing the tank and reliability for a single household, before connecting it the communal system. The output of this task will be a reference point in terms of maximum tank size and minimum reliability achievable by the communal setting.

3. Optimize tank size and reliability of the communal system

This step is essential to determine the sizes of the individual tanks and the backup tank for multiple reliabilities. In this task, a scenario consisting of two connected households will be considered. The adapted sizing model derived from Phase 1, will be used to estimate the individual tank sizes, the communal backup tank size and the optimal reliability of the system.

4. Optimize communal system in terms of number of houses for optimal reliability

The resulting optimal tank sizes and reliability obtained in the previous task, will determine the optimal size of users of the system where we can maintain the highest reliability with the smallest tank sizes. Once an optimal balance in terms of number of users, tanks sizing and reliability is reached, we will use the optimized number of users, tank size and reliability to calculate the total cost of ownership of the system in Phase 3.

Limitations: The water demand will be assumed to be constant as not enough information is available on daily water demands in the USA. This study will be limited to homogenous users, i.e., households that are expected to use the same water volume per day, similar to the communal system sizing in Gurung and Shamra (Gurung and Sharma, 2014) and to one scenario in Seo et al. (Seo et al., 2012).

Outcomes: The outcome of Phase 2 is a communal RWHS for an optimal number of homogeneous houses and for a given reliability.

Phase 3: Optimizing the TCO to individual households

Objective: Optimize the system design in terms of cost

Research approach: In order to assess the total cost of ownership, reliability and size of the system will be fixed and the cost of the system will be calculated based on multiple scenarios.

Study population: The study population will be new communal system with the optimal number of users as determined in Phase 2.

Data collection/Analysis techniques: The main data needed for this phase are market inventory of parts and prices as related to the new system. After reaching the optimal number of users in Phase 2, the total cost of ownership of the system will be determined to understand its impact on individual users in terms of the variability of costs associated with the system.

1. Identify the components of the system and their costs

   Since the system now includes connections from and to the backup communal tank, several components have to be added to the total cost of the system. Some of these components include: piping for the distribution system to and from the backup communal tank, pumps, additional tank(s), capital costs (excavation and installation of system), ongoing costs (power and maintenance costs).

2. Determine the total cost of ownership associated with the system

The cost contributions will be estimated for the connected RWHS. The total cost of ownership will be estimated considering capital (laying pipe network + additional tank + pumps), operation (cost of power running the pumps), maintenance (maintaining the tank and pumps) and replacement (replacing components at the end of their life span) costs. Two scenarios will be explored to determine the best cost-scenario for individual house owners, as follows:

a. The first cost scenario will be to look at the TCO of an individual system that is not communal nor connected. This first step will provide the basis for future analysis in terms of cost.

b. The second scenario will consider the TCO of the novel approach to communal RWH, by connecting the multiple individual systems to a backup tank for the same number of households as in Step 2.

Phase 3 will build on Phases 1 and 2 to a) develop a total cost of ownership model for the novel approach to RWHS and b) compare the TCO of three scenarios, especially novel communal approach versus the original approach

Limitations: The first limitation of this study is the assumption that the households considered will be on flat terrain. The second limitation will be the homogeneous use of water across all households. Hence, we will consider a homogeneous yield. The third limitation will be the assumption that the siting of the communal backup tank will be favorable to all residents and well secured.

Outcomes: The outcome of Phase 3 is a cost model of the total cost of ownership of the system based on three proposed scenarios.

CHAPTER THREE: SIMULATION VALIDATION OF RAINWATER HARVESTING SYSTEMS PERFORMANCE

Introduction

In general, to ascertain whether a computer simulation model's output is valid, the model has to go through verification and validation. Model verification is defined as "ensuring that the computer program of the computerized model and its implementation are correct" and the model validation is generally defined to mean "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" (Sargent 2009).

The verification and validation of the modeling process can be summarized as follows:

The *problem entity* is the real problem that is being modeled, the *conceptual model* is the representation of that problem (mathematical, logical or verbal representation) and the *computerized model* is the conceptual model implemented on a computer.

The role of conceptual model validation is to verify a) the theories and assumptions underlying the conceptual model and b) the model representation of the problem entity. Computerized model verification reinforces that the computer programming and implementation of the conceptual model is correct. Operational validation determines that the model's output behavior has sufficient accuracy for the model's intended purpose over the domain of the model's intended applicability. Data validity ensures that the data necessary for model building, model evaluation and testing, and conducting the model experiments to solve the problem are adequate and correct (Sargent 2009).

Validation techniques

The following describes several validation techniques and tests used in model verification and validation of the submodels and the overall model of computer simulations (Kleijnen 1995; Martis 2006; Sargent 2009). A combination of these techniques is generally used.

Animation: the model's operational behavior is displayed through time (Dargham and Semaan 2008; Niazi et al. 2017).

Comparison to other models: outputs of the simulation model being validated are compared to results of other valid models (Dawson et al. 2014; Standridge et al. 2015).

Degenerate tests: the degeneracy of the model's behavior (limiting values) is tested by appropriate selection of values of the input and internal parameters (Lemke and Łatuszyńska 2013; Zambrano et al. 2014).

Event validity: the "events" of occurrences of the simulation model are compared to those of the real system to determine if they are similar (Abu-Taieh and El Sheikh 2007; Chen et al. 2012).

Extreme condition tests: the model structure and outputs should be plausible for any extreme and unlikely combination of levels of factors in the system (Pierie et al. 2016; Skawina et al. 2018).

Face validity: individuals knowledgeable about the system are asked whether the model and/or its behavior are reasonable (Celio et al. 2012; Kutluay and Winner 2014).

Historical data validation: part of the data is used to build the model and the remaining data are used to check whether the model behaves as the system does (Celio et al. 2012; Suryani et al. 2010).

Historical methods: the three historical methods of validation are rationalism, empiricism, and positive economics (Ramirez-Hernandez et al. 2016).

Internal validity: several runs of a stochastic model are made to determine the amount of internal stochastic variability in the model (Bernard Nicolau de França and Horta Travassos 2015; Korb et al. 2013).

Multistage validation: this validation method consists o0f (1) developing the model's assumptions on theory, observations, and general knowledge, (2) validating the model's assumptions where possible by empirically testing them, and (3) comparing the input-output relationships of the model to the real system (Érdi et al. 2015; Fu and Gross 2013).

Operational graphics: values of various performance measures are shown graphically as the model runs through time to insure they behave correctly (Crespo and Ruiz 2012; Érdi et al. 2015).

Parameter variability – sensitivity analysis: this technique consists of changing the values of the input and internal parameters of a model to determine the effect upon the model's behavior or output (Olsen and Raunak 2013; van Vliet et al. 2016).

Predictive validation: the model is used to predict the system's behavior, and then comparisons are made between the system's behavior and the model's forecast to determine if they are the same. The system data may come from an operational system or be obtained by conducting experiments on the system (Eek et al. 2015; Glenn et al. 2005).

Traces: the behaviors of different types of specific entities in the model are tracked through the model to determine if the model's logic is correct and if the necessary accuracy is obtained (Fang et al. 2018; van Vliet et al. 2016).

Turing test: individuals who are knowledgeable about the operations of the system being modeled are asked if they can discriminate between system and model outputs (Colasante 2017; Zemla et al. 2011).

Validation of Rainwater Harvesting Simulations

This dissertation involves a simulation of two submodels: individual and communal RWHS. Hence, this section will examine the validation strategies for the two submodels.

Submodel 1: Individual RWHS sizing (summary shown in Table 4*).*

Table 4 - Summary of validation techniques used in works related to optimal tank sizing

	Animation	**Comparison to other models**	**Degenerate tests**	**Event validity**	**Extreme condition test**	**Face validity**	**Historical data validation**	**Historical methods**	**Internal validity**	**Multistage validation**	**Operational graphics**	**Sensitivity analysis**	**Predictive validation**	**Traces**	**Turing test**
Fewkes (1999)						x			x	x		x	x		
Fewkes (2000)		x				x			x						
Fewkes and Butler (2000)						x			x				x		
Liaw and Tsai (2004b)						x			x	x					
Guo and Baetz (2007)						x			x			x			
Su et al. (2009)						x			x						
Basinger et al. (2010)		x				x			x			x			
DeBusk et al. (2010)						x			x	x					
Eroksuz and Rahman (2010)						x			x						
Ghisi (2010)						x			x			x			

	Animation	Comparison to other models	Degenerate tests	Event validity	Extreme condition test	Face validity	Historical data validation	Historical methods	Internal validity	Multistage validation	Operational graphics	Sensitivity analysis	Predictive validation	Traces	Turing test
Jones and Hunt (2010)						x			x	x					
Khastagir and Jayasuriya (2010)						x			x			x			
Ward et al. (2010)		x				x			x	x					
Imteaz et al. (2011a)						x			x						
Imteaz et al. (2011c)						x			x	x					
Palla et al. (2011)						x			x			x			
Campisano and Modica (2012)						x			x			x			
Imteaz et al. (2012)						x			x						
Mun and Han (2012)						x			x	x		x	x		
Roebuck et al. (2012)		x				x			x			x			
Matos et al. (2013)						x			x						
Santos and Taveira-Pinto (2013)		x				x			x						
Campisano and Modica (2014)						x			x						

	Animation	Comparison to other models	Degenerate tests	Event validity	Extreme condition test	Face validity	Historical data validation	Historical methods	Internal validity	Multistage validation	Operational graphics	Sensitivity analysis	Predictive validation	Traces	Turing test
Hanson and Vogel (2014)						x			x			x	x		
Liaw and Chiang (2014)						x			x						
Raimondi and Becciu (2014)						x			x			x			
Burns et al. (2015)						x			x	x			x		
Mashford and Maheepala (2015)		x				x			x			x			
Okoye et al. (2015)		x				x			x						
Liuzzo et al. (2016)						x			x			x			
Notaro et al. (2016)						x			x			x			
Pelak and Porporato (2016)						x			x						
Khan et al. (2017b)						x			x						
Lopes et al. (2017a)						x			x						
Ndiritu et al. (2017b)						x			x				x		
Notaro et al. (2017)						x			x						

Prior work has mainly approached validation through two validation techniques: face validity and internal validity as shown in Table 4. Here, it is interesting to note is that only three works (Hanson and Vogel 2014; Khastagir and Jayasuriya 2010; Mun and Han 2012) have a concretely defined verification/validation section. Operational validation is the preferred method of validation for sizing rainwater tanks which several works (Burns et al. 2015; DeBusk et al. 2010; Fewkes 1999; Imteaz et al. 2011b; Jones and Hunt 2010; Liaw and Tsai 2004; Mun and Han 2012; Ward et al. 2010) were able to do. In this case, operational validity entails verification of the simulation with an actual working system. However, most of the literature verified the simulations with systems that were already in place, which, in a way, verifies the underlying assumption of the model using water mass balance equations to understand the performance of a RWHS.

Some prior works compared their simulation results to other models in the literature (Basinger et al. 2010; Mashford and Maheepala 2015; Okoye et al. 2015; Roebuck et al. 2012; Santos and Taveira-Pinto 2013; Ward et al. 2010). Other prior works performed sensitivity analysis (Basinger et al. 2010; Campisano and Modica 2012; Fewkes 1999; Ghisi 2010; Guo and Baetz 2007; Hanson and Vogel 2014; Khastagir and Jayasuriya 2010; Liuzzo et al. 2016; Mashford and Maheepala 2015; Mun and Han 2012; Notaro et al. 2016; Palla et al. 2011; Raimondi and Becciu 2014; Roebuck et al. 2012), especially when using stochastic processes to solve for optimal tank sizing. Several works used prediction validation to verify some of the hypotheses they formulated during the simulations (Burns et al. 2015; Fewkes 1999; Fewkes and Butler 2000; Hanson and Vogel 2014; Mun and Han 2012; Ndiritu et al. 2017).

Submodel 2: Connected RWHS sizing (summary in Table 5 *)*

Table 5 - Summary of validation techniques used in works related to communal RWH

	Animation	**Comparison to other models**	**Degenerate tests**	**Event validity**	**Extreme condition test**	**Face validity**	**Historical data validation**	**Historical methods**	**Internal validity**	**Multistage validation**	**Operational graphics**	**Sensitivity analysis**	**Predictive validation**	**Traces**	**Turing test**
Ward et al. (2010)		x				x			x	x					
Seo et al. (2012)						x			x						
Cook et al. (2013)						x			x	x					
Hashim et al. (2013)						x			x			x			
Gurung and Sharma (2014)						x			x			x			
Seo et al. (2015)						x			x						

With regards to validation techniques used for the second submodel (communal RWHS), all five prior works rely mainly on face validity and internal validity. Two works (Cook et al. 2013; Ward et al. 2010) were able to use operational validity but both papers were published after the communal project was fully operational. Ward et al. (2010) compared several models to establish the effect of time-step on optimal tank sizing. Gurung and Sharma (2014) and Hashim et al. (2013) performed a sensitivity analysis on the prices of connected RWHS.

Strengths of the validation approaches used

- All of the prior works have chosen the modelling approach that works best with what they expected the outcome to be. The introductions are clear on the purpose of the proposed studies and arguments are provided as to which method works better.
- Most prior works are clear on the sources of their data or the reason why they are choosing one model over the other, which makes their work better verified.
- When possible, some simulation methods are tested against the performance of the designed system and the conclusions usually agree with the design. This conclusion actually validates the mass balance approach that is being used by most authors to optimally size tanks.

Weaknesses of the validation approaches used

- Only three prior works (Hanson and Vogel 2014; Khastagir and Jayasuriya 2010; Mun and Han 2012) have an explicit verification/validation section. This does not negatively affect the works that do not include a verification/validation section but it makes the method and results of those three prior works stronger in terms of methodology and conclusion.
- Only a few prior works list clearly the limitations, conditions, and assumptions of their works. This has at least two drawbacks:

    a) If a researcher tried to reproduce their work and couldn't because the authors weren't clear on their assumptions, then the work can be easily discredited;

b) If the authors make an assumption that is not clear or clearly stated in the work, the results are not as reliable.

- Some tank sizing programs are available to download and use, which makes the results of the papers using those programs verifiable and reproducible, boosting their validity. However, most of the tank sizing literature, even though using a simple mass balance to arrive to certain conclusions, have not provided access to their developed simulation programs. This makes reproducing their results challenging which can be seen as a weakness in terms of validation.

This study will approach the question of validity in a different way than what is currently available in prior works to make the output stronger. The proposed validation/verification plan is as follows:

A. Internal validation

1. *Be clear on the assumptions and limitations of the work:* even though most prior works have laid out their assumptions in the introduction part of their work, the limitations of their works is practically non-existent. This has the effect of misinterpreting the outcomes and threatens the *validity* of the results. The proposed mitigation plan would be to a have clearly defined section stating all the assumptions that are being made and the arguments as to why they'd be made as we had previously done (Semaan and Pearce 2018). We will also *clearly state the limitations* of the model. This section is sorely lacking in prior works and we believe it makes the results stronger. This plan works equally for submodels 1 and 2.

2. *Validate/ verify the simulations:*

    a. *Submodel 1*: based on the literature pertaining to RWHS tank sizing, except for a few seminal works (e.g. (Basinger et al. 2010; Fewkes 2000; Ghisi 2010), prior works rely on the proven or most adopted models for their work (such as yield-before-spillage model, yield-after-spillage model, etc.). And given that the underlying problem entity is fundamentally well-established (mass balance with few inputs and outputs), there is no need to elaborate on the programming tool or code used. However, most results with similar starting conditions tend to converge, hence, once we decide on a model (in accordance with the well-established norms), there is no need to validate the model itself. The variation then becomes inherent in the data chosen, the granularity of the time-steps and the values for the external variables. The limitation of this approach is the lack of transparency in terms of reproducibility of the results. However, if a need arises to show the underlying work, we will be able to do so.

    b. *Submodel 2*: the *challenge* with submodel 2 is the fact that neither the problem entity (network of connected individual RWHS) nor the conceptual models are validated or verified in prior works because of the novelty of the approach. However, parts of the model are validated. For example, we know from Seo et al. (Seo et al. 2012; Seo et al. 2015) that sharing rainwater storage has a direct effect on reducing individual storage. Hence, we can verify the assumption that the optimal storage results will decrease by comparing them to the reductions achieved by Seo et al.

The *limitations* of this approach is the fact that neither the traditional communal approach nor the proposed novel approach can be verified operationally (due to the need for an expensive large-scale experimental system that is operational). However, being very clear on the assumptions and limitations of the model can strengthen its conclusions and provide a proof of concepts for future experimental works.

3. *Perform a sensitivity analysis on parameters or variables in the submodels:* a sensitivity analysis is performed to determine how independent variables will impact a dependent variable under a given set of assumptions (Ghisi 2010; Guo and Baetz 2007). In submodel 1, based on prior works (Basinger et al. 2010; Fewkes 2000), it is reasonable to use the model without a sensitivity analysis on the different variables seeing that this work has already been done. However, in submodel 2, a new variable (the cost function) to measure the total cost of ownership of the new system is introduced, hence a sensitivity analysis on the TCO will be performed as in Gurung and Sharma (2014); Nurhadi et al. (2014). Some questions that sensitivity analysis can answer include the following:

    a. Which factor is the most influential and significant when the TCO is determined? The answer to this question could help reduce the uncertainty factors that may impact the TCO, since economic factors such as future investment costs, operating expenses, energy cost, and others may not be known with great precision.

    b. "What if questions", such as: What happens to the TCO of an RWHS owner if…

        i. … the price of the metered MWS increases?

        ii. … number of operational years of the communal system varies?

iii. … energy cost changes?

iv. … maintenance cost changes?

B. External validation

External validity is making sure that the internal workings of the simulation corresponds to the way the system would function outside the simulation. Cook and Campbell defined the issue of external validity as the probable validity with which we can deduce that the simulation model can be generalized (Cook and Campbell 1979). Hence, external validation can be summarized by the following question: does the simulation model represent actual external events?

The measures for external validation include an evaluation of the correctness and fitness of the model vis-à-vis its application. The most important external validity criteria include the following characteristics (Murray-Smith 1995):

a. *Theoretical validity*: the model should show generally consistency with conventional concepts or is grounded on a reasonable theoretical basis.

The proposed research does indeed satisfy the theoretical validity aspect because a) it is based on methods that have been proven in previous works(Fewkes 2000; Ghisi 2010; Imteaz et al. 2011a) and b) is an improvement on a model (traditional communal RWHS) that has also been proven in prior works (Cook et al. 2013; Gurung and Sharma 2014).

b. *Empirical validity*: the model needs to show acceptable agreement between its behavior and that of the real system.

> The proposed research describes a novel approach to communal RWHS. The model is similar to the proposed model in prior works where the model did measure up to the actual real system's performance (Cook et al. 2013).

In essence, the proposed methods for conducting this research will rely on simulation methods used by prior works to verify and validate the results.

The main challenge of this approach is the inability to compare the system model to a real system because of the novelty of the approach. The way to overcome this task is by, a) clearly delineating the system with the use of explicit boundary conditions, b) being transparent with regards to the data and parameters used in the model and c) validating the final results (costs) with RWHS sellers in the geographic area pertaining to the case study.

CHAPTER FOUR: SYSTEMATIC LITERATURE REVIEW OF OPTIMAL TANK SIZING OF RAINWATER HARVESTING SYSTEMS FOR DOMESTIC WATER USAGES

Introduction

Urbanization and shrinking cities are having an impact on infrastructure, particularly aging water infrastructure. At the center of decentralized water infrastructure lies rainwater harvesting systems (RWHS). The vital importance of RWHS is the effect they have on the three water networks (potable, stormwater, and wastewater) in terms of decreasing water demand on the potable water network, decreasing stormwater runoff, and, if coupled with greywater recycling systems, decreasing the quantity of wastewater generated by using water multiple times before discharge (Ghisi and Ferreira 2007).

Tanks are the costliest individual component of the system since they account for 30% of the whole-of-life costs (Gurung et al. 2012). As a result, capital costs make up (80% - 82%) the majority of the lifecycle costs (Stewart 2011). Simulations have shown that installed tanks can be oversized with respect to demand (Ward et al. 2010), and thus to optimize lifecycle costs, care should be taken to correctly size the system to decrease the cost associated with an oversized tank and to avoid increasing water age (Wales 2006). In fact, modeling tools have been developed to simplify the evaluation and design of RWHS with a specific focus on the task of storage sizing. Different types of models include:

- Empirical relationship methods (e.g., Ghisi 2010; Palla et al. 2011), where empirical relationships are used to describe the sizing of rainwater tanks. Parameters used typically include rainfall, water demand, and roof area.
- Stochastic parametric and non-parametric methods (e.g., Basinger et al. 2010; Cowden et al. 2008a; Guo and Baetz 2007), which use stochastic techniques to simulate important parameters in tank design, for which data is missing or incomplete.
- Continuous mass balance simulation of the tank inflow and outflow (e.g., Campisano and Modica 2012; Fewkes 2000; Imteaz et al. 2011b; Liaw and Tsai 2004a; Mitchell 2007; Sample and Liu 2014), where mass balances typically represent the inflow, outflow, and losses of the tank in order to characterize the tank size. The models may use different time scales and algorithmic models (yield before spillage and yield after spillage) to estimate tank sizes (Jenkins and Pearson 1978).

The purpose of this systematic literature review (SLR) is to define what is typically being optimized in the literature with respect to RWHS, the methods used, limitations of existing studies, and implications for practice. In this SLR, we focus on articles related to optimizing the variables related to RWHS design that directly impact the tank size.

It is also worth noting, from a credibility standpoint, that while storage size is a significant determinant of system cost, other moderating variables could result in cost changes. For example, incorporating a treatment system for potable use may only be feasible above a certain system capacity. Thus, cost functions for smaller sizes would have an advantage if this factor was considered, mainly for the primary purpose of optimization. The nature of optimization is to find the best or most effective use of resources. Hence, with regards to RWHS, optimizing a RWHS goes beyond the sizing of the tank and could involve other objectives. This research will take the intent of optimal sizing into account in the SLR.

Methodology

We performed an SLR on the optimal sizing of RWHS in order to get a clear understanding of how these analyses are implemented. We chose to use the SLR as our main method for gathering and processing information because: a) it closely follows scientific methods, b) it limits bias with the general goal of producing a methodical synopsis of the research in a particular field of study, and c) it identifies research or knowledge gaps and areas for future studies (Petticrew and Roberts 2008). An SLR is needed here in order to get an accurate picture of existing approaches for optimally designing RWHS to uncover opportunities for future research and development. We adopted the Cochrane method for conducting the SLR, supplemented by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) checklist to ensure consistent and complete presentation of methods (Higgins and Green 2011; Moher et al. 2015).The Cochrane method allows researchers to ground their outcomes on the results of studies that meet specific quality criteria, since the most dependable studies will offer the best proof for making decisions about a variety of topics, which minimize the effect of bias across different sections of the review.

The first step of a meta-analysis using this method is defining the research questions related to the research subject; hence, we defined the following questions that needed to be answered by the SLR:

Research Question 1: What variable(s) is being optimized to size RWHS in the literature?

Research Question 2: What methods are being used in the literature for the optimization process?

Research Question 3: What are the limitations of the current optimization analyses and how can they be overcome in future work?

We searched for publications in the following databases: Engineering Village (Compendex, 1884-present and Inspec, 1898-present), Web of Science (core collection, 1900-present), Scitech Premium (Proquest, 1946-present) and Scopus (1800s-present). RWHS are generally defined as systems harvesting rainwater from rooftops with the purpose of providing water for domestic usage (potable and non-potable). The first step was to define the relevant keywords in order to find pertinent publications related the topic of research. A preliminary analysis of some of the related literature revealed that "rainwater" was the most commonly used term to describe RWHS. Hence, our first search term was "rainwater". The terms "optimal" and "optimum" were also commonly used in the pertinent and relevant literature. Hence, our search string ended up being (rainwater) AND (optimal) and its variations (optimum), (optimize), (maximize) (maximum), (minimize) and (minimum). The search terms were found in the title, abstract, and keywords of existing publications in the databases. We did not limit the categories of the search areas given that this field is multi-disciplinary by nature. We only selected journal articles dating from the year 2000 (at the start of the previous decade) published in English. Identical publications found using different databases were excluded. The screening process is as follows: we read the titles first, the abstracts next and the complete texts last and at each stage of the process, we discarded the unrelated works for the defined area of research and works which did not state sizing as a main objective. Journal articles in other languages were excluded, as well as a nominal amount of articles that we did not have access to through our university libraries.

After the selection process, the following information was compiled:

- Year of publication.
- Author-specified keywords used.
- Country of publication.
- Optimization purpose as stated in the objectives section. If the objectives section was missing, we extracted the optimization purpose from the introduction. We excluded works where optimization or sizing was not listed in the objectives of the paper.
- Key parameters that characterized the optimization being described (RWHS design variables, simulation methods, and optimization decision variables).

We performed an examination of the data collected and compiled our conclusions in the following sections.

Analysis

The review was performed in March 2019, then updated in September 2019. We found 2,695 relevant journal articles to the search criteria we used:

- Engineering Village (Compendex and Inspec databases): 476 relevant articles were found in both databases.
- Web of Science: 795 relevant articles were found after the search in the Web of Science database.

- Scitech Proquest (main database): 652 relevant articles were found after a search of the Scitech Proquest main database.
- Scopus: 772 articles were found after a search in the Scopus database.

After the thorough screening process previously described, we were left with 45 directly relevant articles based on PRISMA as shown in Figure 6.

