A Spatial Life Cycle Cost Comparison of Residential Greywater and Rainwater Harvesting Systems

Rebecca Maskwa[1], Kevin Gardner[2], Weiwei Mo[3,*]

[1]Department of Civil & Environmental Engineering, University of New Hampshire, 35 Colovos Road, Durham, New Hampshire, 03824, United States

[2]Department of Civil & Environmental Engineering, University of Louisville, Jouett Hall, Louisville, Kentucky 40292, United States and Department of Civil & Environmental Engineering, University of New Hampshire, 35 Colovos Road, Durham, New Hampshire, 03824, United States

[3]Department of Civil & Environmental Engineering, University of New Hampshire, 35 Colovos Road, Durham, New Hampshire, 03824, United States

[*]Corresponding Author: 35 Colovos Road, 334 Gregg Hall, Durham, New Hampshire 03824, Ph: +1-603-862-2808, Email: weiwei.mo@unh.edu

Abstract – Decentralized, household water systems have been increasingly integrated into the centralized urban water networks to address challenges related to water stress and shortage, sustainable water production, and network resilience. However, our understanding regarding how different geospatial, housing type, and climate conditions can potentially influence the economic and water saving benefits of different decentralized water systems remains limited. This study combined system dynamics modeling with life cycle cost assessment to investigate the payback time and water saving benefits of household greywater recycling (GWR) and rainwater harvesting (RWH) systems in a typical single family and a typical multi-family house across 12 different cities within the United States. We found that for GWR systems, cities had optimum tank sizes of 2-3 m^3 for multi-family housing and 0.75-0.85 m^3 for single-family housing. Optimal tank sizes for RWH ranged from 5-10 m^3 for multi-family housing and 4-6 m^3 for single-family housing. Percent demand met for GWR systems ranged from 70-90% of the designated non-potable usages, while RWH systems ranged from 50-70% across all cities. When the tank size is optimized for payback time, the percent demand met is generally 10% lower than the highest achievable demand met. This indicates a tradeoff between sizing for minimized payback time or maximized demand met. Overall, Boston, Seattle, and Atlanta performed the best in terms of payback time and demand met regardless of housing and system types.

Keywords: Greywater recycling; rainwater harvesting; payback time and demand met; system dynamics modeling; life cycle cost assessment; cross-city analysis

1. Introduction

Globally, water resources are being stressed due to increasing water demand driven by population growth, urbanization, and industrialization (WWC, 2014). Almost 700 million people suffer from water scarcity currently and by 2050 it will increase to 2.5 billion (Hameeteman et al., 2013; UNDP, 2006). Research related to the U.S. shows that future water supply in some regions are likely to be affected by severe water shortages (Brown et al., 2019). Lifestyle changes and new technologies, such as taking fewer showers or installing water efficient appliances, are being suggested and developed to help alleviate the overall water shortage globally (Das et al., 2015; SOW, 2018). One type of technology that has been increasingly discussed is household decentralized water systems, such as rainwater harvesting or greywater recycling systems (EPA, 2016). Decentralized water systems are defined as the collection, treatment, and use of rainwater harvesting or greywater recycling systems (Mankad & Tapsuwan, 2011). Decentralized water systems have the potential to provide many benefits to a community, especially the ability to alleviate water stress in the centralized water systems, improve system sustainability and resiliency, and increase water availability (EPA, 2016). Many researchers are looking to understand how decentralized water systems work and the true benefits that they provide (Mankad & Tapsuwan, 2011).

Greywater recycling (GWR) is water that has been used once by the consumer, treated, and then used again for another purpose (Ilemobade et al., 2013; Jefferson et al., 2000). Guidelines for GWR are proposed for both restricted and unrestricted use, which are determined by the water quality requirements. However, these guidelines vary between technologies and individual states (Li et al., 2009). Typical uses of greywater include toilet flushing and irrigation of ornamental plants and grasses (Lazarova et al., 2013; Maeda et al., 1996; Nolde, 2000). The water that is reused for this purpose comes from sources such as the shower, bathroom sink, or the washing machine (Eriksson, 2002; Jefferson et al., 2000; Otterpohl et al., 1999). Greywater often contains additional nutrients that have a positive influence on irrigation. GWR systems can be separated in two different categories: diversion systems and filtration/purification systems (Friedler, 2008). Diversion systems are integrated as permanent piping within the original plumbing network of a building and primarily used for irrigation. This system type does not require extensive treatment (often coarse filtration and disinfection suffice) since the storage time can be less than a few hours (Friedler, 2008). Purification/filtration systems include treatment of the greywater before being redistributed for reuse for either potable or near potable uses (Friedler, 2008; Li et al., 2009). Many different treatment processes have been considered including membrane filtration, sand filtration and disinfection in combination, coagulation and granular activated carbon sorption in combination, and membrane bioreactor (MBR) (Li et al., 2009).

Rainwater harvesting (RWH) is another type of technology that aims to reduce water stress from centralized drinking water services (Campisano et al., 2017; GhaffarianHoseini et al., 2016; Hamel & Fletcher, 2014). Conventional RWH systems capture stormwater runoff from impervious cover for both potable and non-potable uses (Siegel, 2015). The catchment area type and end-use outlets determine the level of treatment needed. Rooftop collection can be suitable for both irrigation, outdoor cleaning activities, laundry, and toilet flushing and requires simple filtration for removal of general debris and disinfection (Campisano et al., 2017; CTCN, 2018; Despins et al., 2009). Ground-surface collection may have a higher loss of water due to infiltration and may require more advanced treatment because of contamination from cars and other pollutants (CTCN, 2018). New RWH designs are continuously being developed with ideas of collapsible tanks and lower-energy processes (Abbasi & Abbasi, 2011; Campisano et al., 2017).

GWR and RWH technologies can be utilized and implemented on a residential scale, both for detached homes and apartment style living. They can theoretically help improve potable water resource availability and reliability with their capability and adaptability of storing, reducing, and/or reusing reclaimed water for non-potable domestic use (Campisano et al., 2017). These systems also improve water source diversification, extend internal water usage, and enable a more efficient resource use (Leigh & Lee, 2019). However, such benefits vary geographically depending on local climate, water supply and use, and socioeconomic conditions. The initial costs as well as uncertainties about the return of investment have often been cited as barriers to broader adoption of RWH and GWR systems (Fewtrell & Kay, 2007; NSFC, 2000). It is therefore important to understand the economic and other performance measures of RWH and GWR systems considering different geospatial contexts.