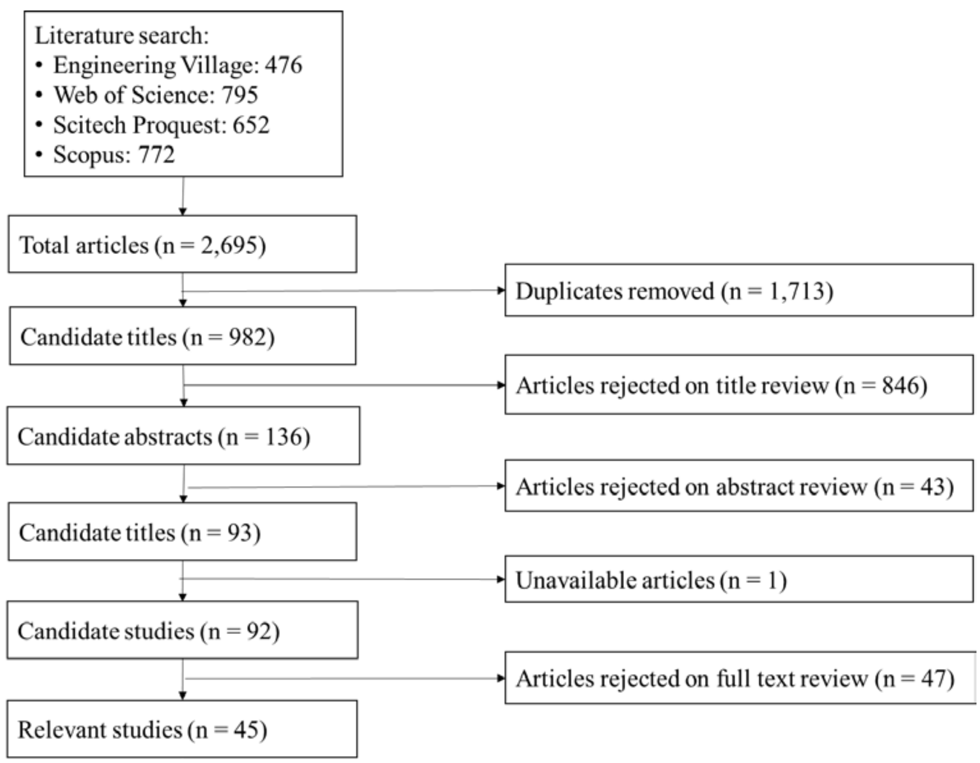


Figure 6 - Flowchart of systematic literature review using PRISMA (Moher et al. 2015)

Works focusing on alternative water usages, (e.g., Al-Ansari et al. 2013; Llopart-Mascaroa et al. 2015; Londra et al. 2018; Panigrahi et al. 2005; Panigrahi et al. 2007; Roman et al. 2017; Traore and Wang 2011) multiple water sources, (e.g., Appan 2000; Behzadian et al. 2018; Gabarrell et al. 2014; Hunt et al. 2011; Notaro et al. 2017; Zhang and Hu 2014) documenting the performance in different climates or climate change (e.g., Mwenge Kahinda et al. 2010; Rashidi Mehrabadi et al. 2013; Zhang et al. 2019), suitability rather than optimality (e.g., Balogun et al.

2016; Imteaz et al. 2013; Nolan and Lartigue 2017), minimizing contaminants (e.g., Won et al. 2019), optimizing top-up rates and volumes (e.g., Barry and Coombes 2008) and sizing for spatial quantity and arrangements (e.g., Huang et al. 2015; Kuok and Chiu 2018) were excluded.

Although these works were excluded from the analysis at the abstract phase of the screening process (Figure 6), we evaluated them to make sure that the findings were not significantly different than the works that were included in the review and that we did not miss valuable insights that would have otherwise been overlooked based on the previously explained search criteria.

Figure *7* summarizes the distribution of the journal articles across the multiple databases, meaning how many of relevant publications were found in each database, namely:

- Engineering Village: 476 journal articles found, 35 articles remaining following screening.
- Scitech Proquest: 652 journal articles found, 38 articles remaining following screening.
- Scopus: 772 journal articles found, 42 articles remaining following screening.
- Web of Science: 795 journal articles found, 40 articles remaining following screening.

Some articles were found on multiple databases while others were only listed on one. Ultimately, the greatest number of journal articles meeting all criteria for inclusion were found in Scopus database, followed by Web of Science, then Scitech Proquest and lastly Engineering Village, as shown in Figure 7.

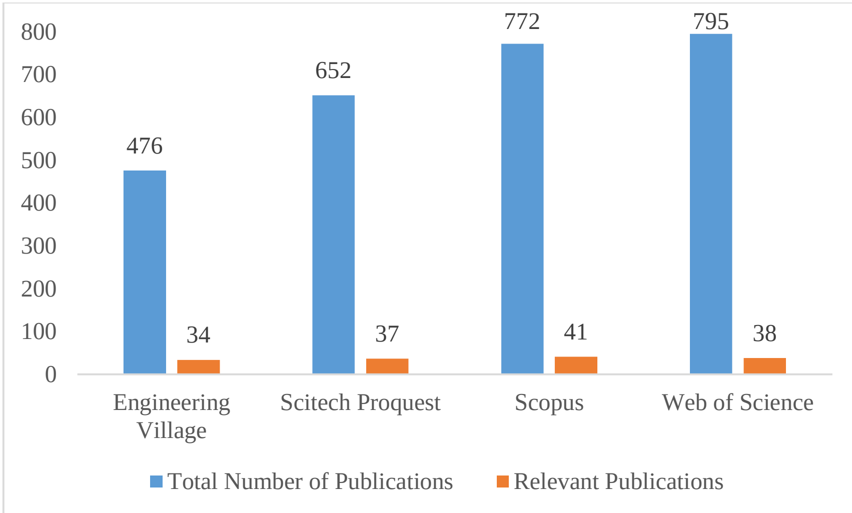


Figure 7 - Total and relevant numbers of publications across the databases.

Most of the publications regarding optimally sizing RWHS were found in "*Resources, Conservation and Recycling", followed by the "Journal of Hydrology*" and "*Journal of Cleaner Production*". The distribution of the publications is summarized in Figure 8.

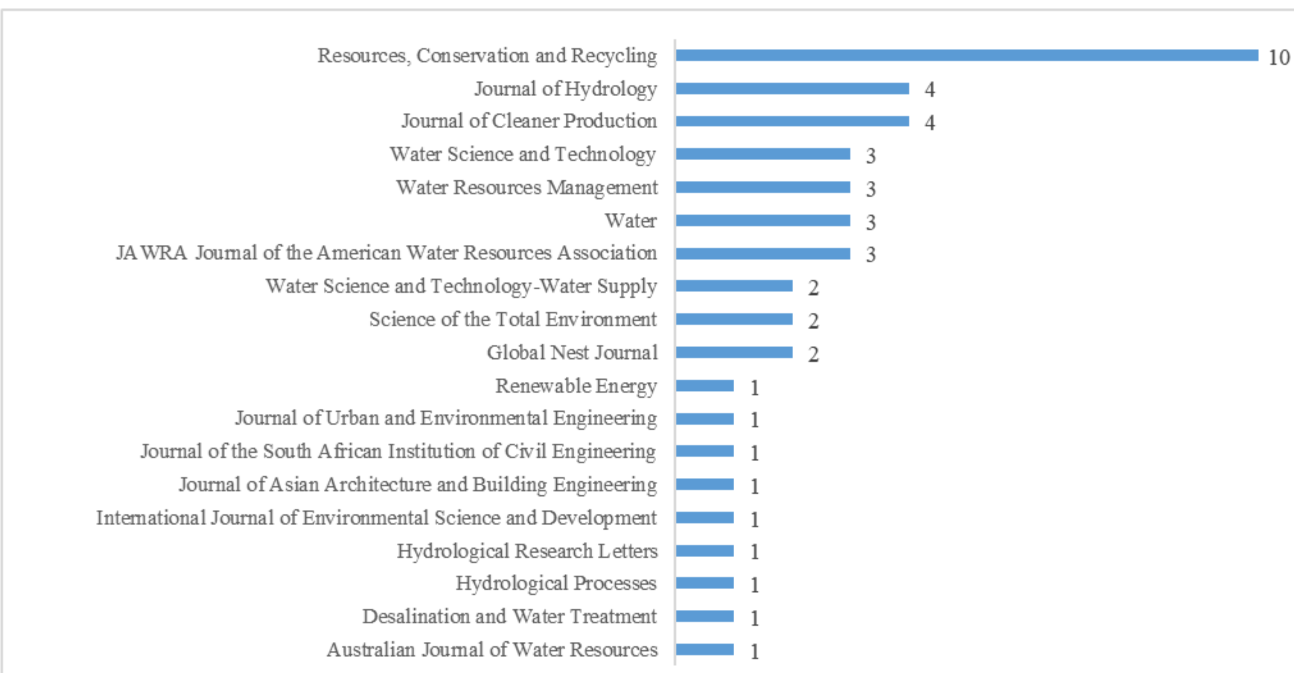


Figure 8 - Summary of the distribution of the relevant publications among different journals.

Figure 9 shows the distribution of journal articles by location of study and year of publication. The country with the most publications related to the optimizing of domestic rooftop rainwater harvesting is the USA (7), followed by Australia and Taiwan (6).

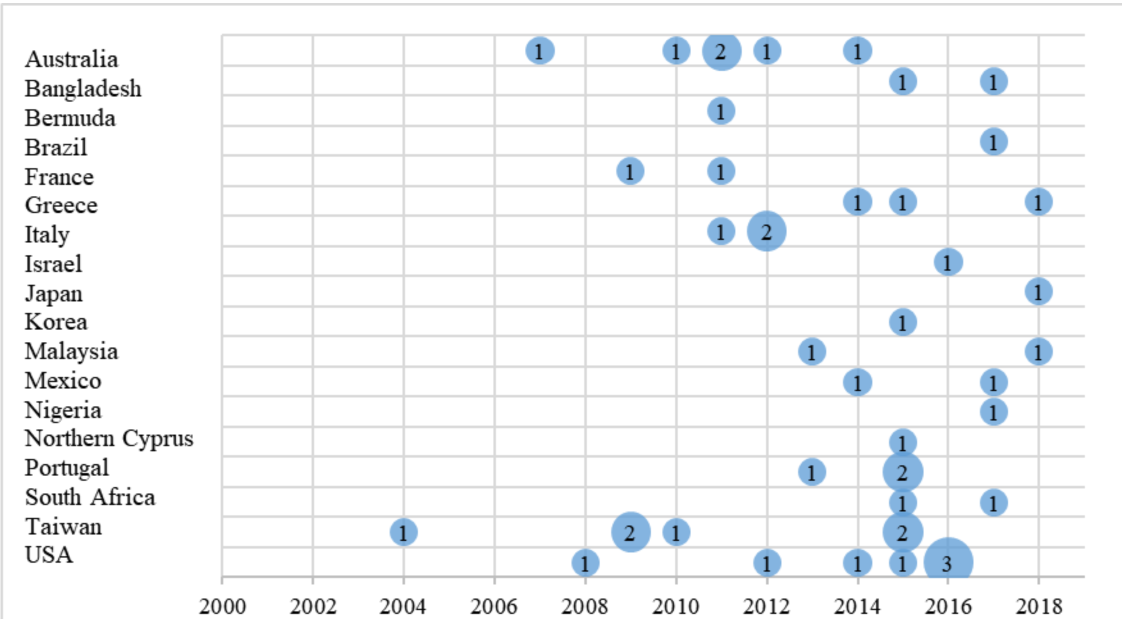


Figure 9 - Distribution of the relevant publications by country and year.

We analyzed the author-supplied keyword strings used in the selected publications. Overall, there were 147 keyword strings specified, except for the two oldest publications (Jenkins 2007; Liaw and Tsai 2004a) which did not specify keywords. Figure 10 shows the most frequently used keyword strings in the selected articles; rainwater harvesting was the most frequently used. The word "optimization" appears three times as a keyword out of the 45 articles.

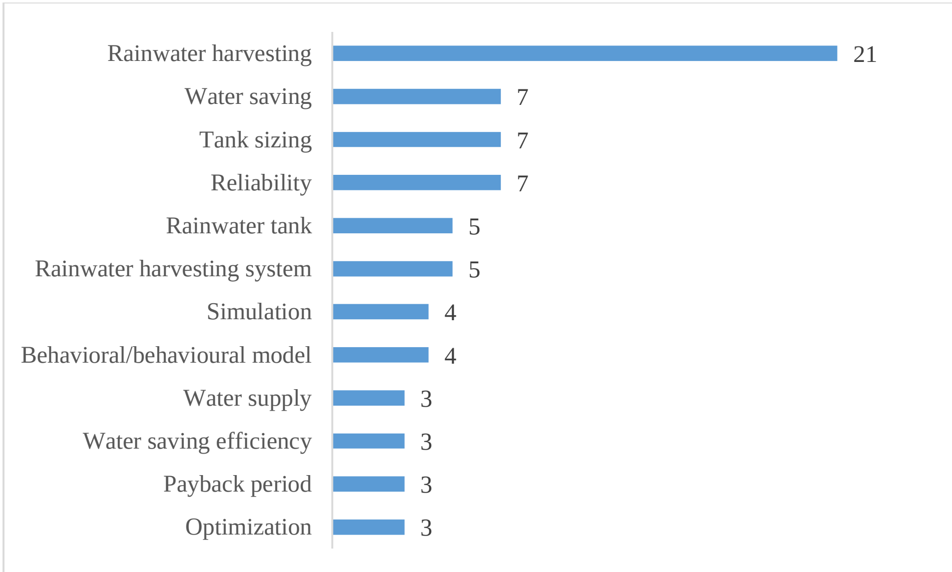


Figure 10 - Keywords frequency in relevant publications.

To get a better insight into the use of the keywords, we analyzed the frequency of the actual words used, rather than the strings that were found originally. The term “rainwater” is the most frequently used, followed by “harvesting”, “water” and “tank”. We illustrated the occurrence of the keywords and their frequency with the help of a word cloud, as shown in Figure 11 where the font size indicates the word frequency (Heimerl et al. 2014).

Figure 11 - Word cloud of the author-supplied keywords.

Given that the driving purpose of the SLR was to address the research questions described in the methodology section, the next section presents the results of analyzing the actual content of the papers and a discussion of those results.

Results and discussion

This section is organized in two parts: in the first part, questions 1 and 2 address the methods and variables used for size optimization of RWHS while question 3 delves into the discussion pertaining to those methods and the recommendations for future research.

What variables are being optimized with regards to sizing RWHS in the literature?

The results of the analysis of the relevant articles show that the general approach to RWHS size optimization can be summed up as follows: Optimizing the size of the tank while optimizing one or more variables related to the design of RWHS. Several variables were optimized in the relevant works, as shown in Table 6. In the following section, we will list the optimization variables associates with the relevant works and we will discuss in details how these variables were optimized.

Table 6 - Optimizing variables employed in literature related to the design of RWHS

Relevant publications	**45**
Cost	**12**
Campisano and Modica (2012); Chiu et al. (2009); Chiu et al. (2015); Gurung and Sharma (2014); Jenkins (2007); Khastagir and Jayasuriya (2011); Lani et al. (2018); Nguyen et al. (2018); Okoye et al. (2015); Pelak and Porporato (2016); Santos and Taveira-Pinto (2013); Silva et al. (2015)	
Reliability	**11**
Cowden et al. (2008a); Imteaz et al. (2012); Islam et al. (2010); Karim et al. (2015); Khan et al. (2017a); Khastagir and Jayasuriya (2010); Koumoura et al. (2018); Lawrence and Lopes (2016); Liaw and Tsai (2004a); Ndiritu et al. (2017a); Nnaji et al. (2017)	
Effectiveness/Performance	**7**
Auguste and de Gouvello (2009); Cheng and Liao (2009); Lopes et al. (2017b); Muklada et al. (2016); Palla et al. (2011); Palla et al. (2012); Vialle et al. (2011)	
Meeting water demands	**5**
Fernandes et al. (2015); Fonseca et al. (2017); Londra et al. (2015); Rostad et al. (2016); Seo et al. (2012)	
Roof area	**3**
Hashim et al. (2013); Rowe (2011); Wallace and Bailey (2015)	
Water savings	**2**
Imteaz et al. (2011c); Tsihrintzis and Baltas (2014)	
Constant water demand	**1**
Allen and Haarhoff (2015)	
Green roofs irrigation	**1**
Chao-Hsien et al. (2015)	
Shared total storage between RWHS users	**1**
Seo et al. (2015)	
Total costs and fresh water consumption	**1**
Bocanegra-Martínez et al. (2014)	
Water supply and runoff capture	**1**
Sample and Liu (2014)	

Cost

Twelve articles in the final data set optimize the costs associated with RWHS design, as shown in Table 6. Those costs are expressed as shown in Table 7. The most used parameter in cost optimization is cost of water from centralized treatment, which would be displaced by the

RWHS. The table headings are the cost elements, investment variables, and investment metrics used to optimize RWHS' costs:

- **Capital costs**: costs associated with the tank, pumps and pipes (when included in the cost).
- **Maintenance costs**: costs associated with the required maintenance of the system over its lifetime.
- **Operation costs**: costs associated with running the system such as the power needed for the pumps and the disinfection.
- **Water costs**: costs associated with the town water supplied or the cost of the water saved by using the RWHS.
- **Environmental costs**: costs associated with any runoff from the site (runoff from the RWHS tank or drainage).
- **Inflation rates**: measure at which the average price of a product increases over time
- **Discount rates**: percent change of prices from one year to the next.
- **Rebates**: amount paid by way of reduction, return, or refund on what has already been paid.
- **Payback period/ Return on investment**: amount of time required to break even
- **Benefit-cost ratio**: relationship between the cost of the project and its benefits expressed in monetary value
- **Net-present value**: life cycle costing tool which decides the values of future investment

Table 7 - Cost elements, investment variables and investment metrics used in cost optimization for RWHS

	Cost elements				Investment variables				Investment metrics		
	Capital costs	**Maintenance costs**	**Water costs**	**Operation costs**	**Environmental costs**	**Inflation rates**	**Discount rates**	**Rebates**	**Payback period or Return on Investment**	**Benefit-cost ratio**	**Net-present value**
Jenkins (2007)	x	x	x	x	x		x		x		
Chiu et al. (2009)	x		x	x						x	
Khastagir and Jayasuriya (2011)	x	x	x	x		x	x	x	x	x	x
Campisano and Modica (2012)	x	x	x	x					x		
Santos and Taveira-Pinto (2013)	x		x						x		
Gurung and Sharma (2014)	x	x		x							x
Chiu et al. (2015)	x		x	x						x	
Okoye et al. (2015)	x		x				x				x
Silva et al. (2015)	x	x	x	x			x		x		

	Cost elements				Investment variables				Investment metrics		
	Capital costs	**Maintenance costs**	**Water costs**	**Operation costs**	**Environmental costs**	**Inflation rates**	**Discount rates**	**Rebates**	**Payback period or Return on Investment**	**Benefit-cost ratio**	**Net-present value**
Pelak and Porporato (2016)	x		x								
Lani et al. (2018)	x	x	x				x		x	x	x
Nguyen et al. (2018)	x		x	x							

It is interesting to note that in all the cost optimization analyses, the capital costs of the RWHS are always taken into consideration because a) the optimization function's output is the size of the tank and b) capital costs make up the majority of the costs (Stewart 2011). The second most used metric in cost optimization is water costs. This "water costs" metric is equally important in most cases because as water prices increase, the value of RWHS increases. The payback period or Return on Investment analysis was the most used financial method to determine the economic feasibility of the optimized sizing while the benefit-cost ratio and net-present value methods were used second most. Jenkins (2007) included the environmental costs (e.g. stormwater fees) associated with using RWHS while Khastagir and Jayasuriya (2011) used included in the analysis rebates offered by the Victorian government in Melbourne, Australia to make RWHS more affordable.

Reliability

As shown in Table 6, eleven papers in the final data set focused on optimizing the system reliability in function of the tank size. Across these articles, reliability was defined in two distinct ways:

- Volumetric reliability or water-saving efficiency, which is the total rainwater supplied divided by the demand for that water (Imteaz et al. 2012; Islam et al. 2010; Liaw and Tsai 2004a; Ndiritu et al. 2017a; Nnaji et al. 2017)
- Time-based reliability, which is the fraction of time that demand is fully met (Cowden et al. 2008a; Karim et al. 2015; Khan et al. 2017a; Khastagir and Jayasuriya 2011; Koumoura et al. 2018; Lawrence and Lopes 2016)

The advantages of using the volumetric reliability are:

- Less restrictive: it takes into account the fraction of the time when demand is partially met.
- Less influenced by the computational time step: the volumetric reliability can be used with sub-daily, daily, weekly, monthly and yearly time-steps.
- Less influenced by the system's characteristics: rainfall data can be missing or unavailable for the desired simulation period.

The advantages of using the time-based reliability are as follows:

- Clearer understanding of the inter-annual rainfall variability.
- Better descriptive of the system's failure: the system fails when it is unable to meet all demand.

The volumetric reliability indicator is most commonly used when the output is a measure of the water saving efficiency while the time reliability indicator can describe the fraction of time, over the analysis period, when the demand will be fully met. If the ultimate purpose of the analysis is to maximize the volume supplied by rainfall, the volumetric reliability is more representative of the system. If the purpose is to design a system that can maximize the amount of time when full water demand is met, then the time reliability is the better factor.

Effectiveness/ performance

As shown in Table 6, seven articles in the final data set optimized the effectiveness/performance of a RWHS to determine the size of the tank. A large-scale analysis for sizing for effectiveness or performance of a RWHS depends on the author-specified indicators chosen in the analyzed works as follows in Table 8.

Table 8 - Effectiveness/performance indicators used

	Effectiveness	**Performance**
Auguste and de Gouvello (2009)		Reliability indicators: fraction of days when demand is 100% met, less than 10% met and daily water-saving efficiency
Cheng and Liao (2009)	Rainwater utilization indicator	
Palla et al. (2011)		Water-saving efficiency, overflow ratio, detention time
Vialle et al. (2011)		System efficiency, water-saving efficiency
Palla et al. (2012)		Water-saving efficiency, median value of detention time
Muklada et al. (2016)		Water-saving efficiency, rainwater use efficiency
Lopes et al. (2017b)		Demand-area ratio, deficit rate

The rainwater utilization indicator, used by Cheng and Liao (2009), is the result of a principal component analysis which is a statistical technique that that uses an orthogonal transformation (linear transformation which preserves a symmetric inner product) to convert a set of observations of possibly correlated variables (entities each of which takes on various numerical values) into a set of values of linearly uncorrelated variables called principal components. In this case, the authors used observations of the demand (annual demand divided by the collection area and the average annual rainfall) and storage (the storage capacity divided by the collection area and the average annual rainfall) fractions for their analysis. Additional indicators include:

- The water-saving efficiency is the volumetric reliability, defined in the previous section.
- The overflow ratio is the fraction of rainfall that is not utilized.

- The detention time is the length of time water is retained in the tank.
- The rainwater use efficiency is the proportion of rainwater actually used.
- The demand-area ratio is the demand per unit area.
- The deficit rate is the percentage of the demand not met.

Auguste and de Gouvello (2009) developed three indicators pertaining to a reliability curve (percentage of days where different water demands are met) to assess the size of the optimized tank from the town water supplier's point of view. Cheng and Liao (2009) developed a rainwater utilization indicator that can be used to analyze regional rainfall characteristics, and to come up with representative variables and weights (which indicate the interrelationship of the variables of a rainwater harvesting system that can be revised to amend the parameters for the optimal system.). Those scores can then be compared to the water saving potential of different RWHS which can lead to an optimized storage design. Muklada et al. (2016) developed the water saving efficiency and rainwater use efficiency indicators to optimize the performance of the system. Lopes et al. (2017b) used the demand-area ratio and the deficit rate indicator in order to optimize the size of the storage tank for a combination of demands and roof areas. Palla et al. (2011; 2012) developed a demand fraction and a storage fraction indicators in order to assess the performance of the RWHS and find the optimum tank size. Vialle et al. (2011) used the water saving efficiency as an indicator of the performance of the system.

It is interesting to note that all the authors used two or more indicators to assess the performance of the RWHS and size the tank, as opposed to the previous section where only the reliability (volumetric or time-based or both) was used for that purpose.

Meeting water demands

As shown in Table 6, five articles in the final data set optimized the size of the tank to meet water demands. The water demands, as specified by the authors, are as follows:

- Seo et al. (2012) introduced variability in daily water demand for four homogeneous and four heterogeneous users and analyzed the impacts of that variability on the individual rain barrel sizes when those barrels are connected (physical and non-physical connections) to the four users. The output is a comparison of the sizes of the barrels before and after connecting them.
- Fernandes et al. (2015) designed a system that could optimize the tank size to satisfy low (non-potable) water demands (such as cleaning cars and washing pavements). Low or non-potable water applications are typical when capacity largely exceeds demand.
- Londra et al. (2015) optimized the size of the tank in order to meet a certain fraction of the total water demands: 30, 40, and 50% of the total water demands for households.
- Rostad et al. (2016) sized tanks to meet the water demand for toilet flushing in four major cities in the US in residential and mixed residential neighborhoods given typical urban household characteristics (roof area, estimated number of residents). The authors track how increasing water demand affects the reliability of the system as well as rainfall runoff.
- Fonseca et al. (2017) developed a web-interface decision support system (DSS) to optimize tank sizing using inputs pertaining to water needs from users. The output of the application is maximum tank sizes and annual efficiency values as well as a probability of non-exceedance in order to establish conditions for wet, mean and dry years. High

non-exceedance values for a particular tank size are more conservative estimates of the estimated efficiency.

It is interesting to note that, in contrast to the previous section, the reliability indicator is being used here to track the performance of the system rather than it being the main design parameter.

Roof area

As shown in Table 6, three articles in the final data set focused on designing the system with an emphasis on the optimal roof area as follows:

- Hashim et al. (2013) proposed a model that can propose optimal roof areas and tank sizes for a large RWHS.
- Rowe (2011) suggested increasing the roof areas of houses in Bermuda in order to meet the existing storage capacity available.
- Wallace and Bailey (2015) recommended increasing both the available catchment areas and storage volumes in order to meet water demands during dry periods for Micronesian communities.