2. Literature Review

Many studies have investigated RWH or GWR systems on an individual basis. Payback time, economic savings, water saving, and stormwater reduction are commonly used to evaluate these systems. *Table 1* provides a list of such studies with their study contexts and reported outcomes. These studies had reported a wide range of RWH or GWR's economic performances, ranging from not feasible at all to a relatively short payback time of less than 10 years. This could be a result of varying site-specific characteristics, such as local climate, system design, household water demand, and greywater generation (Hashim et al., 2013). Hence, it is difficult to compare the reported outcomes across the previous studies. Only a small number of studies compared both types of technologies considering daily variations of rainwater/greywater supply and household water demand (Marinoski et al., 2018; Morales-Pinzón et al., 2015; Willuweit & O'Sullivan, 2013), but most of the studies only used them in a capacity to compare simulation modeling programs instead of comparing their environmental or economic benefits/costs (Morales-Pinzón et al., 2015; Willuweit & O'Sullivan, 2013). Morales-Pinzón et al. (2015) anticipated that in the future an expansion of their analysis will involve a more integrated look at the results comparing RWH and GWR. Marinoski et al. (2018) found that in residential households consisting of three people in southern Brazil, RWH had a potential water saving of 3,500 liters per month, while GWR had a potential to save 2,400 liters per month. However, these studies focused on individual case applications, while the influence of spatial context on systems' performance was not discussed. Location is a significant characteristic when discussing environmental benefits and economic potential because it dictates the climate, precipitation, and economic restrictions within the location in question (Wang & Zimmerman, 2015). To the authors' knowledge, only three studies were able to further incorporate spatial variations and dynamic modeling when investigating decentralized GWR and/or RWH systems, but they lacked applicability to varying scales of building composition (Memon et al., 2005; Mwenge Kahinda et al., 2009; Wang & Zimmerman, 2015). Previous studies seldom included analyses pertaining to both economic and environmental benefits of GWR or RWH to allow comparison between the two.

Table 1 Condensed literature review summary highlighting payback time, technology investigated, and whether the technology resulted in water savings.

Source	System type	Payback time (years)	Water saving considered? (Y/N)	Water uses	Household type	Location
(Friedler et al., 2005)	GWR	7-14	System dependent	Toilet	Multi-family	Israel
(Ilemobade et al., 2013)	GWR	Unfeasible	N	Toilet	Multi-family	South Africa
(Jeong et al., 2018)	GWR	System dependent	Y	Toilet and irrigation	Single-family and multi-family	Atlanta, GA
(Memon et al., 2005)	GWR	Utility price dependent	Y	Toilet	Multi-family	UK
(Lam et al., 2017)	GWR	Not provided	N	Toilet	Multi-family	Hong Kong
(Wang & Zimmerman, 2015)	RWH	Unfeasible in cities with low utility costs	N	Not specified	Commercial	Various U.S. cities
(Vialle et al., 2011)	RWH	Not provided	N	Toilet	Single-family	France
(Ward et al., 2012a)	RWH	6-11	Y	Toilet	Commercial	UK
(Way et al., 2010)	RWH	Not provided	N	Not specified	Single-family	UK
(Ward et al., 2010)	RWH	14-22	N	Toilet	Single-family and commercial	UK

(Morales-Pinzón et al., 2015)	RWH	Utility price dependent	N	Toilet, irrigation, and laundry	Single-family and multi-family	Spain
(Mwenge Kahinda et al., 2009)	RWH	Not provided	N	Soil recharge	Commercial	South Africa
(Domènech & Saurí, 2011)	RWH	60-80	Y	Toilet and irrigation	Single-family and multi-family	Spain
(Hashim et al., 2013)	RWH	25	Y	Toilet and irrigation	Single-family	Malaysia

Accordingly, this study captured and compared RWH and GWR systems applied to a typical single family and a typical multi-family house through system dynamics modeling and life cycle cost assessment. The objective of this study is to understand how specific precipitation patterns and other geographic-specific parameters influence the economic and environmental benefits of decentralized, household GWR and RWH systems considering daily water supply and demand variations.

3. Methodology

In this section, we first describe the key equations and assumptions involved in simulating the daily operations of the RWH and GWR systems (Section 3.1) and their associated economic costs and savings (Section 3.2). We then introduce the climatic conditions and utility rates associated with each of the 12 studied cities (Section 3.3) as well as the characteristics of the two types of housing studied for each city (Section 3.4). Lastly, we detail the process and the variables considered in the Monte Carlo analysis for uncertainty quantification (Section 3.5).

3.1 System Dynamics Modeling of the RWH and GWR Systems

The system dynamics models (SDMs) for RWH and GWR were developed using the Vensim® software. System dynamics modeling is a technique used to mimic changes in system status over time (Ford, 1999). They utilize stocks, flows, auxiliary variables, and connectors to show how different variables within a system interact with one another and how the system reacts when one or more variables change. Stocks represent changes of system levels over time (e.g. GWR or RWH tanks). Flows represent the additions to and subtractions from the stock (e.g. rainwater and greywater inflows, yield, or water being spilled out of the tank). Auxiliary variables can influence the system in both internal and external capacities. Connectors visually show how all the auxiliary variables, stocks, and flows are interconnected and how they influence each other (Song & Mo, 2019). The SDMs developed in this study simulate dynamic water volume changes in RWH and GWR tank systems using ten years of precipitation data (Silva et al., 2015), on a daily time step for both a typical single-family and a typical multi-family homes.

The GWR model incorporates the average consumer water use rates for bathing, laundry, and handwashing to determine the potential water reclamation capacity for GWR provided in *Figure 1*. *The* RWH model incorporates the average collection of rainfall based on the typical roof-top size to determine the potential water collection capacity for RWH provided in *Figure 1. The* volume of water collected in the storage tank is then analyzed to determine the yield based on the total non-potable demand. The total non-potable demand is determined by for the amount of water used for residential irrigation and toilet flushing provided in *Figure 1*. A second part of the model is the simulation of the net economic savings. Inflow of the net economic saving stock was calculated based on the cost savings obtained through reduced use of services from the utilities. Outflows of the net economic saving stock include initial construction, operation, and maintenance of the decentralized systems. Equations that correspond to each of the auxiliary variables, stocks, and flows are described in Section 2.1.1.

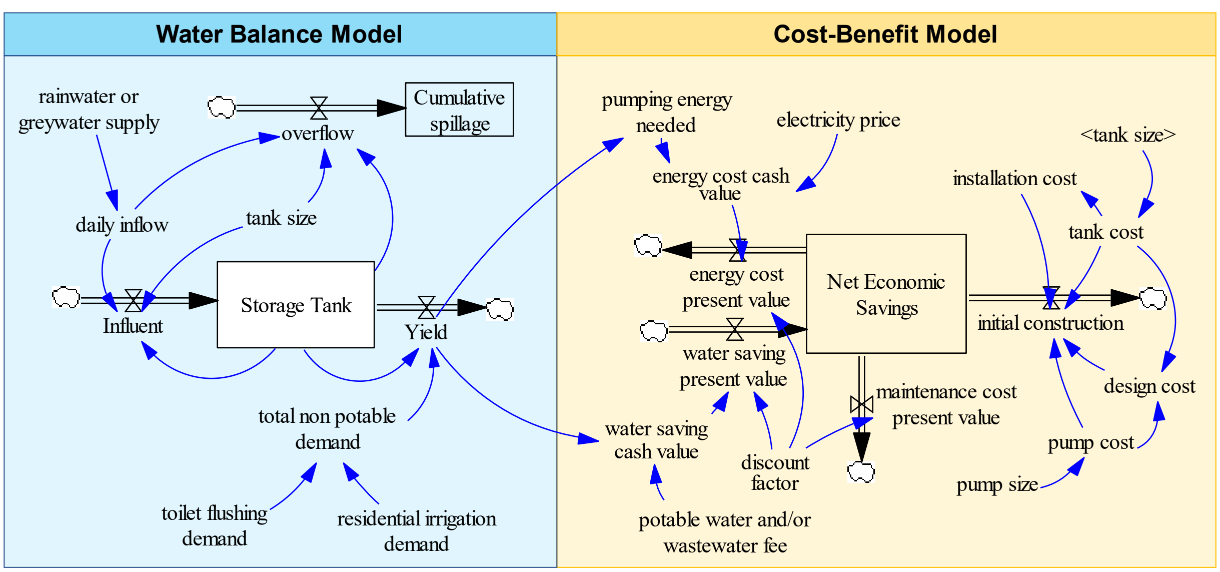

Figure 1 A simplified diagram of the stock and flow components that contribute to the SDM of GWR and RWH. Aspects of the model that are in boxes are stocks, while the arrows valves are

flows. Variables without boxes are auxiliary variables, and blue arrows that connect to other auxiliary variables are connectors.

3.1.1 Demand of Alternative Water Supply

In this study, we assume rainwater and greywater are being collected for two types of non-potable uses: lawn irrigation and toilet flushing. The amount of toilet flushing at each household was calculated using Equation 1.

$$D_f = n * V_f \qquad \textit{Equation 1}$$

where D_f is the total toilet flushing demand, m^3/day; n is the number of tenants per household; and V_f is the volume of water used for toilet flushing, 0.072 m^3/day/person (Hamm, 2010; USGS, 2016). The amount of water used for lawn irrigation was calculated using Equation 2.

$$D_{i,t} = \begin{cases} A * f * ET_t/eff, & P_t = 0, t \in IP \\ 0, & Otherwise \end{cases} \qquad \textit{Equation 2}$$

where $D_{i,t}$ is the lawn irrigation demand on day *t* during the irrigation period *IP* of a given city, m^3/day; We assumed *IP* is when the average monthly temperature is between 10 and 32 degrees Celsius (Forrester et al., 2018; Goatley Jr., 2015; Lawns, 2018; Murphy, 2001; Waltz & Landry, 2017). P_t is the amount of precipitation that occurs on Day *t*. *A* is the total lawn area of a household, m^2; f is the plant factor, assumed to be 0.7, *unitless;* ET_t is the daily evapotranspiration of each city, m/day, and, *eff* is the irrigation efficiency, assumed to be 0.75, *unitless,* for the rotor sprinkler distribution network (EPA, 2016). The total demand of alternative water supply is calculated as the sum of D_f and $D_{i,t}$.

3.1.2 Simulation of Rainwater and Greywater Inflow

Rainwater inflow in the RWH model is solely dependent on the amount of rainfall. Equation 3 describes how the initial collected rainwater inflow was determined,

$$I_{RW,t} = P_t A \mu \qquad \textit{Equation 3}$$

Where $I_{RW,t}$ is the initial amount of rain collected, m^3/day; P_t is the amount of rainfall each day, ft/day (NOAA, 2018); A is the total roof area, m^2 (NAHB, 2015); and μ is the runoff coefficient, which represents water loss associated with the amount of debris that diverts the rainwater away from the collection system as well as the initial wetting of the surface, assumed to be 0.8, *unitless* (SWRCB, 2011).

Greywater inflow in the GWR model was assumed to be water coming from showering, bathroom sink, and laundry. The average American uses approximately 0.32 m^3 of water per day (USGS, 2016). The breakdown of the residential indoor water consumption has been provided in *Figure 2*. Overall, around 50-80% of the water can be utilized for GWR. Equation 4 represents the collected inflow calculation:

$$I_{GW,t} = n(v_{sh,t} + v_{hw,t} + v_l) \qquad \textit{Equation 4}$$

Where I is greywater inflow volume on day t, m^3/day; n is number of tenants; v_{sh} is volume of water for showering, 0.065 m^3/day/person (HWW, 2018; USGS, 2016); v_{hw} is volume of water from the bathroom sink, 0.022 m^3/day/person (HWW, 2018; USGS, 2016); and v_l is the volume of water used for laundry, 0.057 m^3/day/person (HWW, 2018; USGS, 2016).

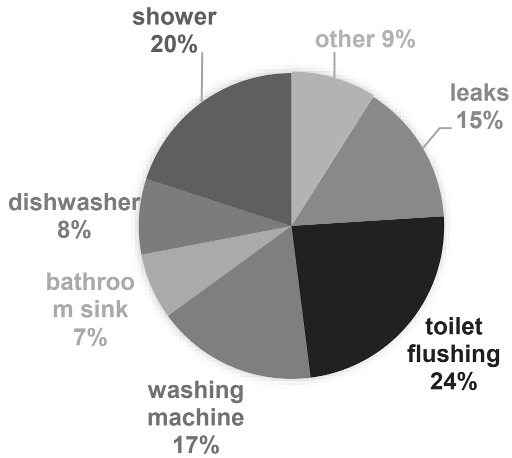

Figure 2. Percentage breakdown for residential indoor water consumption and end uses (HWW, 2018; WRF, 2018)

3.1.3 Water Balance Simulation

The method that was implemented for the evaluation of the storage tank dynamics includes a yield-after-spillage behavioral model approach previously developed by Fewkes & Butler (2000) and Jenkins (1978). Yield-after-spill methodology is a widely used and accepted in the RWH and GWR literature and provides a conservative approach in comparison to a yield-before-spill, which assumes yield is taken before spill/overflow occurs. The amount of rainwater or greywater collected for use is dependent upon whether there is room in the storage tank or not. If there is no room for collection within the storage tank, the excess water is diverted away from the system and was assumed to be spilled onto the ground in the RWH system or deposited to the local sewer network in the GWR system (Equation 5). Yield was defined as the amount of rainwater or greywater used for meeting the demand. It was calculated based upon the amount of water remaining in the tank from the previous day and the current day's non-potable demand for the household type (Equation 6). The yield of the system will either meet the non-potable demand or only take what is available based upon what is remaining from the previous day. The amount of water remaining in the tank after the day's use was calculated based on the remaining water in the tank from the previous day and the current day's inflow, spillage, and yield (Equation 7).

$$O_t = \begin{cases} V_{t-1} + I_t - T & |V_{t-1} + I_t \geq T \\ 0 & |V_{t-1} + I_t < T \end{cases} \qquad \textit{Equation 5}$$

$$Y_t = \begin{cases} D_t & |D_t < V_{t-1} + I_t - O_t \\ V_{t-1} + I_t - O_t & |D_t \geq V_{t-1} + I_t - O_t \end{cases} \qquad \textit{Equation 6}$$

$$V_t = V_{t-1} + I_t - O_t - Y_t \qquad \textit{Equation 7}$$

Where O_t is overflow from the tank storage, m^3/day; I_t is the inflow of water collected from the current day, m^3; V_{t-1} is the volume of water remaining in the storage tank from the previous day, m^3; T is the tank storage capacity, m^3; Y_t is total yield for the current day, m^3; and D_t is the total toilet flushing and lawn irrigation demand for the current day, m^3. Percent demand met, $\% DM$, was calculated by the division between Y_t and D_t (Equations *8*).