Two of these articles describe island communities (Rowe 2011; Wallace and Bailey 2015), where conventional thinking would focus on increasing the tank size in order to meet more water demands. However, Rowe (2011) found that a) many existing water tanks were oversized in Bermuda, hence, either overfilled or underfilled and b) that the optimum capacity of tanks is 0.37 m^3 per 1 m^2 of catchment area. Wallace and Bailey (2015) recommend increasing the rainwater catchment areas because of unused storage available that can then be used to sustain water demands during drought periods. In the third article, Hashim et al. (2013) optimized the rainwater catchment area to sustain a large rainwater harvesting system (communal RWHS).

Water savings

As shown in Table 6, two articles in the final data set focused on optimizing the tank size to save on the use of centrally-treated municipal water as follows:

- Imteaz et al. (2011c) optimized the size of two large existing tanks with the optimization criteria being total overflow losses (≈ 0) and water saved (= constant value).
- Tsihrintzis and Baltas (2014) optimized the tank size to not use public water, allowing additional water to overflow, with tanks sized to provide adequate supply throughout the year.

Other variable optimization

As shown in Table 6, five articles in the final data set focused on the following variables or system characteristics to size the tank:

- Bocanegra-Martínez et al. (2014) optimized the system to minimize the fresh water use and its total cost.
- Sample and Liu (2014) optimized the system for the dual purpose of meeting water needs and providing runoff capture.
- Allen and Haarhoff (2015) optimized the design of the system for constant water demand, i.e., for daily consumption.
- Chao-Hsien et al. (2015) optimized the system specifically for irrigating green roofs.
- Seo et al. (2015) proposed a rainwater harvesting sharing scheme whereas the individual storage would be reduced.

The aforementioned works analyzed the variables used for optimally sizing the RWH tank. As reported in Table 6, the authors have mostly optimized using the cost and reliability of the system as the main decision variables. The following section looks at the optimization process and the methods used.

What methods are being used in the literature for the optimization process?

The following section looks at the methods and variables used for the sizing of the tank in the 45 relevant studies, as well as the optimization methods used.

Methods and variables used for the sizing of the tank

Of the 45 relevant papers that look at storage sizing for RWHS, we extracted the following data points: the resolution with which rainfall data are incorporated in the model, the approach to simulating the level of water in the tank at any point in time, and the rate and resolution with which demand is modeled. Mass balances typically represent the inflow, outflow, and losses of the tank in order to capture water levels in the tank and calculate the optimal tank size. The model may use different time scales and algorithmic models such as yield before spillage (YBS) and yield after spillage (YAS) to estimate tank sizes (Jenkins and Pearson 1978) as well as parametric methods such as the storage-reliability-yield (SRY). The results of the data points extracted from our units of analysis are shown in Table 9.

Table 9 - Results of the extraction of data points from our units of analysis

	Rainfall	**Simulation approach**	**Water demand**
Liaw and Tsai (2004a)	Daily, historical	YBS	Daily, average
Jenkins (2007)	Daily, historical	YBS	Daily, variable (monthly)
Cowden et al. (2008a)	Daily, stochastic	Water mass balance	Daily, average
Auguste and de Gouvello (2009)	Daily, historical	YBS, YAS	Daily, variable (weekday and weekend)
Cheng and Liao (2009)	Daily, historical	YAS	Daily, average
Chiu et al. (2009)	Daily, historical	YBS	Daily, average
Islam et al. (2010)	Daily, historical	YAS, YBS	Daily, variable (weekday and weekend)
Khastagir and Jayasuriya (2010)	Daily, historical	Water mass balance	Daily, variable (daily and seasonal)
Imteaz et al. (2011c)	Daily, historical	Water mass balance	Daily, average
Khastagir and Jayasuriya (2011)	Daily, historical	Water mass balance	Daily, average
Palla et al. (2011)	Daily, historical	YAS	Daily, average
Rowe (2011)	Daily, historical	Water mass balance	Daily, average
Vialle et al. (2011)	Daily, historical	Water mass balance	Daily, average
Campisano and Modica (2012)	Daily, historical	YAS	Daily, average
Imteaz et al. (2012)	Daily, historical	Water mass balance	Daily, average
Palla et al. (2012)	Daily, historical	YAS	Daily, average
Seo et al. (2012)	Daily, historical	SRY (based on YAS)	Daily, variable (lognormal distribution)
Hashim et al. (2013)	Daily, historical	Water mass balance	Daily, average
Santos and Taveira-Pinto (2013)	Daily, historical	YAS	Daily, variable (weekdays)
Bocanegra-Martínez et al. (2014)	Monthly, historical	Water mass balance	Monthly, variable (seasonal)
Gurung and Sharma (2014)	6-minute interval, historical	Water mass balance	Daily, average
Sample and Liu (2014)	Daily, historical	YBS	Daily, average
Tsihrintzis and Baltas (2014)	Daily, historical	Water mass balance	Daily, average

	Rainfall	Simulation approach	Water demand
Allen and Haarhoff (2015)	Daily, historical	YBS, YAS	Daily, average
Chao-Hsien et al. (2015)	Yearly, historical	YBS	Yearly, variable (seasonal)
Chiu et al. (2015)	Daily, historical	YBS	Daily, average
Fernandes et al. (2015)	Weekly, historical	Water mass balance	Weekly, variable (seasonal)
Karim et al. (2015)	Daily, historical	Water mass balance	Daily, average
Londra et al. (2015)	Daily, historical	Water mass balance	Daily, average
Okoye et al. (2015)	Monthly, historical	Water mass balance	Daily, average
Seo et al. (2015)	Daily, historical	SRY (based on YAS)	Daily, variable (lognormal distribution)
Silva et al. (2015)	Daily, historical	YAS	Daily, average
Wallace and Bailey (2015)	Daily, historical	YAS	Daily, average
Lawrence and Lopes (2016)	Daily, historical	Water mass balance	Daily, average
Muklada et al. (2016)	Daily, historical	YAS	Daily, average
Pelak and Porporato (2016)	Daily, stochastic	Water mass balance	Daily, average
Rostad et al. (2016)	Daily, historical	Water mass balance	Daily, average
Fonseca et al. (2017)	Daily, historical	Water mass balance	Daily, average
Khan et al. (2017a)	Daily, historical	YAS	Daily, average
Lopes et al. (2017b)	Daily, stochastic	Water mass balance	Daily, average
Ndiritu et al. (2017a)	Daily, historical	YAS	Daily, variable (weekday, weekend, monthly)
Nnaji et al. (2017)	Daily, historical	Water mass balance	Daily, average
Koumoura et al. (2018)	Daily, historical	Water mass balance	Daily, average
Lani et al. (2018)	Daily, historical	Water mass balance	Daily, average
Nguyen et al. (2018)	Daily, historical	YAS	Daily, average

As shown in the first data column in Table 9, rainfall is represented in most studies using historical data, which does not explicitly take into account potential large changes that could occur quickly due to climate change. In fact, in one study in Australia, the authors found that climate change will adversely impact residential RWHS by reducing water savings and reducing reliabilities (Haque et al., 2016). Adding more storage without minimal increase in the total cost of ownership or even redistributing rainwater could help manage the effects of climate change on RWH. Running or verifying the analysis on wet and dry years using sensitivity analysis can better inform about the performance of a RWHS under a climate change scenario.

What the second data column in Table 9 shows is that the most used tank sizing method to model the performance of a RWHS is the water mass balance method, proposed by Jenkins and Pearson (1978). In fact, 51% of the simulation modeling is done using the mass balance method, followed by 29% using the YAS, 11% using the YBS and 7% using both YAS and YBS methods. The YAS release rule is more conservative than the YBS rule in terms of output (Fewkes and Butler 2000). According to Rostad et al. (2016) and Mitchell et al. (2008) , the mass balance approach strikes a balance between the outputs of both release methods.

As for the third data column in Table 9, the variability in water demand is not typically accounted for because most works consider daily average water demand except for two works where a lognormal distribution is used to reflect the daily variability in water demand. Eight of the studies use average daily values for water demand but vary those averages based on weekdays/weekends, humid/dry weather, monthly changes in water demands. This gap could be managed by conducting a sensitivity analysis to the water demand or varying the water demand.

It is noteworthy that the columns are sorted by year, and there have been no easily observable trends in the literature regarding these various approaches.

Optimization methods

Optimization is the process of choosing the best solution out of a set of multiple outputs. Hence, the optimal solution is the one with the highest expected utility (Gigerenzer and Selten 2002). For any given real-world problem, an optimization problem can usually be formulated in a generic form as follows:

$$\begin{aligned} &\text{minimize/maximize } f_0(x) \\ &\text{subject to } f_i(x) \leq b_i,\ i = 1,\ldots,m \end{aligned} \tag{1}$$

where x is the optimization variable and b_i the constraints or firm requirements that limit the possible choices. A solution of the optimization problem (1) matches to a choice that has minimum cost (or maximum utility), from all available choices (Boyd and Vandenberghe 2004). The optimization approaches used in existing RWHS studies are all based on single-objective or multi-objective optimization. The sizing studies evaluated in the SLR deal with the decision-making related to appropriate sizing of the system while maximizing/minimizing one or more variables related to the design of a RWHS.

Based on the review of the optimization methods of the selected works, the RWHS sizing optimization articles are divided into two primary decision-making styles: simulation-based optimization and satisficing (which is a combination of satisfy and suffice (Chun 2015)). Simulation-based optimization problems are formulated in terms of a defined objective function that a) is based on mathematical proofs and b) has an extreme solution or an optimal solution. In contrast, satisficing problems, as proposed by Simon, have moderate goals where optimality may be difficult to implement because of the presence of uncertainty or ambiguity (Simon 1959; Stirling and Goodrich 1999). With this approach, one keeps on looking for an optimal outcome until an acceptable solution is found according to a standard chosen by the user (Stirling 2003). According to Byron (1998), satisficing represents a stopping instruction that can decrease the search time for other, better options as defined by the user. For example, in the case of RWHS, when one variable is pre-defined by the author (e.g., finding the optimal size for a defined volumetric reliability), then the solution to the problem becomes a local solution rather than a global solution as defined by the simulation-based optimization problem. The advantages and disadvantages of both optimization methods are as follows:

- Mathematical optimization can find the absolute optimal solution whereas satisficing finds a local optimal solution based on the decision maker's preference (Wierzbicki 1982).
- In some situations, uncertainty and complexity can inhibit the search for an optimal solution, making it reasonable to stop when finding a functioning one (Stirling and Goodrich 1999).
- Optimization requires having all the relevant facts, which is nearly impossible to comply with (Stirling 2003).

The main methods for simulation-based optimization can be classified as follows (Carson and Maria 1997):

- Gradient based search methods: these methods evaluate the response function gradient to measure the form of the objective function and employ deterministic mathematical programming techniques such as the finite differences, likelihood ratios, perturbation analyses and frequency domain methods.

- Stochastic optimization: this method allows the location of a local optimum for an objective function whose outputs are unknown analytically but rather can be estimated or measured.
- Response surface methodology (RSM): this method includes fitting a series of regression models to the output variable of a simulation model and optimizing the resulting regression function.
- Heuristic methods: these methods represent the field of direct search methods (requiring only function values) and mix exploration with exploitation resulting in efficient global strategies. Those methods include genetic algorithms, evolutionary strategies, simulated annealing, tabu search and Nelder and Mead's simplex search.
- Asynchronous teams: this method is a process that involves multiple problem solving strategies that can cooperate in tandem.
- Statistical methods: these methods involve the use of statistics in order to solve optimization problems, such as, importance sampling methods, ranking and selection, and multiple comparisons with the best.

The criteria for classifying the selected works as a simulation-based optimization problem or a satisficing problem is based on whether the optimization method used follows the definition of simulation based optimization. The following criteria for simulation-based optimization methods are:

- The optimization problem is formulated in a mathematical form as shown in (1).

- The problem solving method can be clearly attributed to one of the methods specified in Carson and Maria (1997), presented in the previous list. Table 10 presents the results of classifying the studies based on optimization methods used.

Table 10 - Results of the optimization methods used in the selected works

	Satisficing optimization	**Simulation-based optimization**
Liaw and Tsai (2004a)	Yes	
Jenkins (2007)	Yes	
Cowden et al. (2008a)	Yes	
Auguste and de Gouvello (2009)	Yes	
Cheng and Liao (2009)	Yes	
Chiu et al. (2009)	No	Heuristic model
Islam et al. (2010)	Yes	
Khastagir and Jayasuriya (2010)	Yes	
Imteaz et al. (2011c)	Yes	
Khastagir and Jayasuriya (2011)	Yes	
Palla et al. (2011)	Yes	
Rowe (2011)	Yes	
Vialle et al. (2011)	Yes	
Campisano and Modica (2012)	Yes	
Imteaz et al. (2012)	Yes	
Palla et al. (2012)	Yes	
Seo et al. (2012)	Yes	
Hashim et al. (2013)	No	Heuristic model - Solution found using GAMS (2019) solver
Santos and Taveira-Pinto (2013)	Yes	
Bocanegra-Martínez et al. (2014)	No	Multiobjective mixed-integer nonlinear programming (MINLP) – using GAMS (2019) solver
Gurung and Sharma (2014)	Yes	
Tsihrintzis and Baltas (2014)	Yes	
Sample and Liu (2014)	No	Non-linear metaheuristic model

	Satisficing optimization	Simulation-based optimization
Allen and Haarhoff (2015)	Yes	
Chao-Hsien et al. (2015)	Yes	
Chiu et al. (2015)	Yes	
Fernandes et al. (2015)	Yes	
Karim et al. (2015)	Yes	
Londra et al. (2015)	Yes	
Okoye et al. (2015)	No	Linear programming model
Seo et al. (2015)	Yes	
Silva et al. (2015)	Yes	
Wallace and Bailey (2015)	Yes	
Lawrence and Lopes (2016)	Yes	
Muklada et al. (2016)	Yes	
Rostad et al. (2016)	Yes	
Pelak and Porporato (2016)	Yes	
Fonseca et al. (2017)	Yes	
Khan et al. (2017a)	Yes	
Lopes et al. (2017b)	Yes	
Ndiritu et al. (2017a)	No	Multiobjective optimization model – Pareto optimal solution
Nnaji et al. (2017)	No	Regression model
Koumoura et al. (2018)	Yes	
Lani et al. (2018)	Yes	
Nguyen et al. (2018)	Yes	

The works that use a simulation-based optimization approach (Chiu et al. 2009; Hashim et al. 2013; Muklada et al. 2016; Ndiritu et al. 2017a; Nnaji et al. 2017; Okoye et al. 2015; Sample and Liu 2014) have a defined objective function, one or multiple decision variables (depending on the output) and a collection of constrains that bound the function as shown in Table 11.

Table 11 - Decision variables used in the simulation-based optimization articles

	Decision variable(s)
Chiu et al. (2009)	Cost and maximum tank volume
Hashim et al. (2013)	Total costs
Bocanegra-Martínez et al. (2014)	Total costs, purchased water
Sample and Liu (2014)	Net benefits (water supply and runoff capture)
Okoye et al. (2015)	Cost of purchased water, cost of RWHS
Ndiritu et al. (2017a)	Yield, reliability, storage
Nnaji et al. (2017)	Reliability

An analysis of the methods of optimization of the RWHS was presented. As reported in Table 9 and Table 10, a few works used simulation-based optimization and most works use a satisficing approach to optimization. The following section looks at the limitations of the current optimization processes used and how to manage them in future works.

What are the limitations of the current optimization analyses and how can these be overcome in future works?

In decision making theory, Beyth-Marom et al. (1991) postulate that an output is optimal when the process is optimized as well, i.e., being able to practice the following steps:

a. List relevant action alternatives;
b. Identify possible consequences of those alternatives;
c. Assess the probability of each alternative occurring;
d. Establish the relative value or utility of each alternative, and;
e. Integrate those values and utilities to find the most attractive course of action.

Having a well-defined mathematical objective function bounded by one or multiple constraints or following a well-defined optimization method appears to be a methodical optimization process, especially when a multi-objective optimization process is required (Bocanegra-Martínez et al. 2014; Chiu et al. 2009; Hashim et al. 2013; Ndiritu et al. 2017a; Okoye et al. 2015; Sample and Liu 2014). In a review of simulation-based optimization methods related to building performance, Nguyen et al. (2014) identified three distinct phases in the simulation-based optimization process: pre-processing, running the optimization and post-processing phases. The major tasks of the three phases are as follows:

- Pre-processing: this phase's main objective is to formulate the optimization problem, to set the constraints and to identify the variables.
- Running the optimization: the main objectives of this phase are monitoring the optimal solution, controlling the termination criteria and detecting any errors.
- Post-processing: the results are analyzed and presented during the post-processing phase.

The RWHS sizing simulation-based optimization works are presented in the same manner as described by Nguyen et al. (2014). The satisficing works are also based on the same structure with three distinct phases using iterative methods which output a local optimum rather than a global one. As Nguyen et al. (2014) found with regards to optimization and building performance analysis, it is often difficult to verify whether a global optimum is achievable by optimization. The same can be applied to the optimization of RWHSs for several reasons:

a) The uncertainty of water demands: in most of the optimization works, water demand was illustrated as a discrete average which realistically is not the case because demand profiles vary between outwardly similar households in comparable locations as a result of a difference in socio-environmental factors. In a recent peak water demand study in over multiple years and in multiple locations across the US for single and multi-family dwellings, the researchers found that the average water use was 60.1gpcd (gallons per capita per day) and almost 98% of homes registered leaks. Interestingly, leakage represented almost 17% of the average daily water use (Buchberger et al. 2015). Toilets had the highest use in terms of gpcd. The tally showed that residential water use has a tendency to be higher on weekends than otherwise. In its latest water use report (for the year of 2015), USGS estimated the average domestic water consumption (indoor and outdoor use) per capita per county and the differences between counties run as low as 2 gpcd up to 1,429 gpcd with a national average of 87.4 gpcd (USGS 2017).

What is sorely lacking in water research across most water-centric disciplines is access to usage data, which in turn reduces the stochasticity inherent to water demand modeling. City and town managers are aware of the privacy concerns associated with releasing water metering data because of inadequate cyber security measures surrounding the usage of those devices (McDaniel and McLaughlin 2009). Smart water metering, intelligent infrastructure and the Internet of Things (IoT) (Saad et al. 2019) are bound to decrease the unpredictability with the increase in digital security surrounding the usage of metering devices. Indeed, the use of big data and machine learning (Chen et al. 2019) will increase the understanding we currently have of water demands, expanding in turn the granularity of the variables which will be conducive to better performing RWHSs.

b) The uncertainty of future rainfall patterns: all of the optimization works considered in this review have based their rainfall analysis on historical data or synthetic data (based on historical rainfall) up to 113 years (Jenkins 2007). The optimal tank size could in effect be optimal for the time of the design; however, RWHS have a lifecycle ranging between 20 and 40 years (and in some analyses up to 60 years) Climate change is expected to impact rain patterns quite significantly over this time period, which could make the optimization analysis that are based on historical rainfall data less valuable for future planning (Haque et al. 2016; Meehl et al. 2007). In fact, in a study of the impacts of climate change on RWH, the authors found that accounting for tank size adjustments, catchment areas and water demand rates will be needed in order for RWHS to be sustainable (Zhang et al. 2019). The use of representative years in terms of rainfall to be used as extreme years to test the system (wet, dry and average) on top of the historical data can decrease the uncertainty associated with changing rainfall patterns, but they may or may not capture the types of changes we may see in a changing climate.

   One way to reduce the stochasticity inherent in predicting future rainfall patterns is better approaches to prediction of weather in the context of global change at the local scale. Future works should also consider the possibility of increasing available storage, such as communal water spaces in order to utilize excess rainfall as well as store available rainfall in times of drought.

c) Lack of grounding in practice: most of the research on RWHS does not necessarily factor in real-world conditions when modeling the performance of the systems. For example, most of the optimization studies considered in this review output a range of sizes or a specific size that the authors consider optimal without taking into account the fact that tanks come in discrete sizes. One solution could be the use of modular rainwater harvesting systems which can be built to hold unlimited amount of rainwater and can fit anywhere. Another example would be that the simulated models do not also take into account the fact that the roof technologies are changing in ways that may make our assumptions about yield less accurate. Hotter temperatures on metal roofs (which are becoming more common in residential construction in many areas) mean more evaporation during the first part of a rain event while the roof cools which are not really accounted for in the models. The use of intelligent sensors can predict future weather patterns and prime the roofs accordingly. The cutoff (the minimum amount of water available in the tank to prevent the system from running dry) and freeboard volumes (the rainwater overflows in the freeboard section of the tank) are not necessarily included in the models which impact the ultimate tank size. The use of discrete tank sizes is a more realistic approach to the simulation process.

In a broader sense, the future of the RWH systems will be a nexus of a traditional modeling approach with the inclusion of all the information collected by the IoT, that are not readily available presently. Currently, researchers rely on rainfall and water usage as the primary inputs for RWH modeling. In the future, inputs such as land cover changes, modular construction, and even future building usage on top of the current inputs will help expand our understanding of RWHS models, transcend the current socio-economic spectrum as well as exploit local weather patterns over the RHWS' lifecycle. Instead of using past data to model today's water usage, researchers will be able to model for tomorrow's water usage, today.

Conclusion

We conducted a systematic literature review of works pertaining to optimal sizing of rainwater harvesting systems for domestic water usages. After the screening process, 45 works were relevant based on our search criteria. The most common optimized variable with regards to sizing a rainwater harvesting system was the cost of the system, followed by the reliability of the system and effectiveness/performance of the system. Most works used historical rainfall and average water demands as input to their systems, while the most used sizing method was the water mass balance method. 7 works used simulation-based optimization methods to find the global optimum while the rest used satisficing approaches to find local optimums in terms of sizing.

Simulation-based optimizations provide the closest, in terms of process and output, means to finding global optimal solutions whereas satisficing decision-making is generally calibrated according to the opportunity cost of delay and the computational cost of considering more options and collecting more data. All optimization publications rely on historical rainfall data to make a decision on the size of RWHS but truly optimal sizes that span the lifecycle of the system will have to take into account the changing rainfall patterns. The uncertainty of water demands and future rainfall patterns, and lack of grounding in practice are all gaps in the current research. The combination of the use of smart water meters, intelligent infrastructure and the IoT will provide better understanding of water needs. More research on climate change on the local level will reduce the stochasticity inherent in future rainfall patterns. Moreover, taking into account more real-world conditions (with the use of smart sensors) can increase the precision of the output of the simulations, hence improve the optimality of the sizing of rainwater harvesting systems.

CHAPTER FIVE: A NOVEL APPROACH TO RAINWATER HARVESTING SYSTEMS FOR SINGLE-FAMILY HOUSEHOLDS, DISTRIBUTED RAINWATER HARVESTING

Introduction

The aging water infrastructure in the United States is becoming a critical issue and investment has not been keeping up with needs. According to the ASCE, there will be an estimated $84.4 billion annual capital gap for water infrastructure by 2020 (Economic Development Research Group of the American Society of Civil Engineering 2016). Water demand is growing (Sabol 2011) and the rate of urbanization is increasing. The latest census of 2010 shows that urban areas are outpacing overall national growth by 2.4% (United States Census Bureau 2012) and water utility bills are on the rise (Walton 2015). City and town managers of growing urban areas are facing increasingly difficult choices with regards to water infrastructure management: Should the status quo be maintained, which is investing in the existing infrastructure, or should there be funding for decentralizing the water infrastructure, or some mix thereof? Rainwater harvesting systems (RWHSs) are situated at the core of the decentralized water structures. RWHSs act as a containment measure for stormwater runoff by storing rainwater which can be used for irrigation, car washing, non-potable domestic functions (laundry, toilet flushing, etc.) and when treated, as a potable water source. The vital importance of RWHSs is the effect they have on the three water networks (potable, stormwater, and wastewater) in terms of decreasing water demand on the potable water network, decreasing stormwater runoff, and, if coupled with greywater recycling systems, decreasing the wastewater generated (Ghisi and Ferreira 2007).

Communal rainwater harvesting at the individual residential scale preserves excess runoff from multiple roofs, stores it in a communal tank, and then treats and redistributes it as potable water to the community for either potable or non-potable uses (Cook et al. 2013; Gurung and Sharma 2014; Gurung et al. 2012; Seo et al. 2012; Seo et al. 2015). Variations of communal RWHSs currently exist in multi-residential buildings (Agudelo-Vera et al. 2013; Eroksuz and Rahman 2010; Ghisi and Ferreira 2007; Marinoski et al. 2018; Silva and Ghisi 2016). Communal RWHSs for single-family houses work best in off-grid locations, where access to the municipal water supply is difficult (Cook et al. 2013; Gurung and Sharma 2014). However, the main advantage of communal RWHSs over private RWHSs in urban settings is that they provide a centralized means for adequate maintenance for individual users who could have difficulties sustaining their own system properly. This centralized approach at the heart of a decentralized water infrastructure management ensures better water quality (Gurung and Sharma 2014) and economies of scale for capital costs, reduced land footprint, centralized disinfection, and flexibility in matching supply and demand for different households (Cook et al. 2013). In order to size the communal system, Gurung et al. (Gurung and Sharma 2014) estimated the dimensions of the communal tank by gauging the hot potable use for one house in the community (shower, taps, dishwasher and laundry) using a water balance approach and the software UVQ (Mitchell and Diaper 2010). The design criteria used was a volumetric reliability ratio (VR) of 94%. The VR is the ratio of rainwater that the communal system is able to provide compared to the total water demand. The next step was to calculate the size of a single RWHS based on the VR of 94%. The last step was to multiply the tank size with the number of households in the community to come up with an estimate of the communal tank size. Hashim et al. (Hashim et al. 2013) used a simulation-based programming approach to estimate the communal tank size for a community of 200 households in Malaysia by minimizing the cost and optimizing the tank size. The authors wound up with a reliability of 60% while saving 58% of the water that would have otherwise been drawn from the municipal supply system for satisfying the daily water demand for non-potable uses.