$$\% DM = Y_t / D_t \qquad \textit{Equation 8}$$

3.2 Cost-Benefit Analysis

A cost-benefit analysis was integrated into the SDMs. Costs of the two types of systems include capital cost and operation and maintenance cost. For this analysis, a discount rate of 0% has been selected following the practices adopted by Vítková et al. (2014) and Ward et al. (2012a). The discount rate was chosen to minimize the potential bias that may result from the static water and electricity rates assumed in the following cost and benefit analyses. However, a Monte-Carlo analysis and a sensitivity analysis were conducted to examine the influence of discount rate as well as utility rates on the model outcome. Capital costs of the RWH and GWR systems include tank cost, installation cost, and design cost (WRF, 2018). Tank cost was calculated using cost curves developed based upon data obtained from various manufacturing companies for estimating the cost of the different sized tanks (RHS, 2017; RHSI, 2017; WRF, 2018). Equation 9 represents the sizing and Equation 10 represents the costing curves that were used for both GWR and RWH in this study. Pump size and pump cost were determined through utilization of WERF LID tool (WRF, 2018). The system installation cost was assumed to be 60% of the tank cost and the design cost was assumed to be 8% of the tank and pump cost (WRF, 2018).

$$hp = (Q * F * \rho * 9.8) * \left({}^{h}/_{2}\right) * \left({}^{0.00134}/_{E}\right) \qquad \textit{Equation 9}$$

$$C_{pump} = -100.71hp^2 + 1327.7 * hp - 39.38 \qquad \textit{Equation 10}$$

Where hp is the pump horsepower, hp; Q is water flow rate, 0.00025 m^3/s (WRF, 2018); F is the number of fixtures, 1.5 for single-family and 7.5 for multi-family; ρ is water density, 1,000 kg/m^3; h is building height, 5 m; E is pump efficiency, assumed to be 0.5 (WRF, 2018); and C_{pump} is the pump cost, $.

System operation cost was calculated based upon the cost associated with pumping energy for delivering the collected water for toilet flushing. Rainwater and greywater collection as well as water delivery for irrigation were assumed to be gravity fed (EA, 2010; Marteleira & Niza, 2018; Vieira et al., 2014). Pumping energy (C_E) was estimated in Equation 11 by yield of the systems Y_t, building height, and the indoor use ratio. The indoor use ratio correlates to the percentage of yield used for used for toilet flushing purposes (Equation 12).

$$C_E = \frac{(Y_t * {}^{h}/_{2} * \rho * R)}{E * C_{kwh}} \qquad \textit{Equation 11}$$

$$R = D_f / D_t \qquad \textit{Equation 12}$$

Where C_E is pumping energy, kWh/day; h is building height, 5 m; ρ is water density, 1,000 kg/m^3; R is indoor use ratio; E is pumping efficiency, 0.5; C_{kwh} is conversion to kWh, 3.6*10^6 Joule/kWh; and D_f is the total toilet flushing demand, m^3/day; and D_t is the total toilet flushing and irrigation demand for the current day, m^3.

System maintenance costs were dependent on the type of system being utilized and the level of treatment needed. For RWH, it was assumed that only simple filtration was necessary for treatment, and annual inspection requirements can be completed by the homeowner. Thus, the system only required an average of $100/year for maintenance (CTCN, 2018; Fewkes & Butler, 2000; IWMI, 2018; Rahman et al., 2012). GWR required additional treatment and maintenance. Many previous studies have considered different technologies and their treatment capabilities, and most have agreed that a household size MBR system can achieve sufficient effluent water quality with relatively lower maintenance costs (Campisano et al., 2017; Leong et al., 2017; Lesjean & Gnirss, 2006; Liu et al., 2005). Therefore, this study considered MBR treatment for the GWR model. The annual maintenance cost for this technology varies greatly between previous studies and an average of the previously reported values, $200/year was used in this study to represent the annual filter changes and minor system replacement costs (Allen, 2019; Campisano et al., 2017; EPA, 2016; Leong et al., 2017; Lesjean & Gnirss, 2006; Marteleira & Niza, 2018; Memon et al., 2005).

Benefits resulted from installing the RWH or GWR system were calculated based upon reductions in drinking water and wastewater fees paid to the city water and wastewater utilities. Particularly, we assume installing RWH system will only result in savings in drinking water fees, while installing GWR system will result in savings in both potable water and wastewater fees. Many of the cities have had inconsistent trends of increases/decreases in fee prices; for this study the most current utility fees were used and remained constant throughout the 10-year period.

Payback period was used as an indicator of economic savings or cost for the household. It addresses the amount of time that it takes for the initial investment to be paid back. Payback period is identified by simulating the numerical integrations of net economic savings starting at zero and cumulating until then end of the 10-year simulation (Equation 13). Previous studies have identified a wide range of payback periods as acceptable amount of time that yields economic benefits (Campisano et al., 2017). In this study, any payback period that went beyond the life span of the RWH and GWR systems (10 years) was deemed an unreasonable/unfeasible (Campisano et al., 2017; Rahman et al., 2007; Roebuck et al., 2011).

$$T = \frac{C_I}{S_a} \qquad \textit{Equation } 13$$

Where T is payback time, years; C_I is initial cost, $; and S_a is average annual savings, $/year over a 10-year period. The annual savings was calculated by taking the average difference in $/year.

3.3 Study Locations

Twelve cities distributed across the US were investigated in this study, each with unique environmental and water supply characteristics provided in *Table 2*. Ten years (2007-2017) of historical daily precipitation data were used to determine the time and amount of rainwater supply for each city (NOAA, 2018). The average monthly-temperatures were also collected (USCD, 2018), which determined the lawn irrigation periods for each city provided in *Figure 3*. The average ET values, provided in *Table 2*, were obtained from the International Water

Management Institute (IWMI, 2018) using the coordinates of each city. The Water Sense Water Budget Tool (EPA, 2018) was used to determine the monthly landscape water requirement (Section B1 of the Supplemental Materials). Current water, wastewater, and electricity rates for each city were obtained from each city's municipality websites. Local government financial incentives for installing RWH or GWR systems were not included in this study, given very few cities have utilized a program for residential homes (Albuquerque, 2016; San Diego, 2016). Some other cities are only in the beginning phases for utilizing such an incentive program (CWRAP, 2019; Espinola, 2018) for industrial and/or commercial sectors, or practices not directly relate to water conservation (i.e. turf replacement, energy efficient water heater) (DSIRE, 2020; Scavetta, 2020).

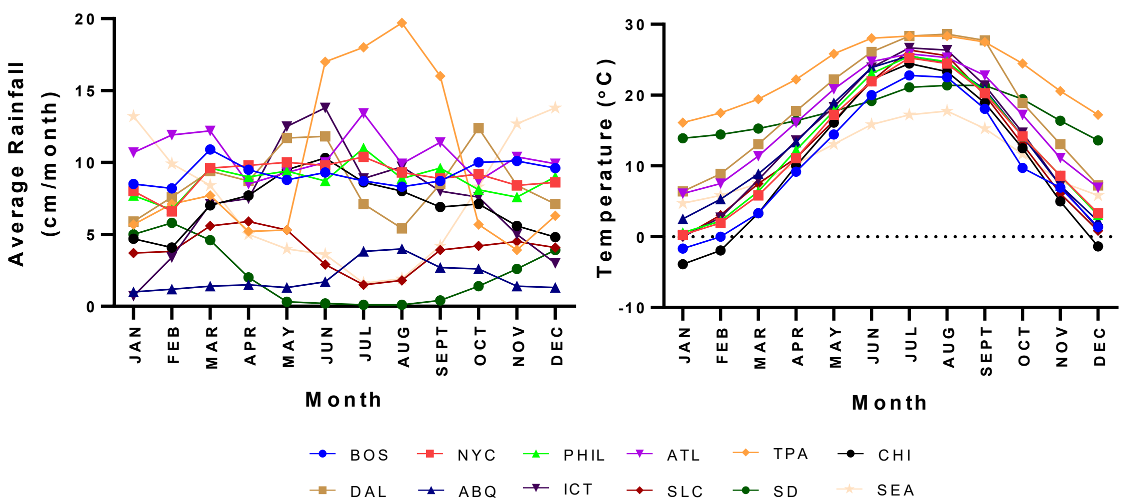

Figure 3 Average monthly precipitation (left) and average monthly temperatures (right) for each city

Table 2 Irrigation periods based on average monthly temperatures, average evapotranspiration (ET) value ranges (mm/day) (IWMI, 2018), and utility rates for all cities investigated within this study.

EPA Region	**City, State (Abbrev.)**	**Irrigation Periods** (USCD, 2018)	**ET Range** (IWMI, 2018)	**Water Utility Rates**		**Electricity Price** (EIA, 2018)
				Potable Water	Sewage	
			mm/day	$/m^3	$/m^3	Cents/kWh
1	Boston, MA (BOS)	June-September	5.14-1.07	2.19 (Boston, 2016)	2.97 (Boston, 2016)	19.94
2	New York, NY (NYC)	May-September	5.67-1.21	1.36 (New York, 2018)	3.53 (New York, 2018)	18.59
3	Philadelphia, PA (PHIL)	May-September	5.37-1.13	1.02 (Philadelphia, 2016)	1.16 (Philadelphia, 2016)	14.41
4	Atlanta, GA (ATL)	April-October	5.43-1.56	2.20 (Atlanta, 2016)	5.60 (Atlanta, 2016)	12.74
	Tampa, FL (TPA)	All Year	5.77-2.37	2.40 (Tampa, 2011)	2.10 (Tampa, 2011)	11.86
5	Chicago, IL (CHI)	May-September	5.42-0.72	1.04 (Chicago, 2016)	1.04 (Chicago, 2016)	12.59
6	Dallas, TX (DAL)	April-October	7.51-1.86	1.94 (Dallas, 2016)	1.20 (Dallas, 2016)	11.11
	Albuquerque, NM (ABQ)	May-September	8.90-1.63	0.48 (Albuquerque, 2016)	0.61 (Albuquerque, 2016)	12.72
7	Wichita, KS (ICT)	May-September	7.44-1.15	2.37 (Wichita, 2017)	0.78 (Wichita, 2017)	13.62

8	Salt Lake City, UT(SLC)	May-September	8.60-0.80	0.72 (Salt Lake City, 2016)	0.78 (Salt Lake City, 2016)	11.62
9	San Diego, CA (SD)	April-November	4.70-2.18	2.70 (San Diego, 2016)	1.28 (San Diego, 2016)	19.02
10	Seattle, WA (SEA)	June-August	4.50-0.68	2.30 (Seattle, 2017)	4.20 (Seattle, 2017)	9.85

3.4 Household types

This study examined two different household types in order to investigate the feasibility of implementing these two decentralized water systems. The two types of households include a typical two-story single-family home and a typical two-story multi-family building. Characteristics of a typical single-family home and a typical multi-family home were summarized in *Table 3*. Household characteristics (i.e., number of tenants, roof size, and lawn size) were estimated based on residential housing data from available datasets obtained from various real estate websites (Otet, 2016; Terrazas, 2014), the National Association of Home Builders (NAHB, 2015), the U.S. Census Bureau (USCB, 2017), and literature (Kaufman, 1962; Silva et al., 2015; Ural et al., 2011).

Table 3 Summary of household parameters that are defined in this study for single-family and multi-family homes in an urban environment.

Variable	Single-family	Multi-family
Roof Size (m^2)	116 (Silva et al, 2015)	427 (Otet, 2016)
Lawn Size (m^2)	526 (NAHB, 2015)	162 (Kaufman, 1962)
Number of Tenants per Building	3 (Terrazas, 2014)	15 (Ural et al., 2011; USCB, 2017)

Building Height (m)	5 (EPA, 2018)	5 (EPA, 2018)

3.5 Monte Carlo Analysis

We conducted both a Monte Carlo analysis to investigate the uncertainties associated with the modelled results. The Monte Carlo analysis tests the possible behavioral boundaries of a model when multiple variables change simultaneously. The Vensim software used in this study allows automatic sampling of constants over a range of pre-defined values. The Latin Hypercube sampling method was used in this study, which enables faster sensitivity testing on large models by dividing the sampling space into a number of equal partitions and then choosing a random data point in each partition. In this analysis, all constants within the multi-family house model were allowed to vary between +/-20% of their base value (except for the discount rate) following a uniform distribution to capture the 50%, 75%, 95% and 100% likelihood of the modelled RWH and GWR net economic savings over the 10-year simulation period (*Table 4)*. The multi-family house model was used for these analyses rather than the single-family house model because of the higher expected economic savings that can be potentially achieved through GWR and RWH installations in multi-family housing. The test range of the discount rate was set to be between 0% and 0.016% per day, which gives an annual discount rate of roughly 0% to 6%. The Monte Carlo analysis was repeated for 200 times with Boston as the sample city given its land size and population are in the middle range of all cities studied (Song & Mo, 2019).

Table 4 Variables tested during the Monte Carlo analysis for the city of Boston for both RWH and GWR.

Variable	**Base Value**	**Test Range**

Building height (m)	5.0	[4.0, 6.0]
Energy fee ($/kWh) (EIA, 2018)	0.199	[0.159, 0.239]
Irrigation efficiency	0.75	[0.600, 0.900]
Lawn size (m^2)	152	[122, 182]
Flushing water demand (m^3/person/day)	0.072	[0.057, 0.086]
Laundry volume per day (m^3/person/day)	0.056	[0.045, 0.068]
Shower volume per day (m^3/person/day)	0.065	[0.052, 0.078]
Bathroom sink volume per day (m^3/person/day)	0.022	[0.018, 0.027]
Pump efficiency	0.5	[0.400, 0.600]
Roof area (m^3)	427	[342,512]
Potable water fee ($/$m^3$)	2.19	[1.75, 2.63]
Wastewater fee (($/$m^3$)	2.97	[2.38, 3.56]
Number of tenants	15	[12, 18]
Runoff coefficient	0.8	[0.640, 0.960]
Daily discount rate	0.008%	[0.000%, 0.016%]

4. Results and Discussion

4.1 Payback Period

Figure 4 shows results for the payback time of each technology investigated under different tank sizes in the 12 testbed cities. Cities not shown in *Figure 4* indicate installation of RWH or GWR in these cities will never be paid back under the modelled conditions.