An improvement on both the communal approaches above could be based in sharing rainwater storages or rain barrel sharing network (RBSN). Seo et al. (Seo et al. 2012; Seo et al. 2015) describe a network of rainwater sharing that can be a physical or a non-physical network (like a community based sharing program) for using the excess rainwater from one household. The authors found that a sharing network actually reduces the total storage needed in some cases by up to 61% for a target reliability of 80% for a scenario with four users.

The first communal approach studied by Gurung et al. and Hashim et al. increases the attractiveness of owning RWHSs for users who do not/cannot handle the maintenance of such systems while the approach described by Seo et al. increases the potential of using the collected rainwater, hence improving on the reliability of existing RWHSs. Both these systems lack a solution to maximize the capture and reuse from the outflow of RWHSs, where “clean” water is going to “waste” in the stormwater drains. Hence, there is a need for a novel way to leverage RWHS.

The main contribution of this paper is a novel approach to communal RWHSs that is a hybrid of the first two approaches described above that increases the VR per user while reducing overall total storage and increasing user autonomy with regards to water processing. It is, in fact, a distributed rainwater harvesting system (DRWH) that closely resembles distributed computer systems. Distributed computer systems do not have a unified definition but they have the following common traits (Ghosh 2014):

a. Distributed computer systems are autonomous, each with their own local memory. Similarly, distributed RWHSs have their own independent usages.

b. Computer systems communicate by message passing. Likewise, a distributed RWHS communicate with water sharing.

c. A distributed computer system has to allow breakdowns in single computers. Equally, if a single RWHS fails, the entire system is not critically compromised.

d. A distributed computer system has a mutual objective; the combined computers then work as a single entity to attain that objective. While each computer has particular requirements, the system allows the management of the usage of the shared resources. Correspondingly, a distributed RWHS allows single users to use their harvested rainwater as they need while storing the overflow to be used when needed by that same user or others in the network.

In particular, we consider single-family households, each connected to their own RWHS but instead of the overflow going to the stormwater system, the overflow of each tank is connected to a communal tank where multiple other outflows from other single-family households are connected as well and the connections at the household level, as shown in Figure 12.

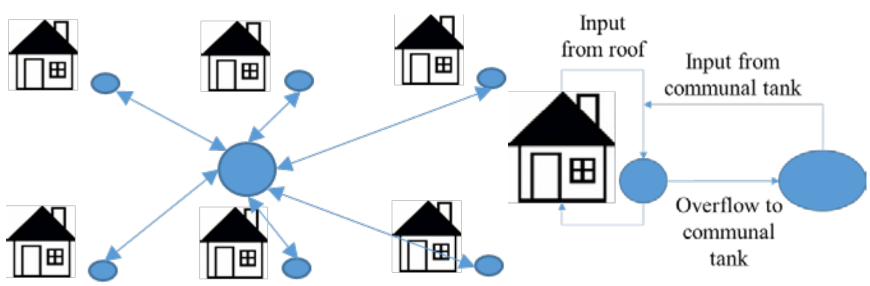


Figure 12 - Distributed RWH and connection at the house level

The potential advantages of this distributed rain water harvesting (DRWH) systems are as follows:

1. Owners have the freedom in using the disinfection method they choose instead of being “forced” to use the “central” disinfection method. They could also opt out of using water treatment depending on the usage they have for the collected water.
2. A smaller amount of rainwater will be wasted compared to using private RWHSs, and less runoff will go into stormwater systems, thus reducing load on the stormwater infrastructure.
3. The increased storage in the form of the communal tank will increase water demand met as well as the reliability of the RWH system.
4. This distributed system will be more resilient in the face of climate change especially since depending on the climate some adjustments would have to be made to size of the RWH system.

The purpose of this study is to determine a) the impact distributed RWH will have on the reliability of the system, the storage (private and communal) required to achieve that reliability, and c) the optimal number of connected households to the distributed system to perform this study, we use simulation tools to build the distributed network and study the output of the simulation for feasibility and gain over tradition RWHSs. For validation, we use representative cities from the nine major US climate zones.

Methodology

This study adopts a daily water balance model using publicly available weather and water consumption data (USGS 2017) to estimate the amount of potable municipal water that can be displaced under different tank size scenarios (private and communal) for each of the nine study cases. In this study, daily rainfall data for 10 years (January 2009-January 2019) as well as average water demand is considered for single-family households. Tank sizes are within the range interval [3.785 m^3; 75.7 m3] with a step size of 3.785 m^3. These tanks represent discrete sizes in thousand-gallon increments commonly available in the U.S. In order to perform the analysis, a daily water balance model was used (Imteaz et al. 2012; Khastagir and Jayasuriya 2011). When the increase in the volumetric reliability VR dips below 1% in terms of increase compared to the contiguous smaller size, that change will determine the choice of tank size for the private storage scenario. In other words, we use less than 1% VR change between adjacent tank sizes in order to determine our optimal storage tank size. The rationale behind this selection method is the fact that it strikes a meaningful balance for the tradeoff between VR gains and tank size cost increase, which is assumed to be proportional to tank size for storage of this magnitude. For all other sizes above the chosen tank size, although a higher reliability can be achieved, the increase in this reliability is too small to justify the additional investments needed for the larger tank sizes.

As for the distributed rainwater harvesting setting, the simulation was designed as shown in Figure 13.

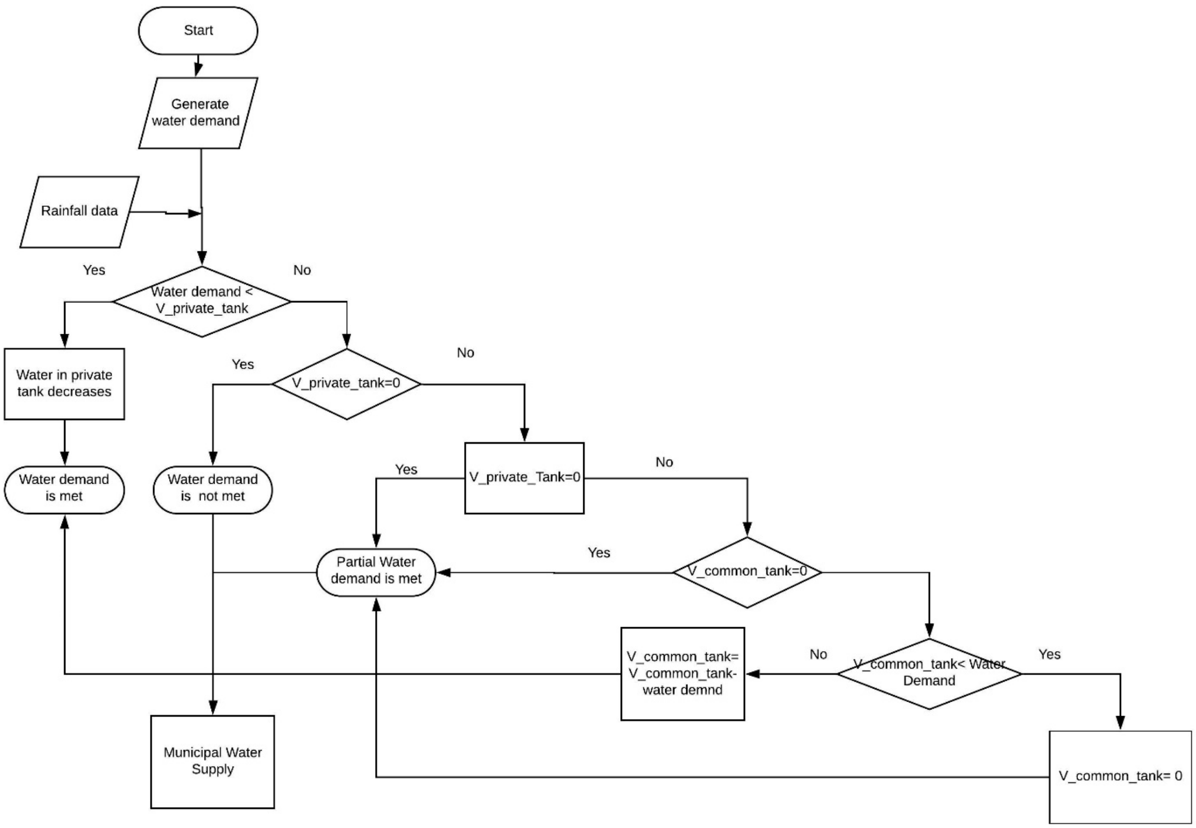


Figure 13 - Flowchart of the logic of the distributed system

As shown in Figure 13, the overflow of the private tank is stored in the communal tank and when the water demand is partially or not met from the private tank, at the end of the day, water is then pumped from the communal tank to the private tank, just enough to meet the water demand for that day for that household. The water level in the communal tank is reduced and the water level in the private tank is unchanged. The overflow from the communal tank is discarded in the stormwater pipes. If the water demand is not fully met by either private or communal tanks, the municipal water supply is then used.

The model derived from the study will determine the following:

a. The private tank size before connecting it the distributed system.

b. The reduced private tank size after connecting it to the distributed RWH system simultaneously with the communal tank size.

c. The optimal number of connected private RWHSs to the distributed system and the total storage needed, which is assumed to be proportional to tank size for storage of this magnitude.

The analysis was based on the daily water balance and the locations of the analysis were chosen based on the climatic regions in the continental US. The National Centers for Environmental Information scientists recognized nine climatically consistent regions in the contiguous United States and they are as follows (Karl and Koss 1984):

- Central: Illinois, Indiana, Kentucky, Missouri, Ohio, Tennessee and West Virginia.
- East North Central: Iowa, Michigan, Minnesota and Wisconsin.
- Northeast: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island and Vermont.
- Northwest: Idaho, Oregon and Washington.
- South: Arkansas, Kansas, Louisiana, Mississippi, Oklahoma and Texas.
- Southeast: Alabama, Florida, Georgia, North Carolina, South Carolina and Virginia.
- Southwest: Arizona, Colorado, New Mexico and Utah.
- West: California and Nevada.
- West North Central: Montana, Nebraska, North Dakota, South Dakota and Wyoming.

Each climatic area was matched with a representative city so that the analysis could be generalized to the entire region. The cities were picked from the most populous cities of the United States (U.S. Census Bureau 2017). The cities representing the climatic regions are shown in Table 12.

Table 12 - Climatic regions, rep. cities and Köppen classification

Climatic area	**Representative City**	**Köppen Classification**	**Average yearly rainfall (mm)**
Central	Chicago, IL	Dfa	914
East North Central	Detroit, MI	Dfa	864
Northeast	New York City, NY	Cfa	1,194
Northwest	Seattle, WA	Csb	940
South	Houston, TX	Cfa	1,270
Southeast	Jacksonville, FL	Cfa	1,270
Southwest	Phoenix, AZ	Bwh	229
West	Los Angeles, CA	Csa	381
West North Central	Omaha, NE	Dfa	787

For this comparative study, we considered a single-family household, with two residents in the representative cities from the major climatic zones in the United States. The house used in our example has a roof area of 68.25 m^2, is two-storied and has a total area of 136.5 m^2 which is the average size household in the US (US Census Bureau 2018). The water demands were extracted from the latest USGS water use report (USGS 2017) by fitting the average demand across all counties in the US to a normal curve. The histogram of the water demands across all counties the US is shown in Figure 14. The national average water demand can be represented by a normal curve with mean 0.330 m^3 and standard deviation 0.205 m^3. The normal curve is an acceptable representation of water demand (Blokker et al. 2010; Schefter and David 1985; Surendran and Tota-Maharaj 2015).

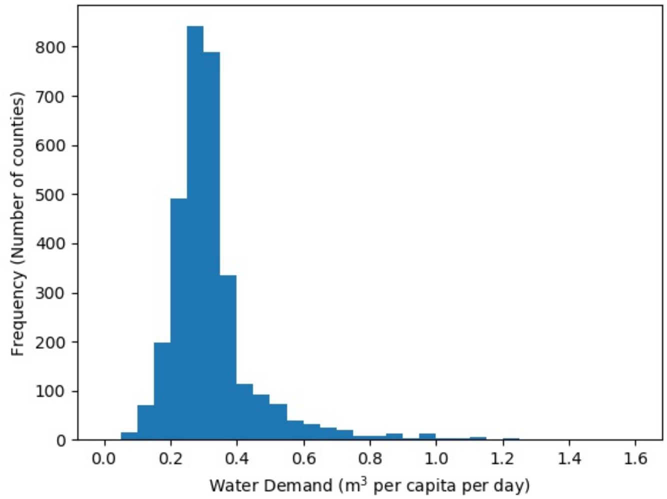


Figure 14 - Histogram of average water demands across all US counties

Several factors affect the daily residential water demand of the households. Some of those of factors are a) socio-economic such as lot size, income, education, employment, price of water b) efficiency of the plumbing features, c) rainfall, temperature and evaporation rates, and d) water prices. A varying daily water demand captures the stochasticity inherent in daily residential water usage. The daily total water demand for the simulation period is shown in Figure 15.

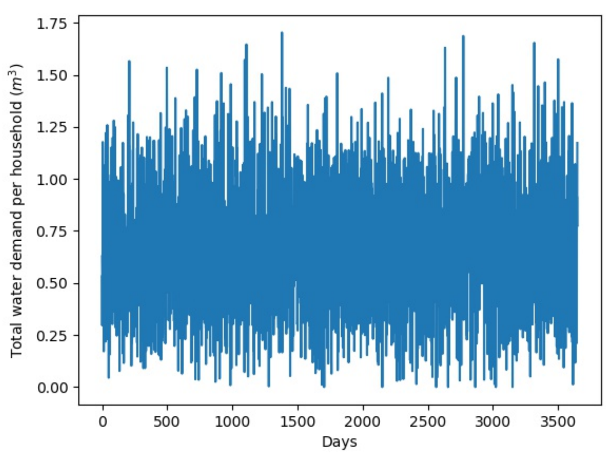


Figure 15 - Daily total water demand per household for the simulation period

The precipitation data was accessed from the National Centers for Environmental Information (NCEI) for the last ten years from January 1, 2009 until January 1, 2019. We assumed that the houses are internally plumbed to accommodate the use of rainwater as potable water. The VR was used to evaluate the performance of the different rainwater harvesting tanks. The assumptions related to the considered household are presented in Table 13. The tanks are assumed to be empty at the beginning of the simulation. The tank size is being used to mean usable volume (the actual amount of water available in the tank). The simulation model was run in Python using rainfall data from1/1/2009 till 1/1/2019 for multiple cities to determine the feasibility of a distributed RWHS in different geographical locations in the continental United States.

Table 13 - Assumptions used in the model

Parameter	**Value**
Rainfall	Daily rainfall available from NCEI
House area	136.5 m^2 ~ average size household in the US (US Census Bureau 2018)
Roof area	68.25 m^2
Roof type	Sloped metal roof
Runoff coefficient	0.9
Tank types	Polyethylene tanks (most commonly used in residential scale across the US (Thomas et al. 2014)
Water demand	National average available from United States Geological Survey (USGS 2017)

Step 1:

The first step of the simulation was to determine which locations would be suitable for distributed RWHSs and the optimal size of the private tank. For that purpose, we ran daily simulations for all nine locations for households with the conditions specified in Table 13. The optimal tank size was chosen based on the change in the VR between two adjacent sizes becoming less than 1%. The simulation results are shown in Figure 16.

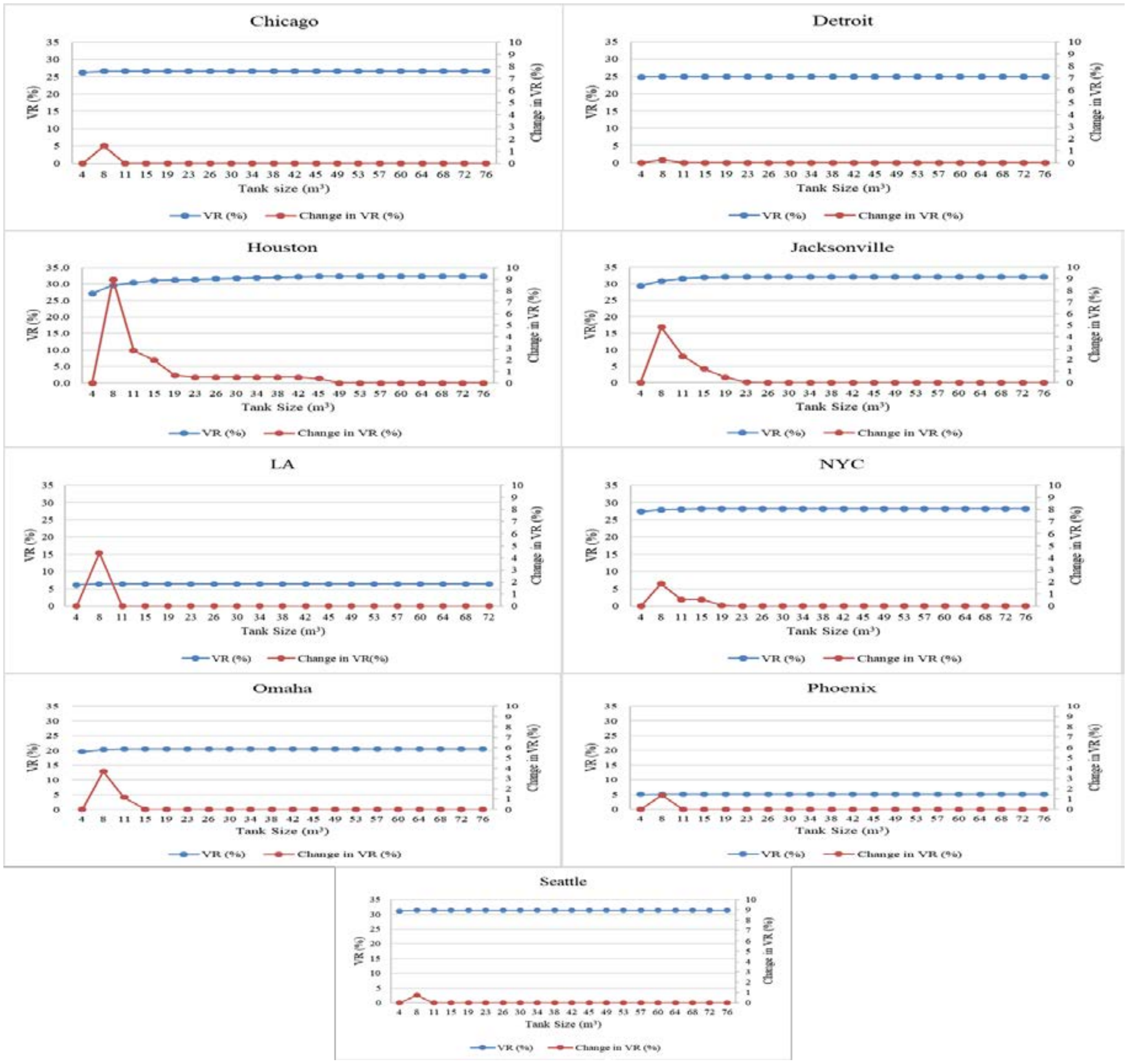


Figure 16 - Private tank sizes and volumetric reliabilities for nine US cities using varying water demands

Figure 16 shows the change in VR for each of the nine cities with the increase of tank sizes. The biggest change in VR with larger tanks can be seen in Houston, Jacksonville and Omaha. LA has a significant VR change between the smaller adjacent sizes but the VR is small (6%) to begin. For the rest of the cities, the VR does not significantly change with larger tank sizes. The cities where the VR change is significant with larger sizes receives generally more rainfall and hence, households would benefit from increased storage capacity.

The criteria for a location for DRWHSs are defined as follows:

- The VR increases must be significant enough to jump between discrete tank sizes (>2%) between the range of tank sizes under consideration, and;
- The VR changes between adjacent tank sizes must also be significant (>2%).

Applying the selection criteria for the suitability of the available locations for distributed RWHSs and the optimal tank size for the individual tank, the following observations can be made based on Figure 16:

- Among our chosen cities, the only locations suitable for distributed RWHSs are Houston and Jacksonville as evident by the notable increase in reliability with the increase of private storage as well as an important increase in VR change.
- For those two locations, the optimal private tank size 15.1 m^3.

We also ran the simulation for a daily average water demand. The averages were extracted from the USGS report (USGS 2017) for the different counties in which these nine cities are located as shown in Figure 17 .

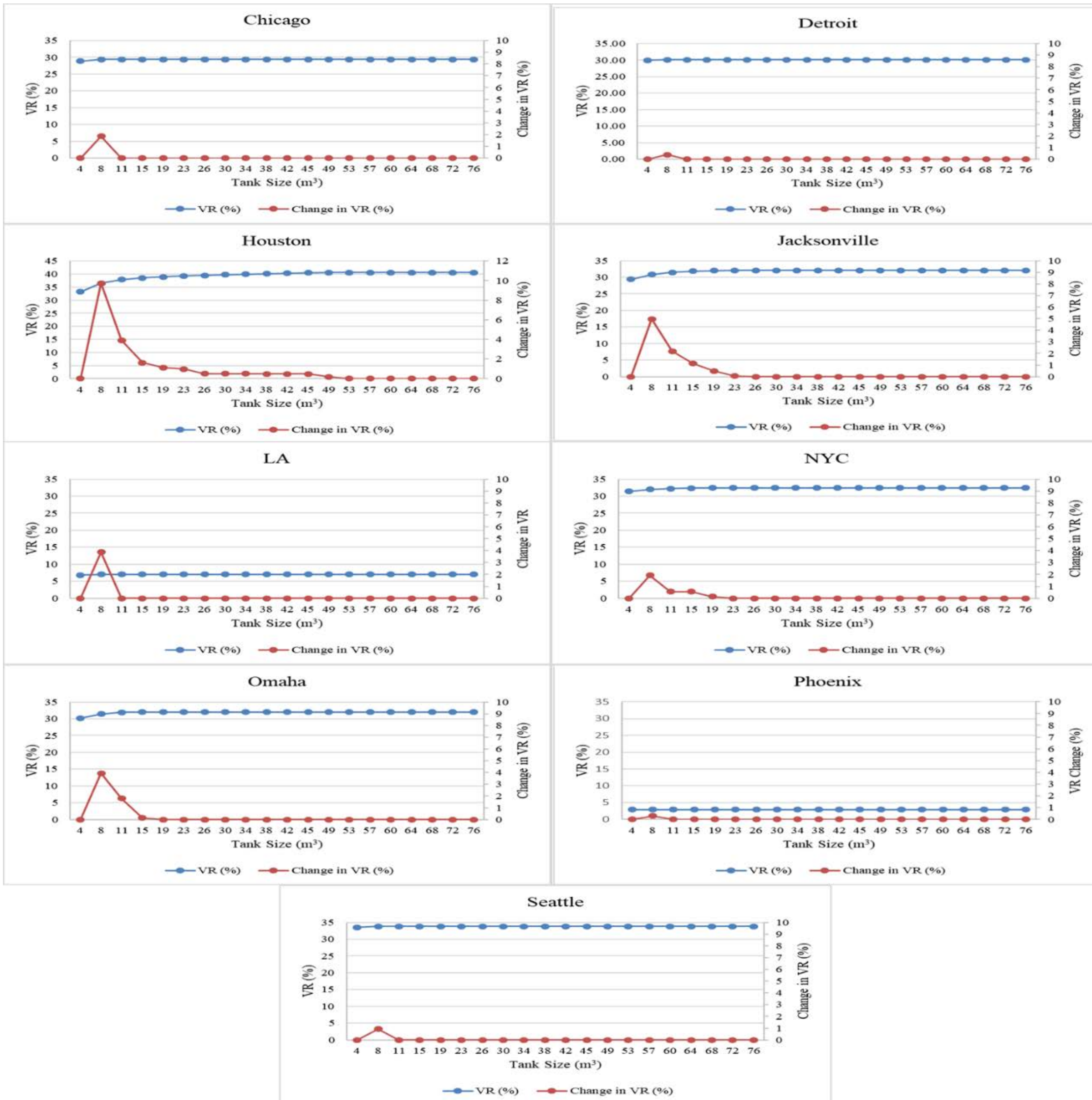


Figure 17 - Private tank sizes and volumetric reliabilities for nine US cities using average water demands

By comparing Figure 16 and Figure 17, we notice that Omaha could potentially be a good candidate location for distributed RWHSs because the difference between the maximum and minimum reliabilities for the average water demand is 1.7% (less than 2% but competitive) while the difference with the varying water demand is 1%. The difference between the outputs from varying and average water demands could be because of the fact that the water demand for Douglas County (where Omaha is located) is 0.216 m^3 while the average water demand used in the normal distribution representing the varying water demand in the US is 0.331 m^3. This observation only highlights the need to have more realistic water usage data in order to accurately assess the potential for distributed RWHSs.

Step 2:

The next step is to run the distributed RWHS simulation for the two selected locations. The simulation will determine three variables: a) The number of connected users per higher VR, b) the optimal private tank size, and c) the optimal communal tank size to determine the highest VR gain. The following criteria will be used as boundaries for the variables:

- The simulation will determine the optimal number of households (users) connected to the system. The optimal number of users will depend on the maximum VR per household for a given number of users connected. The simulation will take into consideration up to 24 users connected to the system to keep the decentralized trait of the system by clusters of maximum 24 households.
- The private tank sizes will be varied from 3.785 m^3 up to the optimal size as determine in the first step.
- The maximum size of the communal tank will be the product of the number of users connected and the optimal sized tank that was determined in the first step. The simulation will consider multiple sized communal tanks starting at 3.785 m^3 up to the maximum size (Gurung and Sharma 2014).

The output of the simulation will be the optimal combination of number of users, private tank size and communal tank size which represents the highest VR gain over users not connected to a distributed RWHS.

Results

We ran simulations to determine the VR gain by having different households connect their RWHSs to a distributed network. The variables of the simulation were the following:

- Number of users (connected households): we varied the number of connected households between 2 and 24
- Size of private storage: we varied the size of private storage between 3.785 m^3 up to 15.14 m^3 (by a step of 3.785 m^3). We assume that all households have the same private tank size per iteration.
- Size of common storage: we also varied the size of the public storage between 3.785 m^3 up to number of users in the given simulation multiplied by 15.14 m^3.

As a result, we conducted $2\sum_{2}^{24} 16x$, or 9,568 iterations where the output of every iteration is the average VR gain per user. The next step was to average the VR gains per group of users to determine the average gain, per private tank size and public tank size. After running the simulations for two locations (Jacksonville and Houston), we obtained the results in Figure 18 and Figure 19.

How does the communal storage vary when the emphasis is on the VR change?

In this section, the emphasis is on evaluating the maximum VR gain and its associated communal storage per group of connected users given the aforementioned four different private storage options.

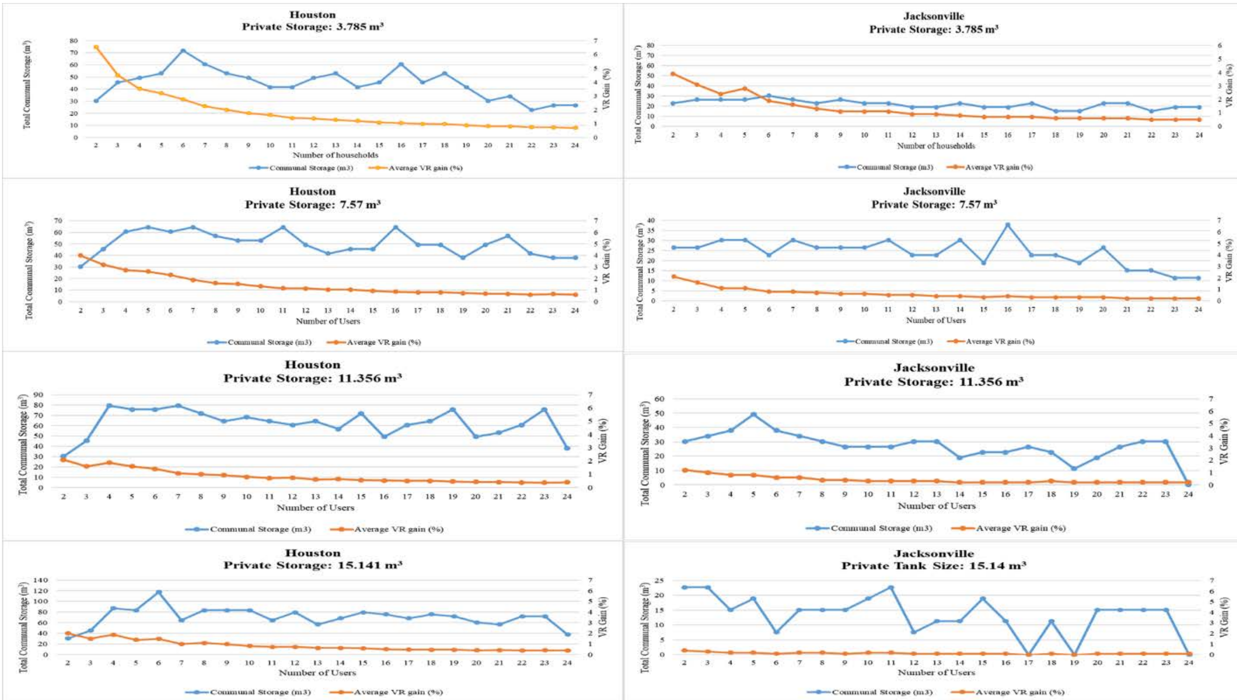
Figure 18 shows the maximum VR gain for the different simulated scenarios for both cities. We looked at the average VR gain for users (households) connected to the distributed RWH network for all the different combinations of private and common tanks. From this figure, we make the following remarks.

- The first observation is the fact that the system achieves equilibrium or steady-state after a certain number of users are added to the system. That equilibrium corresponds to 9 or 10 users for the Houston system and 6 to 7 users for the Jacksonville system for all private tank sizes used in the simulation. Common sense would predict that given an "unlimited" storage capacity, the average VR gains would be the same no matter how many users are added to the system because, even though the water demand increases by adding more users to the system, that demand is offset by the addition of common storage capacity. In reality, after a certain number of users, the balance of water inflows and outflows between the users (households) and the common storage tank becomes negligible. This is an interesting observation because, after reaching equilibrium, the communal storage capacity does not increase with the addition of users. This could imply that the multiple water demands are not occurring at once and nor for the same amounts, especially given the fact that the water demand was simulated according to a normal distribution.
- The largest VR gains for the four private tank scenarios were for the smallest tank size of 3.785 m^3 and for around 9 or 10 users in the system for Houston and around 6 or 7 users for Jacksonville, the equilibrium point. Beyond that point, for the four private tank sizes, the average VR gains saturate around 1%. The system achieves equilibrium regardless of the input increase.

- The average VR gains follow a log function distribution as shown in Figure 19 and it is clear that a DRWH system works best with private storage sizes of 3.785 and 7.57 m^3 for both cities.

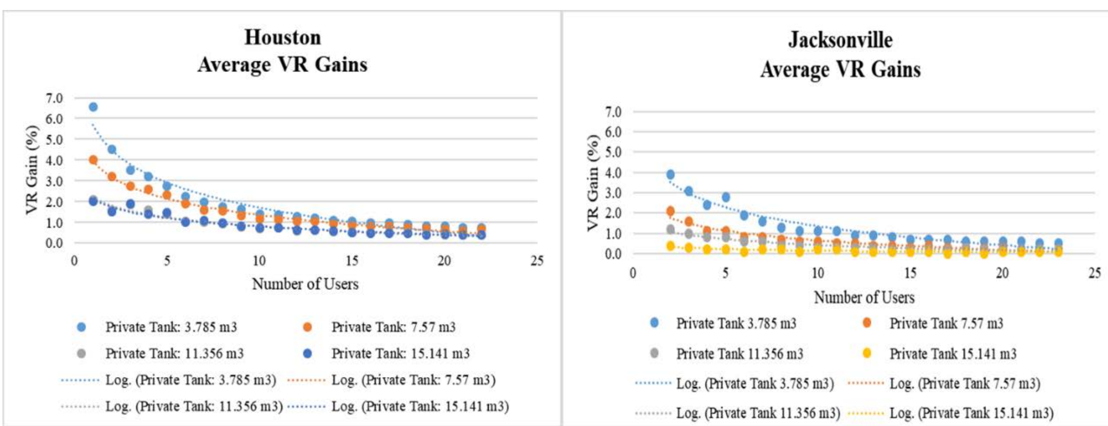
The impact of the DRWH system is two-fold: VR increases and the total water storage capacity of the system increases compared to an individual RWHS. To further examine both those impacts, we look closely at a DRWH system of 2, 3 and 4 users, each with a 3.785 m^3 tank and variable communal storage for both cities.

The peaks in the storage capacity shown in Figure 18 can be attributed to the variable water demands that we used in the simulation instead of average water demands. For example, the peak in Figure 18 a) for private tank of 3.785 m3, the highest VR is at 72 m^3 for a VR of 29.9% while for previous and following storage capacities the maximum VR is 29.8% which occurs for a communal storage capacity of 53 m^3. The difference between both VR outputs is minimal and the higher VR can be attributed to lower water demands in that particular simulation.



a) Houston b) Jacksonville

Figure 18 - Maximum VR gains for each group of users for four private storage options



a) Houston b) Jacksonville

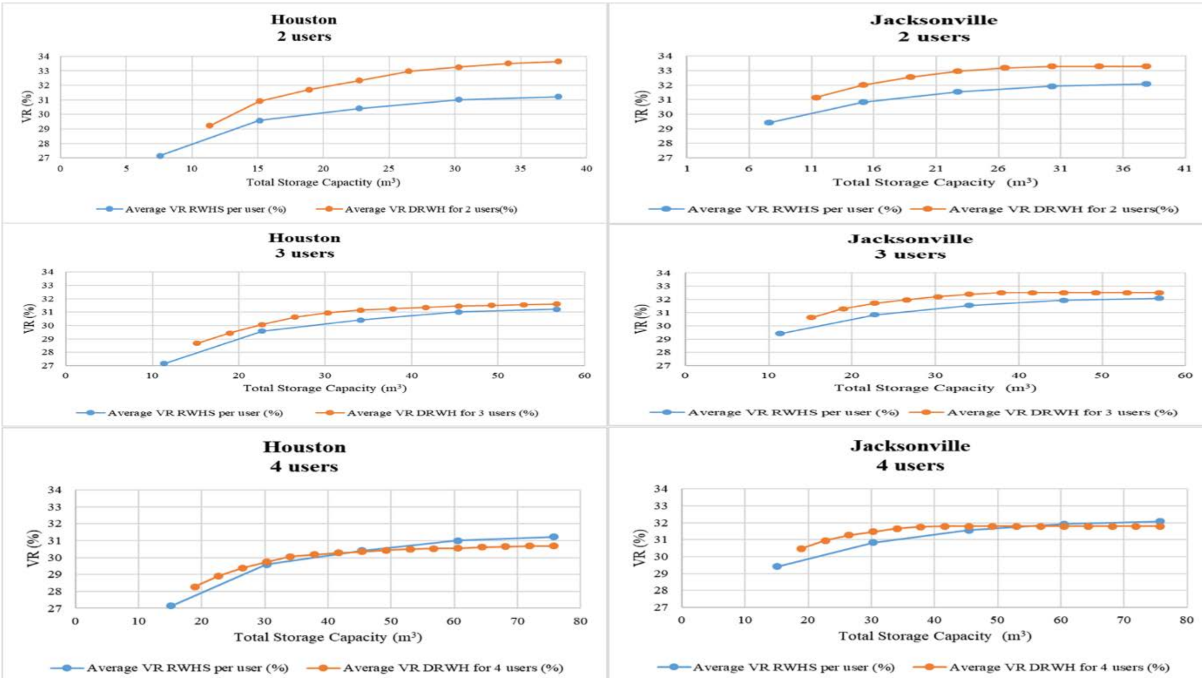
Figure 19 - Maximum VR gains and best fit curves for Houston and Jacksonville

How does the VR vary when the emphasis is on storage capacity (private and communal storage)?

In this section, the emphasis is on reducing the total storage capacity (private and communal storage) and its effect on the VR.

As can be observed from Figure 20 with respect to both cities, an addition of a small communal storage connected to the existing private storage per household (3.785 m^3) will produce a VR gain when compared to the total storage capacity. For instance, for two households for the city of Houston, the distributed RWH system produces an average gain of 1.3 % per user for two connected users for the same total storage capacity as for two traditional, not connected RWHSs. For a total capacity storage of 22.5 m^3, the DRWH system averages a VR gain of 2% per household. As for the DRWH system with 4 users, the traditional rain water harvesting system produces better gains for a total storage capacity of around 40 m^3.

In the case of Jacksonville, 2 connected users produce average VR gains compared to a traditional rain water harvesting system (with no exchange between systems) for all storage capacities, while for 3 users and 4 users, the larger the communal tank, the closer the VR gains to an individual RWH system.

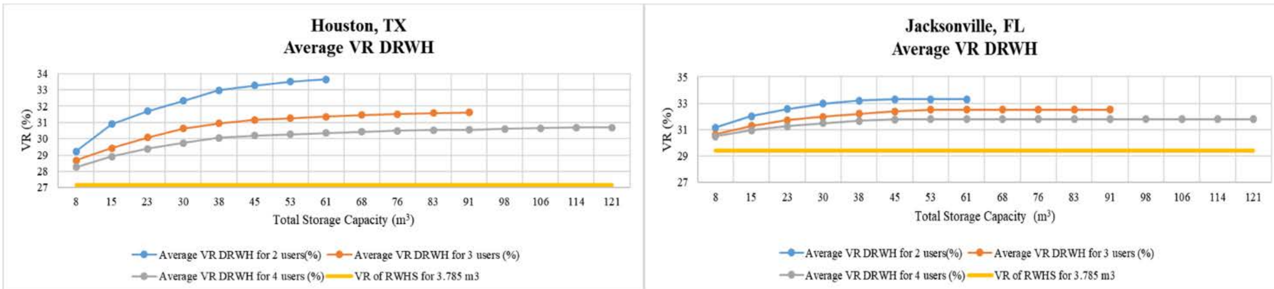


a) Houston b) Jacksonville

Figure 20 - Average VR per total storage capacity for Houston and Jacksonville

How does the VR compare between a DRWH system and a RWHS (with no exchanges and no communal storage)?

In Figure 21, for the city of Houston, we compare the VR resulting from the DRWH system of multiple households, each using a private storage of 3.785 m^3, with the VR of a single household with the same storage tank capacity, not connected to a communal tank. The average VR for each user from the three DRWH systems shown is higher than for a comparable household with the same storage capacity rain water harvesting system (3.785 m^3). As for the city of Jacksonville, in the case of two connected users, the average VR is higher than that of a single user, as for the case of three and four connected users, the average VR increases when the total storage capacity (private and communal storage) increases with the highest gains for private storage of 3.785 m^3.



a) Houston b) Jacksonville

Figure 21 - Average VR for DRWH compared to a RWHS for Houston and Jacksonville

Discussion

The purpose of this research was to determine a) the impact distributed RWH will have on the reliability of the system, the storage (private and communal) required to achieve that reliability, and c) the optimal number of connected households to the distributed system.

In Houston's case, connecting up to 7 to 10 users can produce average VR gains above 1.5% (Figure 18) compared to the VR expected from a traditional, not connected rain water harvesting system with the highest gains for 6-7 users connected with private tanks of 3.785 m^3. As the number of users goes beyond 24 users, the communal storage needed to sustain a VR gain does not increase above a certain storage capacity which means that the system achieves saturation.

As for Jacksonville, connecting up to 7 users can produce average VR gains above 1.5 % (Figure 18) with the highest gain noted by the use of private tanks of 3.785 m^3. As the number of users increases, there are no notable gains in VR, hence, in Jacksonville the ultimate number of connected users should not go beyond 4.

The importance of connecting the overflow of RWHSs and hence the existence of DRWH systems serves multiple purposes:

a) to reduce potential flooding and property damage: excessive stormwater can enhance the potential for flooding, erosion and potentially hazardous events. Reducing the overflow from the storage tank by diverting it to a communal tank reduces the likelihood of such events.

b) to reduce impacts on the stormwater infrastructure: indeed, collecting the overflow from one individual rain water harvesting system, storing it then re-purposing that stored overflow for that same household or another household reduces the amount of rainfall going to waste in the stormwater pipes. The risk of exceeding the stormwater infrastructure's capacity is reduced, hence minimizing potential infrastructure breakdown or malfunction.

c) to decrease the pressure on the municipal water supply (MWS) network: the presence of a communal storage system increases the volumetric reliability of RWHSs (which could be as high as 25% increased reliability as per Figure 21, Houston), which means an increase in meeting water demands from rainfall which means a decrease in the water supply from the MWS which could translate to financial gain to the household (reducing the water bill) and freeing up the resources on the municipality's side to upgrading the existing infrastructure.

d) to increase the resilience of the water and stormwater infrastructures in the face of climate change: one of the potential impacts of climate change is the change in rainfall patterns. Areas that used to receive a certain amount of rainfall could be receiving more/less which in turn will mess with the storage capacity of a single rain water harvesting system, especially that planners use data previous years to determine the storage capacity of a given system. Having a backup storage could alleviate that problem, which in turn directly impacts the water and stormwater infrastructures in the event of more/less water demand or more/less rainfall runoff respectively.

The two candidate cities chosen both have a Köppen classification of Cfa and an average yearly precipitation of 1,270 mm. Interestingly, those climates make stormwater management of paramount importance mainly because, a) frequent and heavy rainfall and, b) the increase in impervious surfaces in urban areas. Hence, a need for a distributed rainwater harvesting system is especially attractive in such climates where there is a need to save space. New York City has almost the same characteristics as the two selected cities, but was not picked for further analysis based on the criteria we set previously. Hence, more research should go into what deems an area suitable for DRWH systems.

Figure 18 and Figure 21 allow us to differentiate between designing the system for a high VR or for a balance between higher VR and total storage capacity. The former can be the case of an expected increase in rainfall due to climate change and a lack of funds from the town managers to update the stormwater infrastructure fast enough or critically enough to mitigate those effects. In that case, the system can become part of the town's stormwater management plan. As such, Figure 18 can be a valuable resource in determining the target private and total storage for a maximum increase in VR with respect to the number of households.

When the emphasis is on maximizing VR without exceeding the total storage capacity of individual RWHSs, then the resource for planners becomes Figure 21. Indeed, the latter minimizes the increase cost of "unlimited" communal storage while at the same time increasing the VR of the individual system per household. This system could work in a communal type development like cohousing communities, which consists of private homes and shared resources, or, in a community of tiny homes where storage/roof area are limited and the pooling of water resources can truly make a difference.

This work looked at identical single-family households with two residents. Based on the criteria discussed in the first section of this work, two cities were selected to validate the simulation. Future work should consider different households, with more/less residents as well as mixing the building types (residential with office/commercial buildings). As such, this DRWH system could be effective in more areas, hence, increasing the resilience of water and stormwater infrastructures, especially in the face of climate change, especially with the use of modular water tanks. What is also needed is more granularity with respect to water demand, the increased usage of smart water meters will help accurately gauge the amount of water needed per building type, thus improving the inputs to the system, especially as we move towards cities based on the Internet of Everything (IoE).

Conclusion

A mix of centralized/decentralized water infrastructure is becoming more appealing in the face of the amount of resources needed to upgrade/improve the existing infrastructure. Communal and individual RWHSs are at the core of the decentralized solution where they impact both the water and stormwater infrastructures. This paper looked at a novel approach to communal RWHSs, which is distributed rainwater harvesting system, where individual households connect the outflow of their RWHS to a communal storage where they could retrieve water when their system is not able to meet all water demands. This approach is based on the distributed computer systems which are autonomous, communicate by message passing, robust against component failure, and work towards a mutual objective.

We simulated the performance of the system in two cities (Houston and Jacksonville) based on our selection criteria which initially comprised nine representative cities from the nine climatic regions in the United States, for multiple private and communal storage capacities combination. Volumetric reliability gains (between 1.5% - 6% and 1.5% - 4%) can be achieved for 7 to 10 and 6 to 7 connected households respectively for Houston and Jacksonville if the emphasis is on VR. As per total storage capacity, the system achieves higher VR gains for lower total storage capacity while the system achieves higher VR gains for higher total storage capacities in Jacksonville.

This proposed decentralized rainwater harvesting system is attractive in the face of climate change, increases the resilience of water/stormwater infrastructures and could potentially decrease the potential effects of flooding and property damage from stormwater. This research focused on two cities, more exploration is needed to a) determine which areas are suitable for this distributed communal rainwater harvesting system, and, b) understand the effect of mixing different types of buildings in the communal mix.

CHAPTER SIX: LIFECYCLE COSTING OF DISTRIBUTED RAINWATER HARVESTING SYSTEMS

Introduction

The aging water infrastructure in the U.S. is becoming a critical issue in many locations, and investment has not been keeping up with the needs. According to the ASCE, there will be an estimated $84.4 billion annual capital investment gap for water infrastructure by 2020 in the United States (Economic Development Research Group of the American Society of Civil Engineering 2016). Water demand is growing (Sabol 2011) and the rate of urbanization is increasing in expanding cities. The latest census of 2010 shows that urban areas on average are outgrowing the national growth by 2.4% (United States Census Bureau 2012) and water utility bills are on the rise overall (Walton 2015). On the other hand, a small subset of cities in the U.S., shrinking cities with dwindling population, are facing two major problems with regards to their water infrastructure: aging infrastructure and reduced water demands, both of which are exacerbated by the dwindling tax base that could have otherwise helped with the network maintenance (Love et al. 2019). City and town managers of both growing and shrinking urban areas are facing increasingly difficult choices related to water infrastructure management: a) maintaining the status quo, which is investing in the existing infrastructure, b) funding investments at the parcel scale, or c) investing in parcel-scale investments and maintaining the current infrastructure. Any investment choice will ultimately affect water, wastewater, and stormwater networks.

At the center of decentralized water infrastructure lies rainwater harvesting systems (RWHS). RWHS act as a containment measure for stormwater runoff by capturing and storing of rainwater which can be used for irrigation, car washing, non-potable domestic functions (laundry, toilet flushing, etc.) and when treated, as a potable water source. Rainwater harvesting is not a new concept; the practice has been available for centuries and multiple countries currently depend exclusively on harvested rainwater for day to day life (Rowe 2011; Wallace and Bailey 2015). The vital importance of RWHS is the effect they have on the three water networks (potable, stormwater, and wastewater) in terms of decreasing water demand on the potable water network, decreasing stormwater runoff, and, if coupled with greywater recycling systems, decreasing the quantity of wastewater generated by using water multiple times before discharge (Ghisi and Ferreira 2007).

Communal rainwater harvesting at the individual residential scale preserves excess runoff from multiple roofs, stores it in a communal tank, then treats and redistributes it as potable water to the community (Cook et al. 2013; Gurung and Sharma 2014; Gurung et al. 2012; Hashim et al. 2013; Seo et al. 2012; Seo et al. 2015). Other types of communal RWH currently exist in multi-residential buildings (Agudelo-Vera et al. 2013; Eroksuz and Rahman 2010; Ghisi and Ferreira 2007; Marinoski et al. 2018; Silva and Ghisi 2016). A communal RWHS for single-family houses works best in off-grid locations, where access to the municipal water supply is difficult (Cook et al. 2013; Gurung and Sharma 2014). The main advantage of a communal RWHS over individual RWHS is that it provides a centralized means for adequate maintenance for individual households who could have difficulties maintaining their own system properly. This centralized approach ensures better water quality (Gurung and Sharma 2014) and economies of scale for capital costs, reduced land footprint, centralized disinfection, and flexibility in matching supply and demand for different households (Cook et al. 2013).

Distributed rainwater harvesting (DRWH) combines the individual rainwater harvesting system with the communal aspect of communal rainwater harvesting by combining individual systems with a communal backup tank that collects the overflow from the individual tanks, then redistributes this communal rainwater among households as needed. As shown in the previous chapter, DRWH works in cities like Houston and Jacksonville for single-family households whereby using individual tanks of 3.785 m^3 with communal storage can increase the volumetric reliability between 1% - 6% for up to 10 and 7 households in Houston and Jacksonville, respectively.

DRWH systems offers multiple advantages over private rainwater harvesting systems by increasing the volumetric reliability (VR) while decreasing total storage. If a community decides that they wanted to install RWH systems in their households, they are presented with two options:

- Option number one is for every household to entirely own their own system (15.1 m^3) rainwater tank, without drawing from the communal tank, hence a traditional RWHS.
- Option number two is for every household to own a smaller system (3.785 m^3) and be connected to a communal tank to draw rainwater from it when needed.

The fundamental question becomes: What is the total cost of the system per household? The main contribution of this paper is to answer this question by conducting a holistic study of the DRWH process that looks at the lifecycle cost (LCC) of the DRWH system (for two up to ten connected households) using the net present value (NPV) method of lifecycle costing. Piping and pumping costs are likely to make larger clusters of housing inefficient, because according to Gurung and Sharma (2014), the optimal amount of connected households to a communal system is between 192 and 288 households. The results of the study of this process will be compared to the cost of owning an individual rainwater harvesting system in the city of Houston (which was shown to be a good candidate for DRWH systems in the previous chapter), which will be considered as the base case. Houston in this case is considered as a case study to test the process represented by DRWH systems.

Methodology

As shown in the previous chapter, a DRWH provides an increase in VR with a decrease in total storage for domestic rainwater harvesting for two story single households with two residents in the cities of Houston and Jacksonville. To illustrate the costs associated with this distributed network, this paper explores a case study of this network in the city of Houston. This study adopts a holistic view to building the DRWH so that we can ultimately come up with the total cost of ownership (TCO) per household. The TCO per household will be compared to the cost of an individual house, owning an RWHS with a storage tank of 15.1 m^3, the optimal size for a single-family household as determined in the previous chapter, for two residents with a roof area of 68.25 $m^{2.}$

Study parameters

This section details how the study is set up in terms of parameters and assumptions. The parameters used in the study for the communal tanks are shown in Table 14.

Table 14 - Study parameters

Parameter	Value
House area	136.5 m^2 ~ average size household in the US (US Census Bureau 2018)
Roof area	68.25 m^2 (assuming that it's a two-story house)
Roof type	Sloped metal roof
Runoff coefficient	0.9
Tank types	Polyethylene tanks (most commonly used in residential scale across the US (Thomas et al. 2014)
Number of residents	2
Total water demand	0.265 m^3/capita/day (USGS 2017)

Common parameters to the base and study cases:

- The water demand was retrieved from the latest USGS (2017) water use report by using the average domestic water demand in the county where the city is located. In this instance, the average water demand in Harris county, Texas is 0.265 m^3/capita/day.
- The houses are assumed to be plumbed appropriately for using rainwater harvesting. Since rainwater could be corrosive to metal pipes, the recommendation would be to furnish all internal pipes with cross-linked polyethylene PEX plastic pipes, that meet the specifications for transporting drinking water.
- The analysis duration is assumed to be 30 years, which is the average time a house is mortgaged in the US.
- The "internal" components of the individual RWHS were not included in this cost (water treatment system, submersible pump and O&M costs associated with these components) study because the base case and the study case both have individual RWHS, hence, these components would not tip the balance in either case. We also did not include the delivery cost of the water tanks because those costs are location-based.

Base case (RWHS):

- The individual system, will have an underground 15 m^3 tank, while the connected systems will have above-ground 3.785 m^3 tanks.