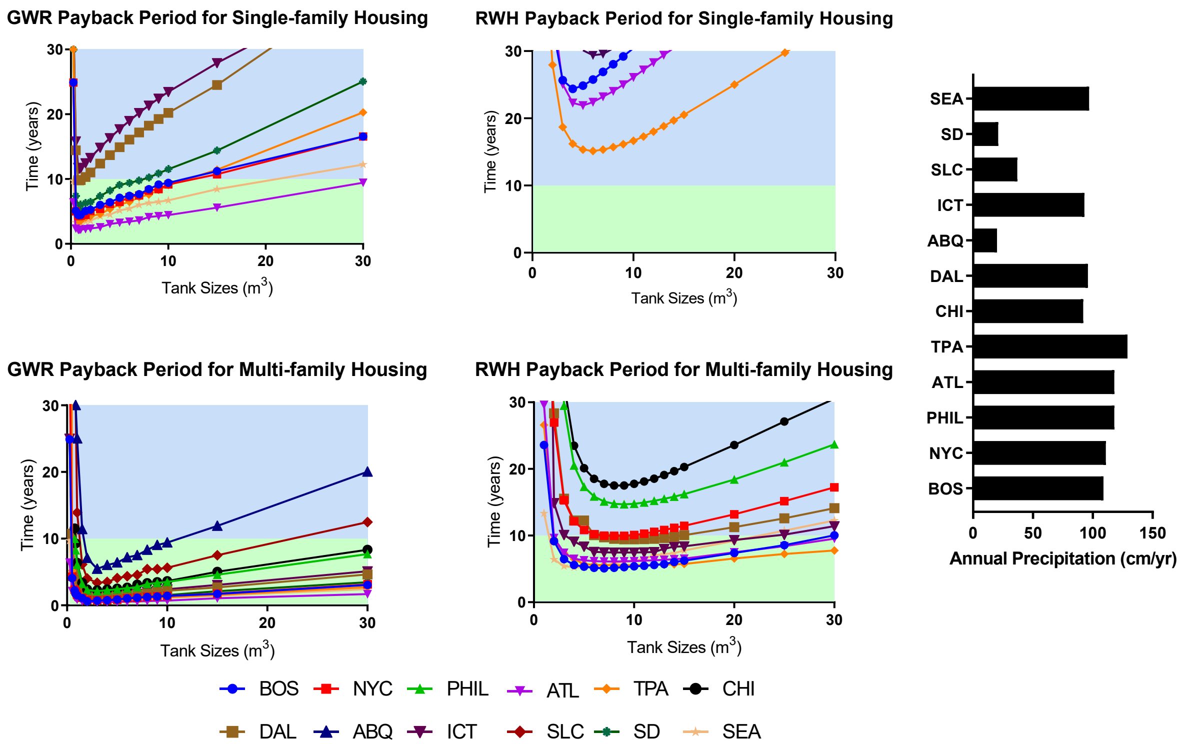

Figure 4 Payback period for all cities investigated. Shows the differences between each city, GWR and RWH, and single- and multi-family homes. The bar graph (far right) shows the total amount of precipitation received each year in the various cities. Cities in green area, are able to be paid back within the 10-year period. Cities in the blue area, do not achieve payback in the 10-year period, but do within a 30-year period

When the GWR system is installed in a typical single-family house, Atlanta and Seattle generally have the shortest payback time (2-3 years) with a tank size of 0.5 – 2.0 m^3, while Tampa, Boston, New York, and San Diego all have payback periods between 3-5 years at tank sizes 0.75-1.0 m^3. Dallas and Wichita generally have a longer payback time, between 9-12 years with a tank size range from of 0.75 – 1.0 m^3. Salt Lake City, Albuquerque, Chicago, and Philadelphia, however, will never be paid back within a 30-year timeframe regardless of system size. Payback time of the GWR systems is dominated by the potable water and wastewater fees within a city. The lower the potable water and wastewater fees are for a city, the longer the payback period will be. Local climate and irrigation demand, however, do not play a significant role in the payback time of the GWR systems. This is manifested in the cases of Salt Lake City and Albuquerque, both of which have dry climates and yet their water and sewer rates are among the lowest across all studied cities. An optimal tank size between 0.75-0.85 m^3 was found in all studied cities for this typical single-family housing. A similar concave pattern was observed between tank size and the payback time across all cities.

All cities were able to achieve a payback time when the GWR system is installed in a typical multi-family housing. This is because there are more tenants utilizing the system, more tenants increasing the influent volume for the GWR storage, and there is less of an overall demand because of the smaller lawn size compared to single-family housing. In this case, all cities will have a return of investment within ten years. Atlanta, Seattle, Boston, Tampa, New York City, and San Diego have the shortest payback time of less than one year, while Philadelphia, Chicago, Salt Lake City, and Albuquerque have longer payback times between 2 and 6 years. For all the cities, the optimum tanks sizes for payback is 2-3 m^3. Household size has a relatively significant impact on the GWR's return of investment because water generation is a limiting factor given the demand of non-potable water (toilet flushing particularly). Yields of multi-family housing are around 2-3 times those of the single-family housing, which has led to much more significant annual savings from the multi-family housing and hence shorter payback periods. An optimal tank size of 2-3 m^3 was found in all studied cities for this typical multi-family housing.

When the RWH system is installed in a typical single-family housing Tampa, Atlanta, and Boston cities generally have the shortest payback time, despite all of them exceeding the 10-year simulation period (15 to 24 years) with tank sizes ranging from 4-6 m^3. This is a combined effect of precipitation patterns and potable water fees. These cities tend to have more frequent precipitation events with relatively constant intensity and higher potable water fees. Wichita and Seattle have longer payback times (30 to 42 years) with tank sizes ranging from 4-6 m^3. New York, Philadelphia, Dallas, San Diego, Salt Lake City, Albuquerque, and Chicago, however, will never be paid back regardless of system size.

When the RWH system is installed in a typical multi-family housing Boston, Tampa, and Seattle generally have the shortest payback time (5-6 years). Atlanta, Wichita, Dallas and New York had payback periods occur between 7 and 10 years. Philadelphia and Chicago do reach payback, but they go beyond the 10-year period (15 to 17 years). The increase in number of cities achieving payback is because the collected inflow is increased due to a bigger roof area. An optimal tank size of 5-10 m^3 was found in the studied cities for this typical multi-family housing. This is because the amount of non-potable water available allows increased usability of the system itself. However, when the tank size and cost of the initial investment further increases, the payback time will increase again because the daily savings will need to accumulate for a longer period of time in order to offset the cost, if at all.

Overall, our results suggest that the GWR system is generally more appealing than the RWH system from an economic perspective. The GWR system is the most suitable for Atlanta, Tampa, and Seattle out of the studied cities based on payback time, while the RWH system is most suitable for Boston, Atlanta, and Tampa out of the studied cities. We found the economic performance of the GWR system is dominated by the water fees alone, while the economic performance of the RWH system is determined by both the precipitation patterns and the water fees. Having a wetter climate does not make a city automatically a top candidate for installing RWH systems. It is important to understand the current and future trends of local utility rates in designing policy incentives. Our study also suggests that sharing a GWR or RWH system within a multi-family building or a closely located local community can potentially increase their economic viability. Hence, policy incentives can be designed to promote the sharing of such decentralized systems to achieve the best possible economic results. The calculated optimal payback time across the different cities is comparable with the payback time reported by previous studies (Friedler et al., 2005; Hashim et al., 2013; Ward et al., 2010; Ward et al., 2012b).