Study case (DRWH as shown in Figure 23):

- The individual tanks used per household are sized at 3.785 m^3 as determined by the design of the network as shown in the previous chapter, by using daily water balance.
- The communal tank will be one fiberglass tank. We are using fiberglass for the communal tank because fiberglass tanks have a longer lifespan than polyethylene tanks, reducing the tank replacement timeframe thus reducing the potential of failure. Although two or more smaller tanks instead of one fiberglass tank could be less expensive, the plumbing of those tanks will be more complicated, raising the risk of a system malfunction or failure.
- Gravity rainwater collection pipes will connect the overflow of the individual tanks to the communal tank. A duplex water pumps at the communal tank site will pump the water back to the individual tank to the communal tank when needed. The gravity pipe will be a 100 mm (4 inches) PVC leading from the individual tank to the communal, while the pressurized pipes will be 75 mm (3 inches) PVC leading from the communal tank to the individual tanks. More information on piping can be found in Appendix A.
- One duplex booster pump will be placed at the communal tank site to transport water from the communal tank to the individual tanks and gravitational flow will transport the rainwater from the individual tanks to the communal tank. The pipes from the communal tank to the houses will be assumed as pressurized.

- We chose to use a duplex booster pump (60 psi) that could supply up to 0.45 m^3/minute to serve the ten-household network, and a smaller one (44 psi) for the network between two and four households. The average lifespan of such pumps is 15 years according to one supplier we interviewed about the feasibility of the system. More information about the pump can be found in Appendix A.
- The electricity rate of the city of Houston can be as low as 6.0 up to 11.0 kWh depending on the location and electricity plan chosen. We chose to use the 7.2 cents/kWh electricity rate because electricity rates in Houston are on a downward trajectory. We will test the other rates in our sensitivity analysis to understand the impact the electricity rate has on the net present value of the DRWH system. The chosen pump uses 1,840 W (per the manufacturer). Assuming that it runs 2 hours per day, then the electricity usage will be 1,343 kWh/year. Hence, the electricity cost for running the pump is $97 per year. More information about the power calculation can be found in Appendix A.
- With regards to the distributed network, the number of houses, corresponding communal storage VR gain and average water demand met per household is shown in Table 15.

Table 15 - Communal storage for possible network scenarios (from previous chapter)

Number of households	**Communal storage size (m^3)**	**Average VR per household (%)**	**Average water demand met per household (m^3/month)**
2	30.2	33.6	5.35
3	45.4	31.6	5.03
4	49.2	30.6	4.88
5	53.0	30.3	4.82
6	53.0	30.0	4.7
7	60.6	29.4	4.67
8	53.0	29.1	4.63
9	49.2	28.9	4.6
10	41.6	28.7	4.56

Site Characterization

According to the ordinance notes obtained from the city of Houston's website (City Of Houston 2020), given that a single-family household's footprint is 68.25 m^2, and given that the lot has to be at least 60% not covered, we assume that the lot size considered is 186 m^2. We assume that the house is placed in the middle of the lot as shown in Figure 22. We also assume that all the houses and lot sizes in this analysis are identical and the housing layouts are as shown in Figure 22 and Figure 23.

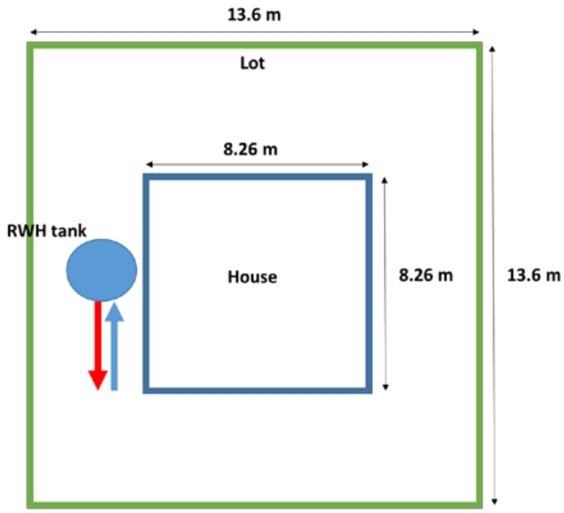
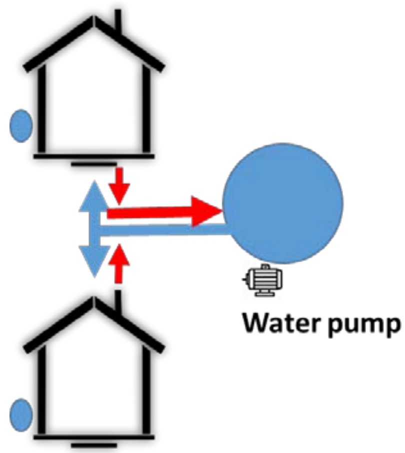
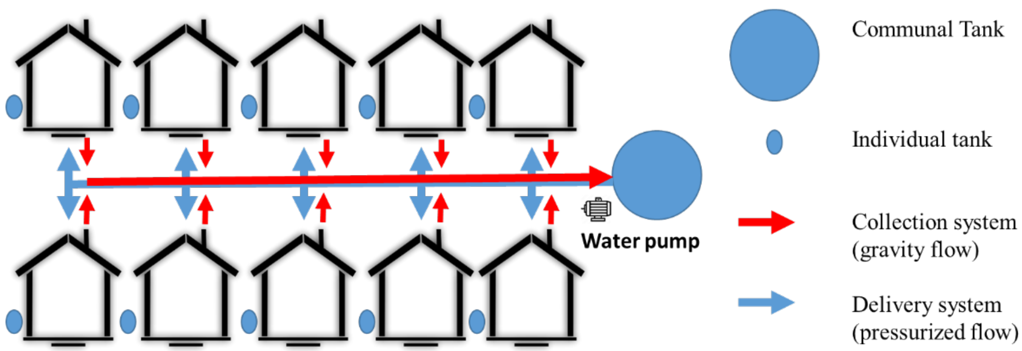


Figure 22 - Lot and house dimensions



a) Two houses connected to the communal tank



b) Ten houses connected to the communal tank

Figure 23 - Example of site layout with a) two houses and b) ten houses

Cost and cost equations

The Association of Physical Plant Administrators (APPA) defines the TCO as an approach to increasing the return on investment of administered physical assets that includes the accounting of all identified and projected costs to include first, recurring, renewal, replacement, and end-of-useful life costs to aid in life-cycle asset management decisions (Association of Physical Plant Administrators 2020). The TCO can be equivalent to the lifecycle cost analysis (LCCA) as it considers both facility occupancy costs and hard capital costs. The National Institute of

Standards and Technology (NSIT) define LCCA is an economic method to evaluate a project where the costs associated with owning, operating, maintaining and disposing of the project are expected to be central to that decision (Fuller and Petersen 1996). The LCCA takes into account initial investment costs, operating, maintenance and repair costs (including water and energy costs) as well as disposal costs over the study period with the costs discounted to show the time-value of money. The LCCA can identify the most cost-effective option that has lowest lifecycle cost (Fuller and Petersen 1996). To make the analysis less complicated, we will assume that there will be no disposal or salvage costs associated with this study.

Indeed, LCCA has been used to determine the costs of rainwater harvesting systems (e.g., Devkota et al. 2015; Ghimire et al. 2014; Ghimire et al. 2017; Rahman et al. 2012; Roebuck and Ashley 2007; Sweeney and Pate 2015). The items and labor estimates were costed using Building Construction Costs with RS Means data (2020) and Green Building Costs with RSMeans data then adjusted to the Houston location cost index (Gordian 2020a; Gordian 2020b). More information can be found about the costs in Appendix A.

Table 16 and Table 17 list the components of both the DRWH and the individual RWHS.

It is worthwhile noting that after speaking to one rainwater harvesting systems vendor in the state of Virginia, they noted that the costs RSMeans cost data were conservative with regards to installing underground tanks. This means that the costs for both the individual system and the DRWH system are likely higher than reported. The expected increase in costs is reflected in both private and communal systems. Further research is needed to understand the impact on the initial costs of both systems.

Table 16 - Itemized cost table for the RWHS

Component	Cost ($)	Service life (years)
Tanks (cost + installation)		
15.1 m^3 (underground)	$7,595	40
Other capital costs		
Earthwork	$52/$m^3$	

Table 17 - Itemized cost table for the DRWH

Component	Cost ($)	Service life (years)
Capital Costs		
Pipes (cost + installation)		80
75 mm (3 in) PVC water pipe	$73.1/m	
100 mm (4in) PVC water pipe	$87.6/m	
Pumps (cost + installation)		15
Duplex booster pump (44 psi)	$6,500	
Duplex booster pump (60 psi) (PumpProducts.com 2019)	$7,500	
Tanks (cost + installation)		40
3.785 m^3 (above ground)	$924.5	
15.1 m^3 (underground)	$7,595	
30 m^3 fiberglass (underground)	$14,905	
37.85 m^3 fiberglass (underground)	$16,556	
45 m^3 fiberglass (underground)	$23,140	
57 m^3 fiberglass (underground)	$26,795	
Other capital costs		
Earthwork	$52/ m^3	
Operation Costs		
Electricity for pumps	1,343 kWh/year	
Maintenance Costs		
Inspection, reporting and information management (EPA 2013)	$260	

Sediment check and cleaning (every 3 years) (EPA 2013)	$390	

The general formula of the LCC present-value method is as follows:

$$LCC = \sum_{t=0}^{N} \frac{C_t}{(1+d)^t} \quad (2)$$

Where: *LCC* is the total LCC in present-value dollars,

C_t is the sum of all relevant costs (initial and futures costs, less positive cash flow) in year t,

N is the study duration, and,

d is the discount rate.

So the LCC of the DRWH system and the RWHS is as follows:

LCC = I + Repl – Res + E + W + OM&R (3)

Where: I is the present value investment costs,

Repl is the present-value capital replacement costs,

Res is the residual costs (salvage value),

E is the present-value energy costs,

W is the present-value water and sewer costs,

OM&R is the present-value operation and maintenance costs.

In this study, we neglect the residual costs or salvage costs in order to simplify the analysis. We also don't include the stormwater utility fee in the water costs for two reasons:

a. Houston includes a yearly "drainage cost" that is based on the impervious lot area. The fee is quite small for the proposed house layout, \$0.032 per sqft of impervious surface for single-family residential houses (City of Houston 2018).
b. Since the lot layout is the same for all the households, adding this cost would not have affected the NPV of the total system costs.

However, stormwater fees are important to consider in future studies because a) rainwater harvesting have a direct impact on the stormwater infrastructure and b) stormwater fees will likely rise in the future in urban areas to accommodate the increase in impervious surfaces and increase in the usage of the stormwater infrastructure.

For annually recurring uniform accounts, like the energy and O&M costs, and water savings, present values are calculated as follows:

$$Pv = P\ \frac{(1+d)^N - 1}{i(1+d)^N} \qquad (4)$$

Where, Pv is the present value per 1\$ of annual cost,

d is the discount rate, and,

N is the study duration.

For annually recurring non-uniform accounts, like replacement costs, the only component that is being replaced once over this lifecycle is the water pump and the present value of this component can be estimated as:

$$Pp = P + P(1 + d)^{-N/2} \quad (5)$$

Where, Pp is the present value of the component that is being replaced during the analysis

period,

d is the discount rate, and,

N is the number of years.

The discount rate

In order to evaluate present value results over the study period, the LCC uses the constant dollar approach where the prices are not affected by the rate of general inflation (Fuller and Petersen 1996). Two methods are used for that effect:

- Method 1: This method approximates future costs and savings in constant dollars and discount with a real discount rate. The real discount rate is the rate that excludes the rate of inflation.
- Method 2: This method approximates future costs and savings in current dollars and discount using a nominal discount rate. The nominal discount rate includes the rate of inflation.

Both methods yield the same present value results. However, since it is simpler to conduct an analysis using the constant dollars method because we wouldn't have to estimate the inflating rate from year to year (Fuller and Petersen 1996). For this reason, we will use the constant dollars method and estimate the present value using the real discount rate.

The real discount rate for the year 2020 according to the Office of Management and Budget (OMB) for public investment is 7%. However, OMB recommends that two estimates be submitted, with a real discount rate of 3% and another discount rate of 7%. For the purpose of the study, we will conform with the discount rate of 7% recommended by the OMB and we will analyze the effect of the other discount rate in the sensitivity analysis section. Given that opportunity costs to a private citizen are typically much higher than for public institutions, the discount rate used for this type of investments should be higher than the government's mandated one for public investments or projects. Indeed, Grout (2003), Grimsey and Lewis (2007) and (Roumboutsos 2010) argue that private investments should use a higher discount rate than public investments. However, we used the OMB rate because, in the absence of a recommendation for private investments, the OMB recommendation to use 7% for the discount rate is the next best decision.

Results and discussion

Results

We first evaluated the scenario of an individual RWHS (without a connection to a communal tank), which is the base case in this study. In Semaan et al. (2020), using the daily average water demand method to simulate tank sizes, the optimal tank size was chosen based on the change in the VR between two adjacent sizes becoming less than 1%. So, for a house with a 15.1 m^3 tank the corresponding VR is 30%. Based on equation 1, after adjusting the costs to the city of Houston, the NPV of the total system costs of the RWHS was equal to $1,224 as shown in Table 18.

Next we computed the NPV of the total system costs of the DRWH system for two, three, four, five, six, seven, eight, nine and ten households, after adjusting the costs to the city of Houston. The NPV of the total system costs per household of a DRWH for ten households is shown in Table 19 and the results of the NPV of the total system costs per household for DRWH for two to ten connected households are shown in Figure 24.

Table 18 - Lifecycle cost of RWHS per household

	Cost ($) (2020 value)	**Present value ($) (30 year)**
Investment cost	7,122	7,071
O&M cost/year	0	0
Replacement cost	0	0
Energy cost/year	0	0
Water cost/year	313	3,884
NPV per household of RWHS		10,955

Table 19 – NPV of the total system costs per household of DRWH for 10 connected households

	Cost ($) (2020 value)	**Present value ($) (30 year)**
Investment cost	5,090	5,090
O&M cost/year	390	420
Replacement cost	750	1,022
Energy cost/year	9.7	120
Water costs/year	313	3,884
NPV per household of DRWH for 10 households		10,535

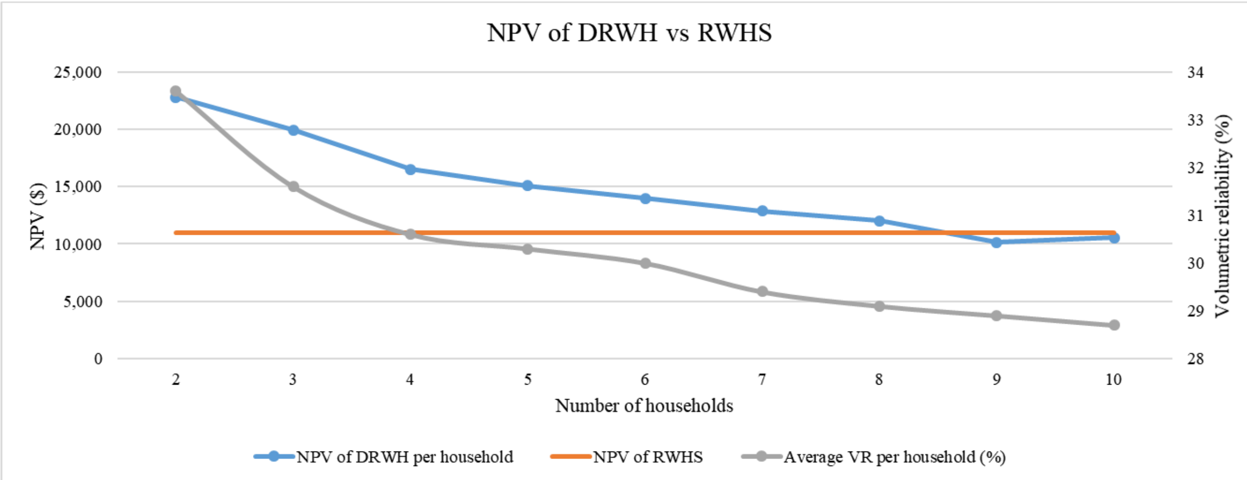


Figure 24 – NPV of the total system costs of DRWH

From Figure 24, we can see that the NPV of the total system costs of the communal system is comparable or lower than the NPV of the total system costs of the individual RWHS when seven households are connected to a communal tank. In fact, when only two households are connected, the VR is the highest at 33.6% and for the highest NPV of the total system costs per household, for 9 and 10 households connected, the VR is around 29%. The VR for the 15 m^3 is at 30% and, hence, if our decision is based on NPV of the total system costs and VR, the highest gains would be between 7 and 8 connected households.

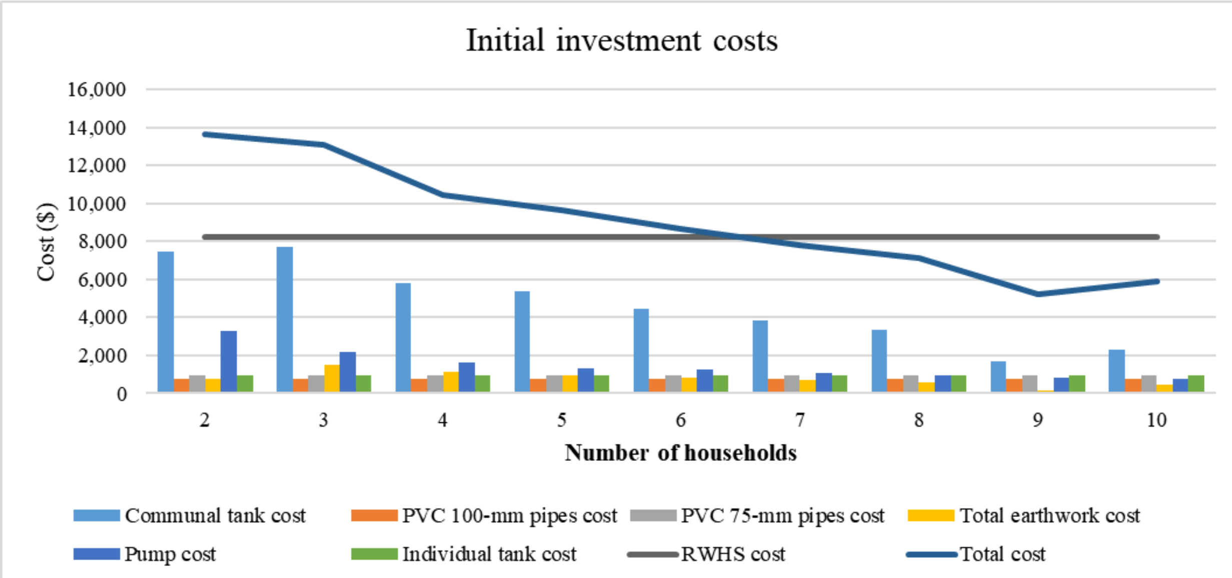


Figure 25 - Initial investment costs per household

As seen in Figure 25, the majority of the initial cost for all households is the communal tank cost. The pump cost is the second highest for four connected households but as the number of connected households increases, the investment costs per household decrease. It's interesting to note that the initial cost for six connected houses to the DRWH system is comparable to the initial cost of the RWHS and the initial investment cost becomes lower per household for more than seven connected houses.

If we compare Figure 24 and Figure 25, we can see that the initial investment costs there is an agreement in terms of investment costs and NPV of the total system costs over the analysis duration with respect to the DRWH system becoming comparable to the RWHS with six connected households, then the DRWH system becoming less costly than then RWHS for more than seven connected households.

Sensitivity analysis

Several components of the system affect the TCO, such as the discount rate, the analysis period, the size of the communal tank, the energy costs, and the water savings.

The discount rate

The discount rate of the NPV of the total system costs for this current study (7%) is in agreement with suggested discount rates for infrastructure projects (Lampe 2004). However, interest rates as low as 2% and as high as 10% have been used in the past, so we analyzed the impact of the interest rate on the NPV of the total system costs as shown in Figure 26 for 2, 3, 5 and 10% interest rate.

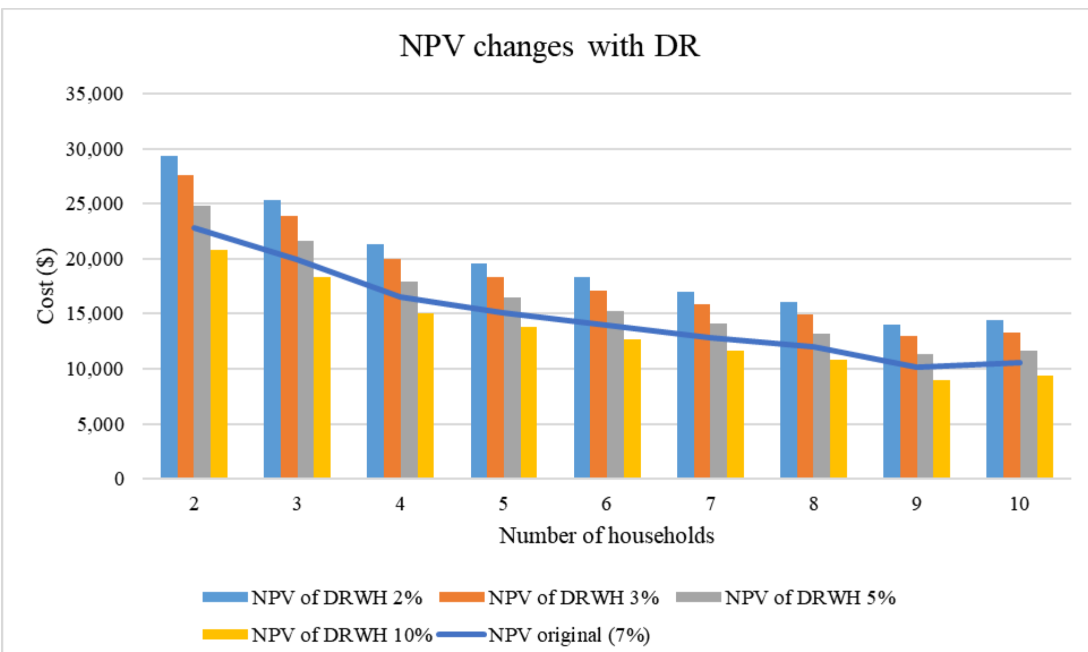


Figure 26 - NPV of the total system costs changes with discount rate

As can be seen in Figure 26, the NPV of the total system costs is indeed sensitive to the discount rate, namely the NPV of the total system costs increases with a higher discount rate and decreases with a lower discount rate. Going back to the OMB's recommendation of the usage of two discount rates for such projects, the biggest difference in the NPV of the total system costs for both rates is for six to ten connected households.

Analysis duration

In this study, we assumed the lifecycle duration to be equivalent to the average duration a house is mortgaged in the US. In this case, we looked at how sensitive the NPV of the total system costs of the DRWH was to the analysis duration. As a result, we analyzed the impact the duration of the lifecycle cost had on the system in Figure 27 for 10, 20, 40 and 45 years. The only component that needed replacement for this whole analysis period was the pump. We assumed that the pump would be changed every 15 years. So, we applied equation (4) to reflect those changes. Hence, we are assuming that there will be no replacement costs in 10 and 15 years, once in 20 years, twice in 40 and 45 years. We assumed all other costs to remain the same for the analysis duration.

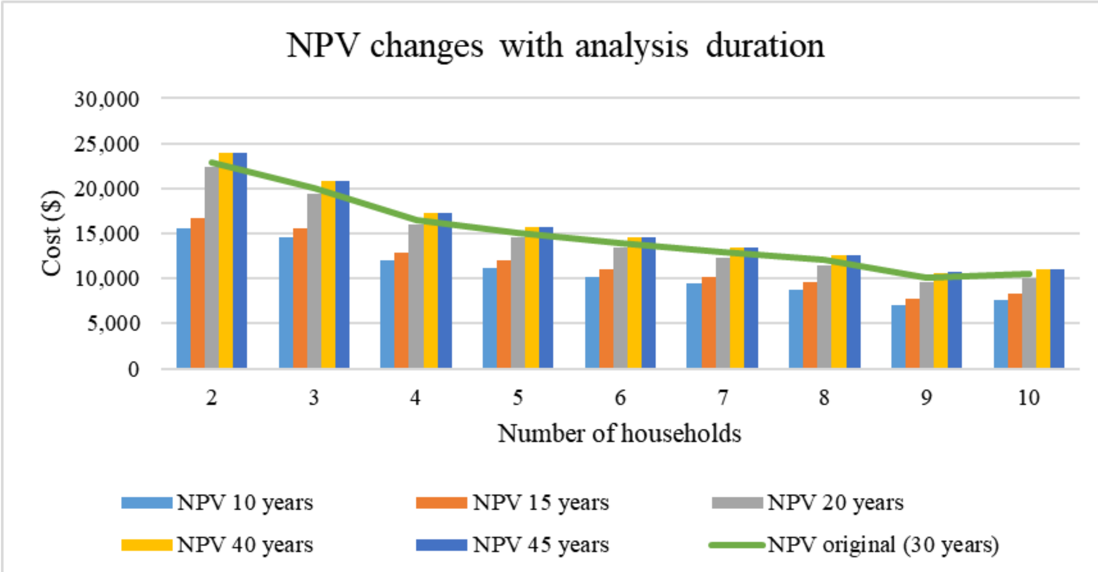


Figure 27 – NPV of the total system costs changes with analysis duration

The NPV of the total system costs is lower for the first two configurations of the system for when the duration is less than 15 years, where the cost of pump is replacement is not being introduced but is comparable to the NPV of the total system costs of the other durations. So the NPV of the total system costs is not sensitive to a change in the analysis duration.

Communal tank size

To analyze the effect of the tank size on the overall NPV of the total system costs, we evaluated the system by using the same communal tank size and redoing the cost analysis. The following metrics are affected by the change in the communal tank size:

- Cost of earthwork: the change in communal size tank changes the earthwork associated with that change. That change is reflected in the investment costs.
- Cost of communal tank: naturally, the cost of the communal tank changes with the size changes. This change is reflected in the investment costs.

- Water and sewer bill: when the communal tank changes, the VR per household changes, which in turn affects the water volume supplemented by the DRWH system, which ultimately affects the water and sewer bill. We calculated the water and sewer bill to reflect the changes in the VR (Appendix C) and there were no changes to the water and sewer bill because the changes in VR between communal tank sizes are very small.

We ran the cost analysis on various communal tanks, 30 m^3 (8,000 gal), 37.85 m^3 (10,000 gal), 45 m^3 (12,000 gal) and 57 m^3 (15,000 gal) as shown in Figure 28.