4.2 Demand Met

Figure 5 shows the results for the demand met for each technology investigated and each household size considered. The highest percent demand met can be up to 70% for RWH systems and up to 90% for GWR systems across the twelve cities. GWR system generally provides a higher percent demand met than the RWH system. This is because GWR has a reliable source of influent being generated daily, RWH is dependent on the amount and timing of precipitation being generated. The calculated maximum percent demand met is within the range of previous reported range of 6-100% (Domènech & Saurí, 2011; Memon et al., 2005; Ward et al., 2012b).

When comparing cities, Seattle and Boston result in the highest percent demand met and Tampa and San Diego have the lowest when the GWR system is utilized. When the RWH system is utilized, Seattle, Boston, and New York City have the highest percent demand met while Albuquerque, Tampa, and San Diego have the lowest. The demand met of GWR systems is primarily determined by the system's capability to meet the irrigation demand. The demand met of RWH systems is primarily determined by the availability of rainwater supply as well as the varying irrigation demand and climate characteristics. Those cities that have longer irrigation periods obtain a smaller demand met percentage, while cities with shorter irrigation periods typically have higher demand met percentages.

RWH achieved a higher demand met percentage for single-family households compared to multi-family households, while GWR stayed at similar percentages between both multi- and single- family housing. This could be because the water collection for GWR is proportional to the usage for both multi- and single-family housing. RWH is not meeting the demand for multi-family housing because there are too many people using the technology and the collection area of the roof and the amount of rainfall that is able to be collected does not correlate to the total number of occupants.

The tank size that achieves the smallest payback time does not align with the tank size that maximizes percent demand met. When the tank size is optimized for payback time, the percent demand met is generally 10% lower than the highest achievable demand met. With the highest achievable demand met, payback time takes generally 2-4 times longer than the optimized tank size for payback. This indicates a tradeoff between sizing for minimized payback time or maximized demand met. In previous studies, people have prioritized socio-economic drivers, such as payback, in their decision of implementing RWH or GWR (Mankad & Tapsuwan, 2011; Wang & Zimmerman, 2015). In cities where there is some overlap in demand met and quick payback, such as Boston, Atlanta, and Seattle, the decision to implement one of the decentralized options is easier to make. For cities where payback and demand met are opposite, such as Tampa and New York, maximizing payback may be the deciding factor on the household-scale. However, in other areas where water scarcity and reliability are major concerns, meeting daily demand should be the top priority. To help alleviate increased demand, policies encouraging water conservation should be implemented to help promote adoption of GWR and RWH. As more decentralized systems are put in place in smaller scale buildings, the potential for financial assistance or resources in urban development and planning may increase (Leigh & Lee, 2019).

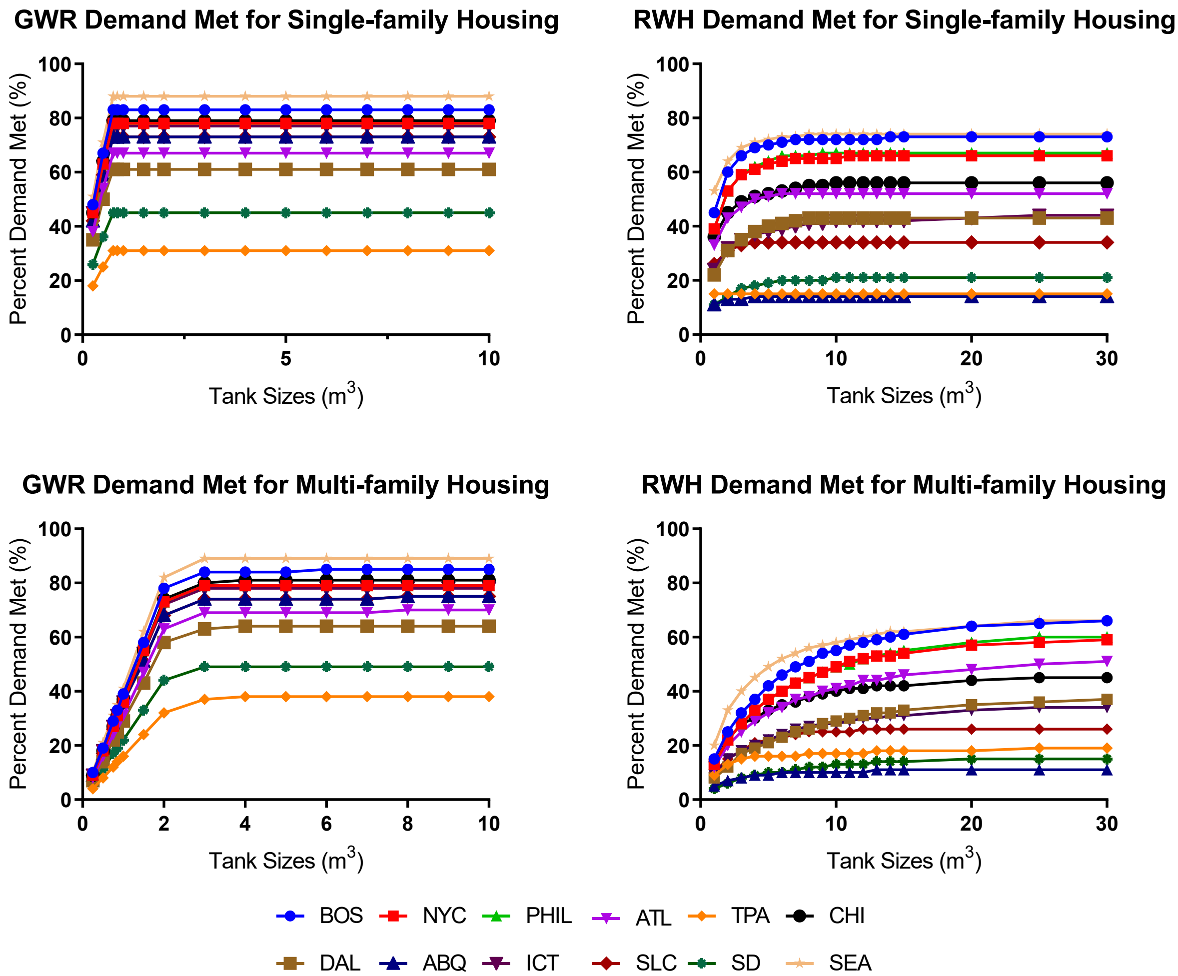

Figure 5 Demand met percentages for all cities investigated, which shows the differences between each city, GWR and RWH, and single- and multi-family homes.