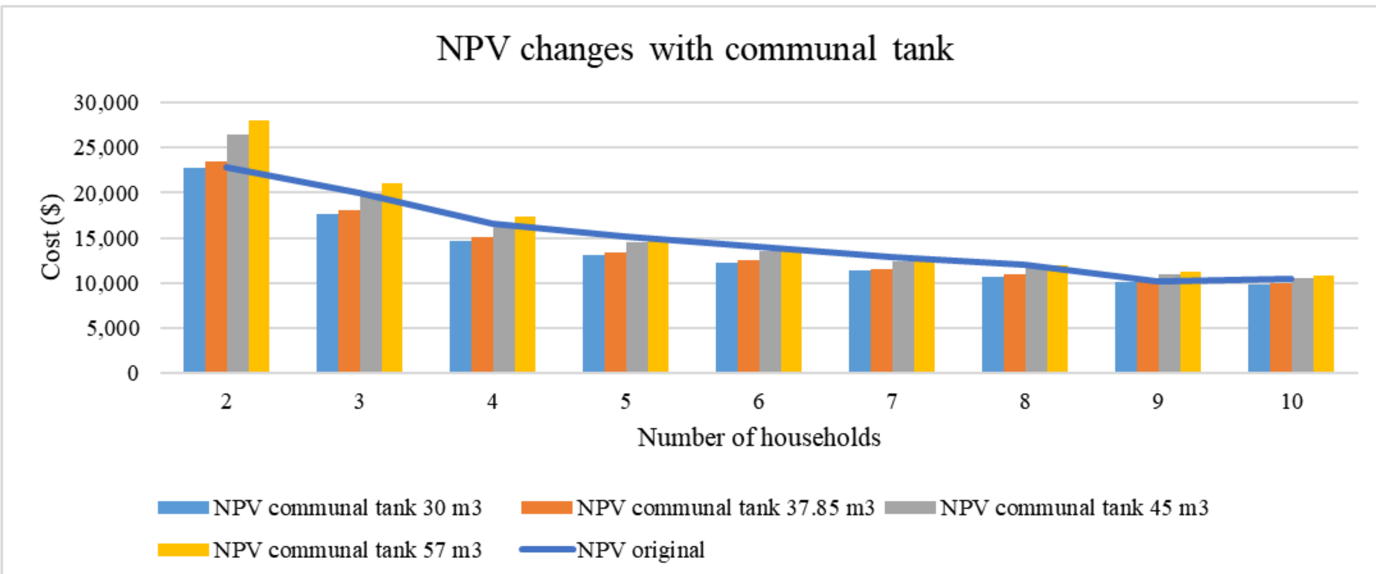


Figure 28 – NPV of the total system costs changes with tank sizes

The sensitivity of the system to the communal tank size change is very interesting for three or more connected households for the following two reasons:

- The change in tank size affects only investment costs in terms of the net present value. Hence, its effect will not be felt otherwise for the duration of the analysis period.
- Downsizing of the communal tank does not affect the water and sewer bill, especially for more than two connected households. This means that the NPV of the total system costs

is lower because the investment costs are lower. A case can be made, in this instance, that the optimal DRWH configuration is with a 30 m^3 (8,000 gal) communal tank for two to ten connected households.

In fact, if we compare the NPV of the total system costs of a communal tank of 30 m3 for the DRWH system with the NPV of the total system costs of the RWHS, we can see from Figure 29 that the NPV of six connected uses becomes comparable with the NPV of the total system costs of the rainwater harvesting system.

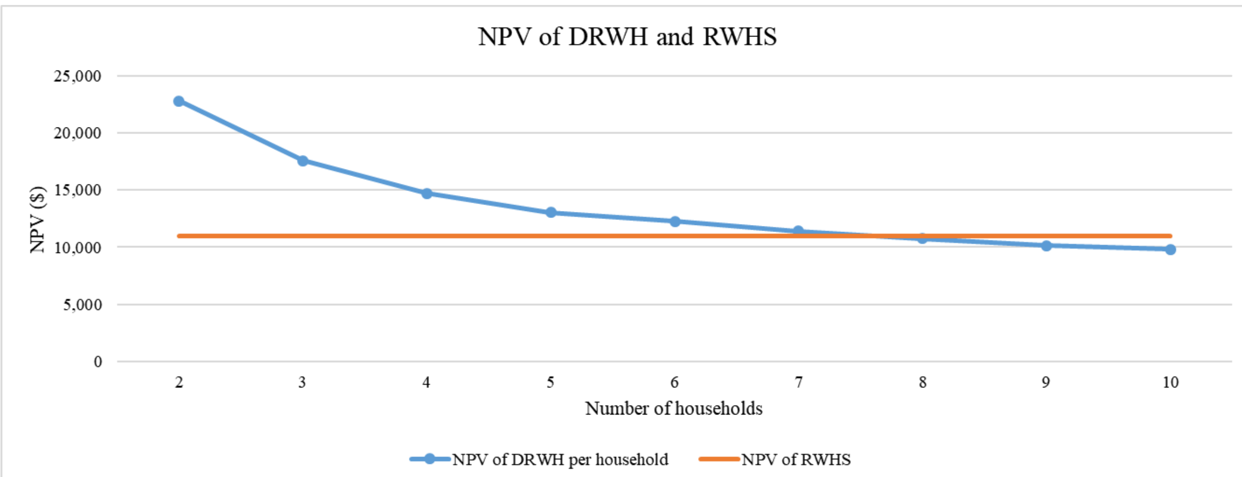


Figure 29 – NPV of the total system costs RWHS and DRWH for 30 m^3 communal tank

Energy costs

The electricity costs in Houston are very competitive, between 6.2 to 11 cents per kWh. In this study, we chose to use one of the lowest electricity rate (7.2 cents per kWh) because electricity rates are decreasing in Houston. Hence, we looked at the changes the energy cost will have on the project. For this analysis, we used the electricity rates of 6, 8, 9, 10 and 11 cents per kWh. The results of the NPV of the total system costs are shown in Figure 30.

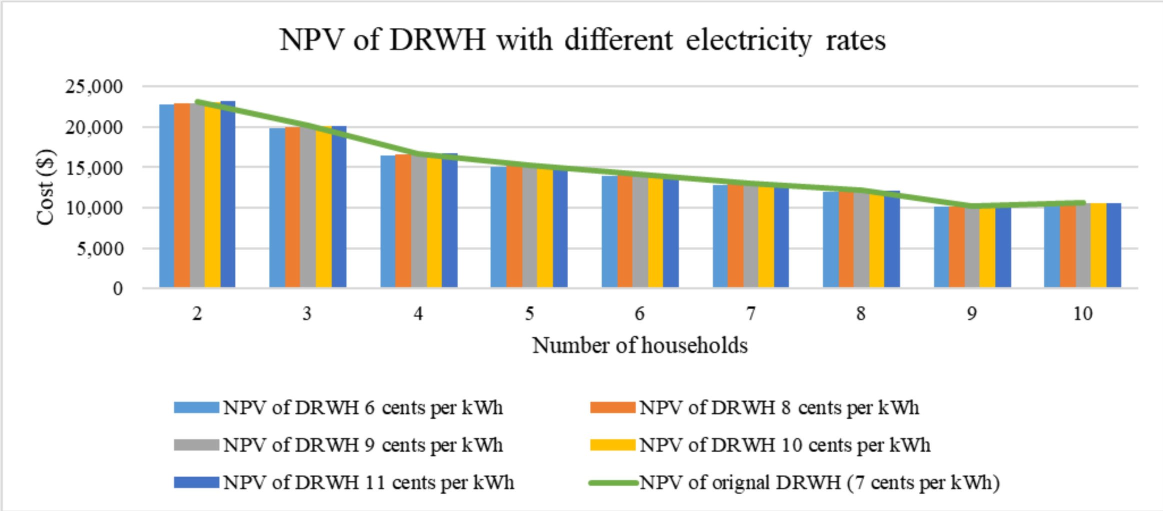


Figure 30 – NPV of the total system costs with varying electricity rate

The change of the electricity rate per kWh does not seems to have a large impact on the NPV of the total system costs per household compared to the initial NPV. Future research should consider the addition of a photovoltaic system to supply electricity to the pump as well as to the households.

Water costs

The major and only return on investment in this system is the water savings that combine water and sewage fees that can be a key component of the returns from the DRWH system. In order to analyze the effect of water costs, we need to distinguish the driving forces behind the water costs: water demand and water rates. In this section, we analyze the effect of both those components on the system.

Water demand

Initially, we assumed that two residents were living in a single-family household. What are the effects of having three or four residents in those households? We assume that the water volume saved by using the DRWH system remains the same with the addition of one and two residents as shown in Table 15. As such, the water savings per month would remain 5.3 m^3 per household.

As can be seen from Figure 31, increasing the number of residents to three or four per household will increase the water demand, decreasing water savings, thus increasing the NPV of the total system costs per household. This conclusion suggests that there's a serious risk of sizing based on number of occupants and the relationship between roof size (collection surface) and number of occupants is more accurate with regards to sizing the system.

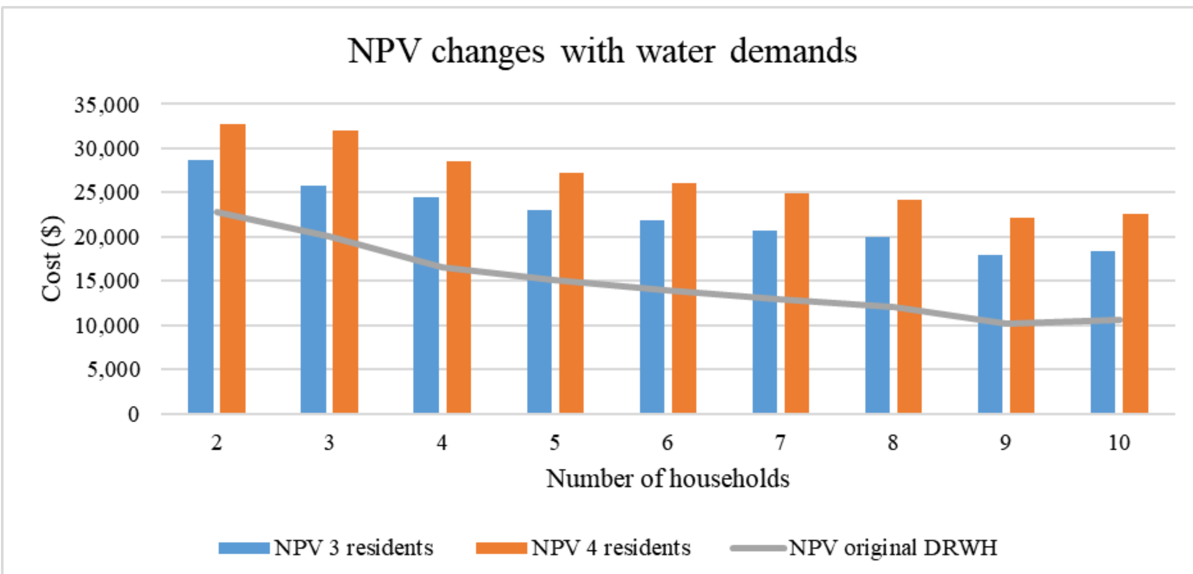


Figure 31 – NPV of the total system costs changes with increased water demand

Water rate

The current water rate for single-family households in the city of Houston is a step-rate system where the households get charged per 3.79 m^3 (1,000 gal) for the first 22.7 m^3 then the rate increases for every 3.79 m^3 up to 45.5 m^3 and a higher rate for higher consumption. Houston also has a sewer utility bill which is based on the water consumption: for every 3.79 m^3 of water consumed for the first 22.7 m^3, the households get charged a step-rate then they are charged the same rate for every 3.79 m^3 consumed afterwards. This is shown in Table 20. The city of Houston has been increasing the water and sewer rate with talks about an increase in rates for the year 2020. More information on water and sewer billing can be found in Appendix B.

Table 20 - Water and sewer rates in Houston

<table>
<tr><th>Water consumption (gal)</th><th>Water consumption (m^3)</th><th>Water rate ($)</th><th>Sewer rate ($)</th></tr>
<tr><td>1,000</td><td>3.785</td><td>5.69</td><td>11.96</td></tr>
<tr><td>2,000</td><td>7.57</td><td>12.97</td><td>12.35</td></tr>
<tr><td>3,000</td><td>11.36</td><td>13.41</td><td>12.67</td></tr>
<tr><td>4,000</td><td>15.1</td><td>25.36</td><td>29.04</td></tr>
<tr><td>5,000</td><td>18.9</td><td>30.39</td><td>34.96</td></tr>
<tr><td>6,000</td><td>22.7</td><td>35.43</td><td>43.57</td></tr>
<tr><td>7,000 – 12,000</td><td>26.49 – 45.4</td><td>Total charge for 6,000 gallons +5.47 per 1,000 gallon</td><td rowspan="2">Total charge for 6,000 gallons +8.61 per 1,000 gallon</td></tr>
<tr><td>Over 12,000</td><td>Over 45.4</td><td>Total charge for 12,000 gallons + $9 per 1,000 gallon</td></tr>
</table>

As such, we analyzed an increase in water and sewer rates by of 1, 5, 10, 15 and 20% per step-rate as shown in Table 21 and the results are shown in Figure 32.

Table 21 - Example of increase water and sewer rates

<table>
<tr><th colspan="2">Original rates</th><th colspan="2">1% increase in rates</th></tr>
<tr><th>Water rate ($)</th><th>Sewer rate ($)</th><th>Water rate ($)</th><th>Sewer rate ($)</th></tr>
<tr><td>5.69</td><td>11.96</td><td>5.75</td><td>12.08</td></tr>
<tr><td>12.97</td><td>12.35</td><td>13.10</td><td>12.47</td></tr>
<tr><td>13.41</td><td>12.67</td><td>13.54</td><td>12.80</td></tr>
<tr><td>25.36</td><td>29.04</td><td>25.55</td><td>29.33</td></tr>
<tr><td>30.39</td><td>34.96</td><td>30.69</td><td>35.31</td></tr>
<tr><td>35.43</td><td>43.57</td><td>35.78</td><td>44.01</td></tr>
<tr><td>Total charge for 6,000 gallons +5.47 per 1,000 gallon</td><td rowspan="2">Total charge for 6,000 gallons +8.61 per 1,000 gallon</td><td>Total charge for 6,000 gallons +5.52 per 1,000 gallon</td><td rowspan="2">Total charge for 6,000 gallons +8.70 per 1,000 gallon</td></tr>
<tr><td>Total charge for 6,000 gallons + 9.00 per 1,000 gallon</td><td>Total charge for 6,000 gallons +9.09 per 1,000 gallon</td></tr>
</table>

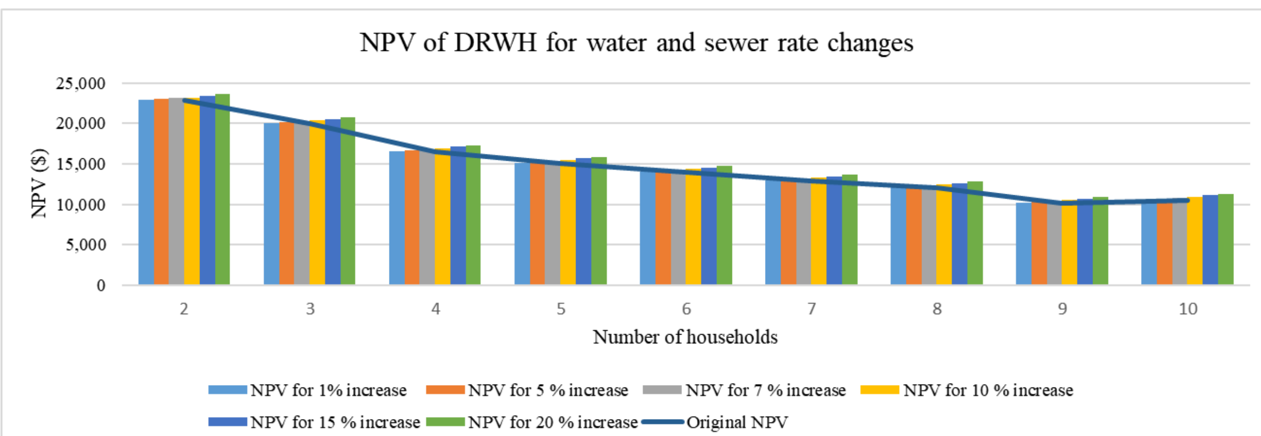


Figure 32 – NPV of the total system costs changes with increase in water savings

The increase in the water and sewer rates increases the NPV of the total system costs per household. As can be seen from Figure 32, even a small increase of 1% on the water and sewer rates has an impact on the NPV. In fact, it is not unusual to expect the water and sewer rates to increase as can be seen in Figure 33. This figure shows the water and sewer bill for a single family household with two residents from 2016 until 2019. The average increase of the bill for two consecutive years is 3% while the increase between 2016 and 2019 is 9.3%.

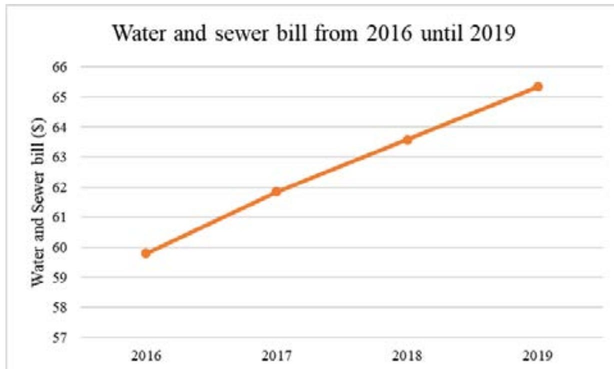


Figure 33 - Water and sewer bill between 2016 and 2019

Discussion

In this study, we analyzed the NPV of the total system costs per household of a DRWH network connecting the outflows of smaller rainwater harvesting tanks to one communal tank, that can supply water back to the households whenever needed, in the city of Houston, Texas. We compared the NPV of the total system costs of the system to the NPV of the total system costs of a RWHS. The lowest NPV of the system was for nine and ten connected households, lower than the NPV of the RWHS as shown in Figure 24. The highest NPV of the total system costs was for two connected households, which makes sense as explained by the economies of the scale: the higher the number of connected households, the smaller the cost per household.

The system is very sensitive to the communal tank size, in other words, to the tank's cost. Indeed, the bigger the tank, the more expensive it becomes and the more earthwork has to be done which drives the cost associated with it. The system is sensitive to the interest rate but not sensitive to the electricity costs. Future research should explore installing PV cells to supply the pump electricity, which could actually be a way to earn money for the residents, especially when considering that they could sell the remaining power to the electric grid as is expected in tomorrow's smart grids (El Rahi et al. 2017; Saad et al. 2016). This addition not only enables residents make money to cover their costs, but it also makes their community more resilient to power outages, power surges or any electricity disruptions.

The system is most sensitive to water demands and rates. Indeed, the system was designed for two residents per household. Upon adding a third and a fourth resident, the NPV of the total system costs increased. The system is equally sensitive to water rates: the higher the rates, the lower the NPV of the total system costs per household. In fact, water rates have been increasing in major cities around the US as cities expand (or shrink) and current infrastructure needs upgrading to deal with the changes (Walton 2015). With the destruction brought by Hurricane Harvey, Houston needs to rethink its current water infrastructure, especially when adding to the mix climate change and the possibility of wetter and more frequent storms. Increasing the water and sewer rates as well as facilitating for residents to own rainwater harvesting systems, or in this case, be part of a distributed rainwater harvesting system, is one way to increase water resiliency in the city. This system could be at the heart of the water and stormwater plan to maximize the available resources and shift some of the burdens of maintaining the infrastructure to the residents, especially with the use of smart water meters.

In this study, we did not investigate the NPV of the total system costs per household of the "do nothing" option because of the assumption of choosing between a RWHS and DRWH. However, to put into context the importance of both these systems, it is important to measure the NPV of the total system costs per household of not collecting and using rainwater. The NPV of the total system costs of a household of two residents that does not have a rainwater harvesting system, for the analysis duration (according to equation (4)) is $9,731 as shown in Figure 34.

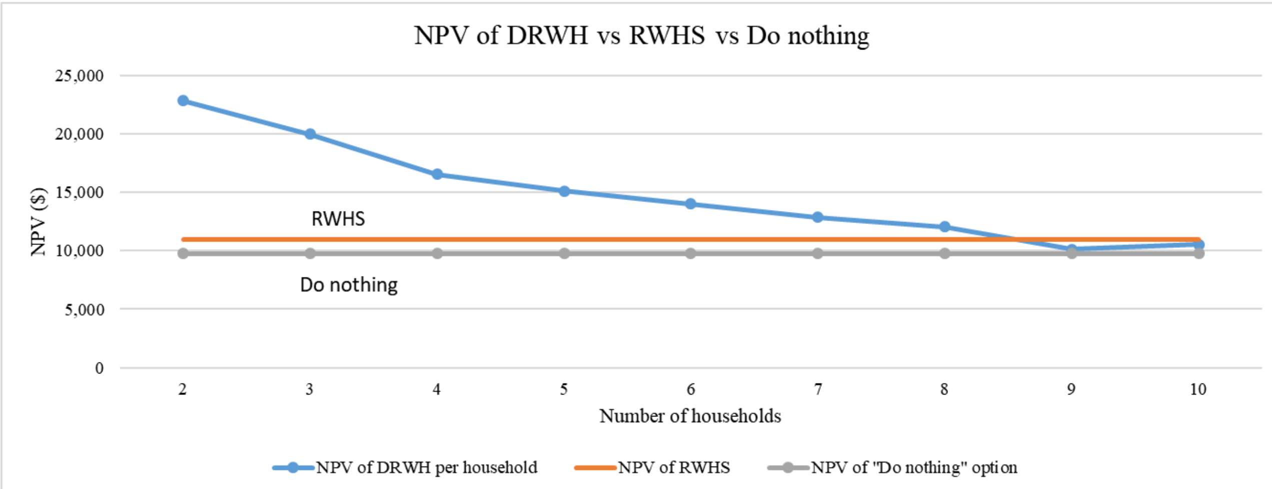


Figure 34 - DRWH vs RWHS vs "do nothing”

It is interesting to see that the “do nothing” option is comparable to three connected households in a DRWH system. The “Do nothing” approach looks to be less costly but that is based on the assumption of the water and sewer cost remaining the same over the duration of the project. In reality, water and sewer prices have been increasing over the last few years, as shown in Figure 33 that it’s not unreasonable to believe that the NPV of the total system costs of RWHS and DRWH could become lower than the “Do nothing” approach.

If we look at Figure 25 and Figure 34 and compare the initial investment costs with the NPV of the total system costs of the three options, from a developer’s point of view, it would make more financial sense to install a DRWH system for ten connected households, embed those initial costs in the total house price and market the community as “green built environments” or sustainable homes (GhaffarianHoseini et al. 2016) which have an increasing appeal in today’s market (Woodruff et al. 2008).

This is the first study that attempts to understand the financial cost of the process of the DRWH system per household. This study focused on similar buildings (single family households) connected together. Further research is needed to understand the impact of mixing up the types of buildings connected together and the financial impact on each individual buildings.

Conclusion

In this work, we have analyzed the lifecycle costs of a distributed rainwater harvesting network process of two to ten connected single-family households in Houston, Texas as a case study. The base case was a single-family household with a 15.1 m^3 rainwater tank while the connected households each had a 3.785 m^3 tanks, and connected to a communal tank that stored the overflows from all the connected tanks. We have calculated the lifecycle costs for an interest rate of 5% over 30 years using the NPV of the total system costs metric. We have shown that the NPV of the total system costs will be comparable to the NPV of the total system costs of a RWHS for seven or eight connected households and lower for nine and ten connected households. Our results have also shown that the NPV of the total system costs is sensitive to the communal tank size, interest rate and, water rates and demands. The distributed rainwater harvesting system is more resilient to water infrastructure failures and could become a staple in a city’s blueprint to manage water and stormwater infrastructures.

CHAPTER SEVEN: IMPACTS OF THE NOVEL COMMUNAL HARVESTING SYSTEM ON WATER USAGE AND THE TRAGEDY OF THE COMMONS

The impacts of the novel communal rainwater harvesting system on water usage

Land changes have a direct impact on water resources (Vandas et al. 2002). Some of those land uses include agriculture, forestry, urbanization and industrialization. The growth of cities and their related infrastructure have greatly impacted the historic uses of water. The pumping of water from streams and groundwater to satisfy increasing water demand and the changes in land use, have costs on the natural environment. For instance, infiltration is reduced as a result of increases in impervious surfaces. As an outcome of those changes, there is an increased cost embedded in the drinking water supply (Abildtrup et al. 2013). Water prices are steadily increasing (Walton 2015), water demand is increasing and supply is decreasing (Bradford 2018) which makes water resources management critical.

Total water use (TWU) in urban settings is important to water resources managers as they balance water supply and demand within municipalities. TWU is the amount of water pumped from city water supply systems inside a precise time period (Council 2002). Residential total water use (TWU) was commonly considered as the predominant water use sector within urban boundaries. Residential TWU is affected by multiple factors such as climate, economy, demographic conditions, building structures, culture, irrigation techniques and policy (Balling et al. 2008; Bougadis et al. 2005; Li et al. 2017; Wentz and Gober 2007). Residential lawn watering is an important aspect of residential water use and could account for up to 50% of TWU (Domene and Saurí 2006; Hilaire et al. 2008; Mayer et al. 1999). Water use would be higher as lots and building size increase and lower as buildings age and building density increases (Chang et al. 2010). TWU and green spaces are positively related as well: the greater the green spaces the higher the TWU (Wentz and Gober 2007). Li et al. (Li et al. 2017) observed an increase in TWU even as landscaped area per capita decreased in three cities in Nebraska and the authors inferred that climate conditions had a more profound effect on outdoor water use than other explanatory factors.

In terms of this research, the communal rainwater harvesting system will be developed to include only one type of sources and sinks configuration, which is the single-family household parcel type. The model will look at the total water use in an urban residential setting, more specifically single-family homes. Water uses will include indoor and outdoor uses (include irrigation). As shown by the previous research (Li et al. 2017), outside water use varied with the climate conditions. Climate conditions are represented in this model by rainfall. We believe that even though one type of configuration is represented, all types of configurations can be accommodated for future works.

The type of the parcel in this research is defined as residential single-family houses. The parcel size for the purpose of this research is fixed. However, as the scope changes and the data related to lot size/use changes, this will be reflected in the choice of values for the variables. A summary of the changes to each variable is shown in Table 22.

Table 22 - How a change in the research impacts the model

RWHS variables	This research	Change of scope	Change within the model
Rainfall	This variable is location dependent	This variable is location dependent	No change
Lot type	This research is only considering single-family dwelling	This could include buildings, office spaces, commercial spaces…	The lot type change will affect the roof area, water demand and number of people served, hence, the A_{roof}, the yield Y and the demand D variables
Building roof area	This variable will be fixed for this research	This variable changes depending on building size	A change in the building type considered will only impact the amount of water going in the tank, Q_{in}
Green area	This research will include water used for irrigation without specifying the size of the green area	Green area size could be included in lot size.	An emphasis on irrigation in terms of water use will impact the water demand D and the yield Y variables
Number of people	This research will look at national averages for the average number of people in households	The number of people considered will depend on building type	A change in the number of people and type of building will impact the number of people, hence, the demand D and the yield Y variables

As shown in Table 22, this research can take into account variations in urban design. It is worth noting that in prior works related to RWHS tank sizing, a specific land type was selected and fixed throughout the analysis. Meanwhile, the prior works that combined land use and water usage used the already established results from the tank sizing works. The reason for the generalization is because it is hard to accurately quantify the water demand. Demand profiles can vary between outwardly similar households in parallel locations due to various socio-technical factors including varying work patterns, household demographics and the use of different water fixtures. That is why RWH assessors frequently need to fix the demand to an average value to enable validations and simulations to be executed (Campisano et al. 2017; Parker and Wilby 2013).

Tragedy of the Commons and the Novel Communal Rainwater Harvesting System

The tragedy of the commons, a concept outlined by William Foster Lloyd in 1833 then made popular by Garrett Hardin in 1968, introduced the notion of overusing of a common by its commoners. In the case of a communal tank, the notion is that householders will become poor stewards of this common water resource. Even game theory's prisoner's dilemma game does not bode well for natural resources management. Interestingly, Corral-Verdugo et al. surveyed 250 residents about their motivation to conserve water and they found that residents were less inclined to conserve water when they perceived that other residents wasted water (Corral-Verdugo et al. 2002).

The common rainwater in this research is closer to a common-pool resource problem (CPR) than a tragedy of the commons scenario (Gardner et al. 1990). The authors define CPR to be "sufficiently large natural or manmade resources that it is costly (but not necessarily impossible) to exclude potential beneficiaries from obtaining benefits from their use”. Individuals using a CPR are presumed to face a tragic situation in which their rationality produces an irrational outcome for the group. This case is known as a CPR dilemma. The following conditions have to be present to produce this dilemma.

Condition 1-- Resource unit subtractability: a resource that is harvested or withdrawn is not available for other users

Condition 2 -- Multiple appropriators: multiple users are withdrawing or harvesting units from this resource

Condition 3 -- Suboptimal outcomes: the strategies of the appropriators lead to suboptimal outcomes from their perspective

Condition 4 – Constitutionally feasible alternatives: at least one set of coordinated strategies exist that are more efficient than current decisions and are “constitutionally feasible”.

Conditions 1 and 2 create a CPR situation. Adding on conditions 3 and 4 constitutes a CPR dilemma.

In the case of this research, we currently have a CPR problem not a dilemma since we have a common resource (common rainwater) which satisfies *condition 1* that is being harvested by multiple users, and satisfies *condition 2*. As such, in order to avoid reaching satisfying *conditions 3 and 4,* the authors proposed the Institutional Design Principles for long enduring Common Pool Resource (CPR) arrangements are as follows (Gardner et al. 1990):

1. Individuals or households who have rights to withdraw resource units from the CPR must be clearly defined, as must the boundaries of the CPR itself.

2. Appropriation rules restricting time, place, technology, and/or quantity of resource units are related to local conditions and to provision rules requiring labor, material, and/or money.
3. Most individuals affected by the operational rules can participate in modifying the operational rules.
4. Monitors, who actively audit CPR conditions and appropriator behavior, are accountable to the appropriators, or are the appropriators.
5. Appropriators who violate operational rules are likely to be assessed graduated sanctions (depending on the seriousness and context of the offense) by other appropriators, by officials accountable to these appropriators, or by both.
6. Appropriators and their officials have rapid access to low-cost local arenas to resolve conflicts among appropriators or between appropriators and officials.
7. The rights of appropriators to devise their own institutions are not challenged by external governmental authorities.
8. Appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are organized in multiple layers of nested enterprises.

The scope of this research is limited in terms of daily demand by individuals. In other words, the model assumes that all participating users will not need more than the average daily demand stipulated in the model's assumptions. We are considering a fixed daily demand hence; we have excluded the problem of overusing the common resource. However, future works will look at how overdrawing water by a few users affect the other users in the network. One way to deal with the eventuality of this problem is following the design principles for managing the common rainwater harvesting tank as proposed by Gardner et al. as follows:

- The households connected to the communal network have to clearly defined as households, owning individual RWHS and physically connected to the communal system.
- A charter has to be drawn where all the residents understand and agree to the appropriations dos and don’ts as well as their contribution to the maintenance of the common resource. For example, no households are allowed to withdraw water when the backup tank reaches the low water cutoff volume.
- Everyone has a say in how this water gets used. For example, the charter could specify that the swimming pools be filled from the municipal water supply (MWS). The charter could also specify rotations for outdoor gardening in the same manner that some cities have mandated in California (The City of Longbeach 2019) in order to give fair water access to all the residents. And there would be a small council made up from the owners of the network who could act as reference and decision makes.
- The residents who violate the charter laws will be sanctioned, depending on the seriousness of the sanction, with possible ousting from the network. Throttling water by the use of smart meters could be one way to deal with transgressions or overages, as specified by the charter.
- Those who transgress will be assessed graduated sanctions by the council. Some of the sanctions include temporary cutting off the connection to the common tank.
- The council can convene whenever needed to discuss problems and resolve conflicts.
- The local government (city council) cannot intervene in the disputes between the users of the communal network.

- The activities of the network have to be very clear and well defined for all the users of this communal network.

The proposed charter would regulate the usage of the common network as well as resolve transgressions. Common questions/answers as it pertains to the DRWH systems are shown below.

Question 1: Is water treated at the communal tank level, or only at the individual tank level? If water is treated at the communal tank level, how will this affect motivation to maintain one's own treatment system?

Answer: The proposed model does not integrate water treatment. It just works as a common storage to the overflow and then re-assigns the overflow to the users as needed. This system has been devised in a way where individual homes are responsible for their own water treatment options, or even not having water treatment and using the rainwater for non-potable uses.

Question 2: If the overflow system for a given household breaks, will the householder repair it?

Answer: There are two ways to answer this question: a) the overflow system is considered part of the communal system (how the rainwater gets delivered to the common tank), then it becomes everyone's responsibility and b) the overflow system belongs to the individual RWHS and hence is the responsibility of the individual owner. This matter will be clear in the charter depending on what the users agree to.

Question 3: How to avoid the tragedy of the commons?

Answer: Having a clear charter where all the users participated in writing will resolve most of the overuse issues. And having a council that represents the users will also help in resolving transgressions and disputes. The scope of the research model that we have proposed assumes that there will be no overuses.

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CHAPTER EIGHT: CONCLUSION, IMPACTS, AND FUTURE RESEARCH

Conclusion

The purpose of this study was to propose and analyze a novel approach to communal rainwater harvesting in which rainwater harvesting systems from single-family households were connected by their overflows to a communal tank. In the proposed system, whenever the households needed water, the communal tank was available to service them.

For validation purposes, the system was simulated in two American cities: Houston (TX) and Jacksonville (FL). Volumetric reliabilities per household were shown to be higher for the communal system than individual RWHS with 1,000 gal tanks for up to 10 users in Houston and up to 7 users in Jacksonville. Moreover, upon investigation of the lifecycle costs per household of the system in Houston, using the Net Present Value metric over 30 years, the novel communal system with 7 connected households was comparable in total project costs to the individual system with 4,000 gal-tank, and lower for nine and ten connected households.

The importance of this system is two-fold:

- Capturing the overflow from the private tank and re-using it reduces the potable water usage from municipalities, and;
- Reducing the overflow reduces the impact on the stormwater infrastructure.

Impacts

The direct significance of this current research is the following: a) Understanding the impact of climate change on water/stormwater infrastructure and managing its effects on the parcel level, b) introducing land development changes to specifically address future changes and

c) increasing the resilience of water/stormwater infrastructure by combining elements of decentralization in the current infrastructure central system.

The direct purpose of this research is to maximize the available water resources while dealing with expanding urban areas. The output of this research is one of the prescient solutions to this impending problem. For instance, if we look at the big picture, as shown in Figure 35, the current research will enhance the water network by optimizing the volume of domestic water needed to meet the demands of the anticipated urban expansion and minimize stormwater runoff.

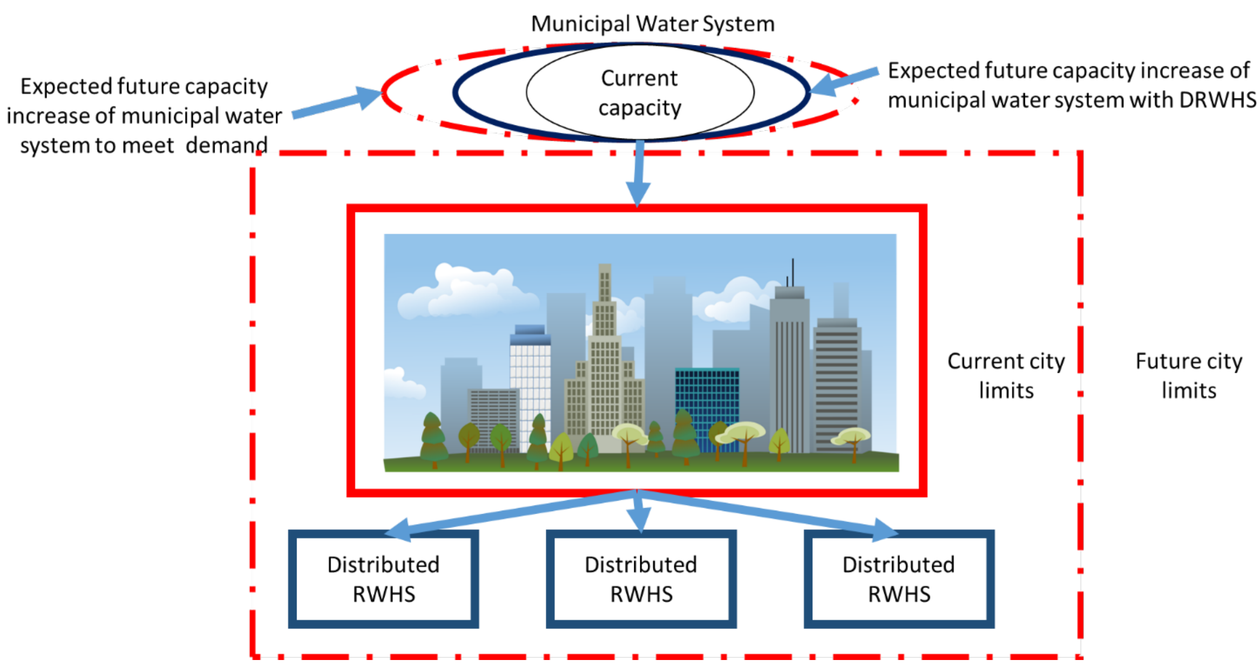

Figure 35 - Big picture overview of current research

The broader outcome of this research is the novelty of the sizing algorithm. Existing sizing algorithms size one private tank with regards to cost or volumetric reliability while the proposed algorithm takes into account multiple private tanks and one communal tank and outputs the volumetric reliability of each option (private tank size/communal tank size). This research attempts to solve a common-pool problem, which is how to optimize on-site and off-site storage of rainwater with equitable returns for all households. More research should go into understanding and dividing equitably this resource between the connected households.

Future Research

Stormwater management

Green infrastructure is a range of measures that use plants and soil systems, permeable surfaces, stormwater harvest and reuse or landscaping to reduce flow to stormwater infrastructure (EPA 2019). Rain water harvesting systems are currently a part of the green infrastructure systems. However, in dense areas, having large tanks to store as much rainwater as possible can be impractical. So a good alternative could be the inclusion of DRWH in the green infrastructure tools, in addition to other containment measures, such as plants and soil systems.

We expect stormwater fees to increase substantially in the future because of a) increased impervious spaces in urban areas and, as a result, b) increased maintenance on the stormwater infrastructure and c) failing infrastructure, particularly in the US, which will cost a lot of money to bring up to standards. As such, it is of the utmost importance to plan the city's current infrastructure with today's needs in mind. Increased containment of harvested rainwater which can be reused as drinking water without increasing the storage at the lot level could potentially make a big difference at the city level and at the household level, where stormwater fees could be alleviated for using DRWH.

The exploration and integration of progressive stormwater fees to the water bill is an interesting avenue to look into in conjunction to the effect of increased rainwater harvesting from DRWH.

Water resources planning

Historically, municipal resources have been directed toward capital and operating costs of conventional centralized infrastructure systems, including both retrofitting existing systems to increase their reliability and resilience, and expanding those systems to meet new challenges**.** More recently, communities are employing a combination of supply-side improvements for improving infrastructure capacity and resilience along with demand-side initiatives to support adoption of innovations by private owners that reduce demand on centralized systems through conservation, distributed infrastructure, or low impact development (LID) measures. In the new approach, owners are incentivized to meet their own water needs on site using technologies such as rainwater harvesting or water recycling/reuse for water supply; green infrastructure and other innovative on-site treatment systems for treating stormwater and wastewater; or combinations of both. Future research could explore the effects of this novel communal RWHS with different types of land developments (e.g., commercial and mixed developments) in such a way that can transfer part of the burden of maintaining the water infrastructure to parcel owners. Indeed, the strategic insertion of this communal RWHS could limit the increase in capacity of municipal water systems projected by decision makers in expanding urban areas as shown in Figure 35. The major challenges for this problem are as follows:

- The first challenge will be to collect high-fidelity data from smart meters, parse them into relevant categories (such as land usage, seasonal, geographical) as well as collect relevant information on the water infrastructure.
- The second challenge will be to devise an optimization framework that can leverage the previously collected data, combine them with the novel communal RWHS model to find

strategic locations that can positively influence the existing infrastructure within a growing urban area.

The effects of water crises on the DRWH system

The current situation with the Covid-19 pandemic and hoarding of essential items makes imagining a scenario where people would hoard their harvested rainwater more likely. For example, not too long ago, Cape Town South Africa was struck by a historic drought and threatened to cut off the water supply to the city in April 2018. Some of the behaviors that averted the crisis was farmers allowing to divert their stored water supply to the city (Christian Alexander 2019).

Similar scenarios are not too far off reality for other regions of the world, especially with climate change and increases in the world urban population. How would a DRWH system perform with “hoarding” behavior?

1. Every household is hoarding the harvested rainwater and the communal tank is empty
   In this scenario, for example, in the city of Houston, the average water demand per capita per day would drop down from 70 gallons to a much lower water demand average. The stored rainwater in the private tanks would last longer than anticipated in this study and the storages would be refilled whenever it rained. The overflow from the individual tank would then go to the communal tank and the cycle would then restart.
2. Every household is hoarding the harvested rainwater and the communal tank is fully or partially full: In the simulation proposed in this work, we assumed that the average demand per person per day was 70 gallons and that the demand per household per day was 140 gallons. However, when hoarding behavior sets, the average water demand per

household will decrease, hence the water demand fulfilled from the communal tank would also decrease to meet the new average water demands. So, when the private tanks cannot meet the water demands, the communal tank will be able to meet those new demands.

3. Water in the communal tank could go to serve underprivileged communities, especially in the rainy season, where rainfall is expected to meet average water demands per household. This behavior could follow the lead of what the farmers in Cape Town did without compromising much their own perceived water security.

This is an interesting avenue for future research that could explore the resiliency of this system in the face of water crises. This research could be adapted to the platform of resilience of the potable water networks.

Other communal resources problem

This research created a platform and a framework for optimizing the common-pool problem. The application of this platform to communal tank sizing was a proof of concept that this approach is successful in optimizing the distribution, use, and storage of common resources (harvested rainwater). This model can be generalizable to other communal resources, e.g., landscape as water storage or even energy distribution. The landscape for water storage as a communal resource resembles the functioning of the distributed rainwater harvesting system because it can be considered as potential “capacitors” in the system. In addition of a groundwater pump or a downstream reservoir for constructed wetland treatment systems could potentially yield more potable water, that can be reused by households.

With regards to energy storage and distribution, even though the energy pooling model in essence behave the same way, in the energy distribution case, there are some significantly different challenges stemming from the underlying operational constraints of the power system that must be accounted for. For example, water is a resource that can be easily transferred between locations, in contrast, transferring energy from a given storage device to a specific destination is not always feasible due to the power system constraints. Nonetheless, conceptually, the proposed communal model can be applied to simulate how a communal energy exchange can be facilitated.

In essence, the proposed framework can model the transactions between entities of any rivalrous common goods, which are goods that consumed by one consumer prevents them from being consumed by another consumer. One interesting example of rivalrous goods are wild fish stocks: what is the optimal number of fish that can be fished by one boat, with multiple boats fishing at the same time while also optimizing the number of fish left in order to maintain sustainable fishing?

In summary, the proposed framework can be adapted to a multitude of research problems in different domains by providing a sustainable and equitable division of a rivalrous common good. This framework can be a tool for guiding decision makers in how to build future cities or even to rebuild the existing ones while maximizing the available resources.

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APPENDIX A: CALCULATION ASSUMPTIONS

Pump usage

The pump's specifications page notes that this particular model uses 230 Volts and 8.0 Amps, which means that the pump uses 1840 W (230*8). In the specifications sheet, the pump is estimated to move up to 70 gallons per minute. The average amount of daily rainwater needed, based on Table 15, is shown in Table 23.

Table 23 - Average amount of harvested rainwater needed

Number of households	Average water demand met per household (m^3/month)	Average water demand met per system per day (m^3/day)	Average water demand met per system per day (gal/day)
2	5.35	0.36	95.1
3	5.03	0.503	132.9
4	4.88	0.65	171.8
5	4.82	0.8	211.3
6	4.7	0.94	248.3
7	4.67	1.09	297.9
8	4.63	1.24	327.6
9	4.6	1.38	364.6
10	4.56	1.52	401.5

As we can see from Table 23 and in addition to the information stated above, the pump needs less than an hour per day to pump the water back from the communal tank to the individual tanks. However, to be on the conservative side and to account for the fact that the pump will run in multiple times during the day, according to the household's needs, we will assume that the pump's electricity usage is 2 hours daily.

Length of piping required

The layout of the houses proposed is a grouped configuration with a 1.52 m (5 feet) walkway connecting the houses. The houses are assumed to be set in the middle of the lot, hence, with the dimensions of the house being 8.26m*8.26m and the lot size being 13.6m*13.6m, the following information can be derived:

The setback = (lot length – house length)/2 = (13.6-8.26)/2= 2.67 m or 8.76 feet (6)

The path length = (# houses * lot width)/2 +(#units * setback) (7)

Hence, the pipe length needed is:

Pipe length = Path Length + (# units *lot length/2) (8)

The water lines are assumed to connect halfway back to the lot, which is the center of the house.

Accordingly, Table 24 shows the length of pipeline needed per system of households.

Table 24 - Pipe length needed

Number of households	**Path length (m)**	**Pipe length (m)**	**Pipe length (ft)**
2	13.60	21.86	69.95
3	20.40	32.79	104.93
4	27.20	43.72	139.90
5	34.00	54.65	174.88
6	40.80	65.58	209.86
7	47.60	76.51	244.83
8	54.40	87.44	279.81
9	61.20	98.37	314.78
10	68.00	109.30	349.76

Since we are using two types of pipes (75 mm and 100 mm pipes), we will need the pipe length shown in Table 24 for each type of pipes.

Pipe sizing

In order to size pipes for rainwater harvesting, we have to account for an extreme rain event and the amount of rain flowing off the design roof.

In the case of this study, the roof area is 750 square feet and if we assume that we have an extreme rain even of 1.5 inches per hour per household, then we would be collecting:

750 sqf*1.5 in/hr *0.62 gal/in per sqf = 698 gal/hr = 12 gal/mn

For the maximum case of 10 households, then the rainwater flow per minute would be equal to 120 gal/mn, which would require a 4-in (100 mm) size pipe, for the gravity-flow pipe.

As for the pressurized pipe, for a flow of 120 gal/mn, the friction loss will be 1.4 psi/100 ft *3= 4.2 psi, for a 3-in (75 mm) pipe, which is acceptable (Engineering Toolbox 2020).

Piping costs

Utility trenching is needed in order to connect a building through underground pipes. In the case of this study, trenching is needed to connect two pipes from each rainwater harvesting system to the communal tank. Trenching for water supply pipes costs $22.3 per L.F. for 3-in PVC water supply pipes and $26.7 for 4-in PVC water supply pipes. The cost includes the cost for material, labor and equipment needed. The total costs of pipe laying is based on the results from Table 24, shown in Table 25.

Table 25 - Piping costs

Number of households	Cost of 3-in PVC pipe ($)	Cost of 4-in PVC pipe ($)
2	1,867	1,562
3	2,801	2,343
4	3,734	3,124
5	4,668	3,905
6	5,601	4,686
7	6,535	5,467
8	7,468	6,248
9	8,402	7,029
10	9,335	7,810

Earthwork costs

We assume that the communal tank will be placed underground. Earthwork will be needed for this particular task: excavation, backfilling and hauling the earth from the site to another location. According to building construction costs with RS Means data (2020a), excavation, backfilling and hauling cost $18.4/B.C.Y., $19.7/L.C.Y. and $6.7/L.C.Y. respectively. We assume that the volume of earth excavated is equal to the volume of the communal tank and that 1 B.C.Y. = 1.25 L.C.Y. Hence, for each configuration, the cost of the earthwork is shown in Table 26.

Table 26 - Earthwork costs

Number of households	Size of communal tank (gal)	Excavation volume in C.Y.	Excavation cost ($)	Backfilling cost ($)	Hauling cost ($)	Total earthwork cost ($)
2	8,000	20.00	368	976	168	1,512
3	12,000	60.00	1,104	2,927	503	4,535
4	12,000	60.00	1,104	2,927	503	4,535
5	15,000	64.00	1,178	3,122	537	4,837
6	15,000	64.00	1,178	3,122	537	4,837
7	15,000	64.00	1,178	3,122	537	4,837
8	15,000	64.00	1,178	3,122	537	4,837
9	8,000	20.00	368	976	168	1,512
10	12,000	60.00	1,104	2,927	503	4,535

We assume the same process for the RWHS: we add to the cost of tank and installation to the earthwork costs and the total cost for RWHS comes up to $8,147 nationally.

APPENDIX B: WATER BILLING

The city of Houston has a step-rate system as shown in Table 20. In order to get the sewer and water bill changes per household with the DRRW system, we need to calculate the monthly bill per household then the new monthly bill for the RWHS case (base case) finally the monthly bill per household for the DRWH system case.

Monthly bill per household

The daily water demand per capita for the city of Houston is estimated at 70 gal (USGS 2017). We are looking a household with two residents, so the average water consumption per household is 4,200 gal. According to the step rate from Table 20, the monthly water rate per household is $30.39 and the monthly sewer rate is 34.96$.

Monthly bill per household after installing DRWH

The water demand from the municipal water supply decreases because partial water demand is being met by rainwater harvesting. We can derive the new water demand and water and sewer bill from Table 15 and Table 20 as shown in Table 27.

Table 27 - New water and sewer bill

	New monthly demand (gal)	**New monthly water charges ($)**	**New monthly sewer charges ($)**	**New monthly water and sewer bill ($)**	**Total water and sewer bill savings ($)**
2	2,789	13.41	12.67	26.08	39.27
3	2,873	13.41	12.67	26.08	39.27
4	2,915	13.41	12.67	26.08	39.27
5	2,927	13.41	12.67	26.08	39.27
6	2,940	13.41	12.67	26.08	39.27
7	2,965	13.41	12.67	26.08	39.27
8	2,978	13.41	12.67	26.08	39.27
9	2,986	13.41	12.67	26.08	39.27
10	2,995	13.41	12.67	26.08	39.27

Monthly bill per household after installing RWHS

The average monthly demand per household that owns a RWHS with a 4,000-gallon tank decreases and the new monthly water and sewer bill is $26.08.

APPENDIX C: AVERAGE VR PER HOUSEHOLD FOR DIFFERENT COMMUNAL TANK SIZES

We chose to design the system described is this paper based on the maximum VR per group of connected households. In this table, the corresponding VR of each group of connected households for several communal tank sizes are shown in Table 28.

Table 28 - VR per household for multiple communal tank combinations

Number of households	VR for 8,000 gal communal tank (%)	VR for 10,000 gal communal tank (%)	VR for 12,000 gal communal tank (%)	VR for 15,000 gal communal tank (%)
2	33.6	33.6	33.6	33.6
3	31.3	31.5	31.6	31.6
4	30.3	30.4	30.4	30.5
5	30.0	30.1	30.2	30.3
6	29.6	29.7	29.7	29.8
7	29.1	29.2	29.3	29.3
8	28.9	28.9	29.0	29.0
9	28.7	28.8	28.8	28.9
10	28.6	28.6	28.6	28.7