4.3 Monte Carlo and Sensitivity Analysis

The 50%, 75%, 95% and 100% likelihood of the RWH and GWR economic savings over the 10-year simulation period in response to changes in tested variables are shown in *Figure 6* and *Figure 7*. The results show that RWH economic savings over ten years are at a range of -$400 - $3,900 with 100% confidence, and a range of $900 - $2,200 with 50% confidence. The analysis shows that uncertainties in the values of the model variables are not likely to result in the collapse of economic saving for RWH, except for the lowest 5% of the simulations, because 95% of the simulations reach payback within the 10-year period. However, the specific time in which it reaches payback varies within the 10-years' time frame.

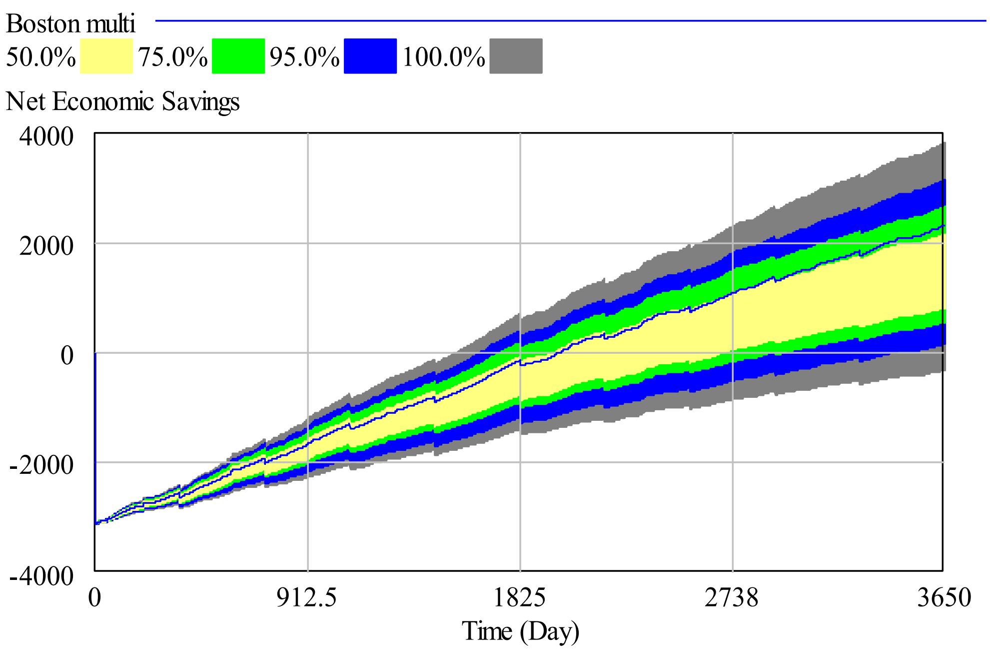

Figure 6 Monte Carlo simulation of RWH model at 11 m^3 tank size for the city of Boston, MA over a 10-year period for a multi-family household.

GWR economic savings over 10 years are at a range of \$8,000 – \$16,750 with 100% confidence, and a range of \$12,000– \$14,500 with 50% confidence. The analysis shows that uncertainties in the values of the model variables are not likely to result in the collapse of economic savings because 100% of the simulations reach payback within the 10-year period. However, the specific time in which it reaches payback varies within a years' time frame.

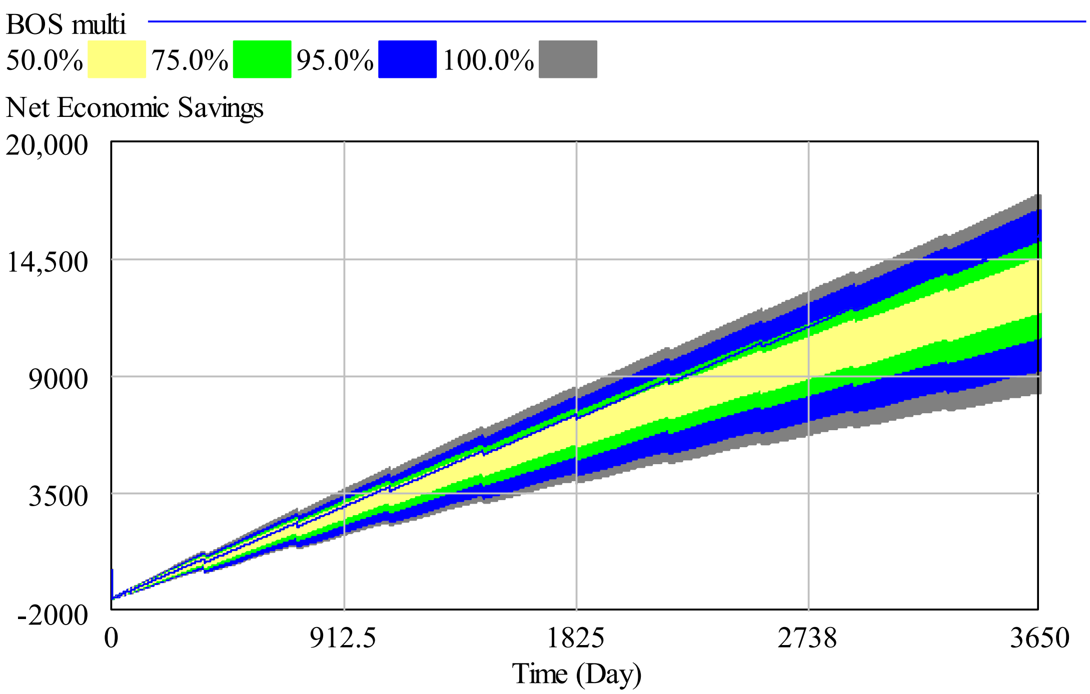

Figure 7 Monte Carlo simulation of GWR model at 2 m^3 tank size for the city of Boston, MA over a 10-year period for a multi-family household.

5. Conclusions

This study conducted a life cycle cost assessment integrated with dynamic modeling to investigate whether GWR or RWH have appropriate payback and demand met capabilities in two different household types across 12 US cities. We found that for GWR, cities had optimum tank sizes of 2-3 m^3 for multi-family housing and 0.75-0.85 m^3 for single-family housing. Payback varied between the cities investigated for GWR, however Atlanta, Tampa, and Seattle are most suitable for GWR. For RWH, optimized tank sizes range from 5-10 m^3 for multi-family housing and 4-6 m^3 for single-family housing. Payback varied between cities and many cities were not able to achieve payback for RWH. Investigation for RWH concluded that Boston, Tampa, and Atlanta were most suitable for installation in terms of payback. Demand met for

GWR ranged from 70%-90%, while RWH ranged from 50%-70% across all cities. For the demand met metric, Seattle and Boston achieved the highest percentages. Boston and Tampa achieved the highest percentages for RWH demand met. Overall, Boston, Seattle, and Atlanta performed the best for both GWR and RWH, single-family and multi-family, and payback and demand met.

While the current study was focused on quantifying payback time and demand met of individual RWH and GWR system applications, environmental impacts and benefits associated with city-scale RWH and GWR system adoptions, such as flooding risk reductions and greenhouse gas emissions (Bonoli et al., 2019), need to be investigated in future studies to provide a more comprehensive understanding regarding the true "costs and benefits" of these systems. This will require acquisition and analysis of the spatial pattern of household characteristics such as lawn area, rooftop size, or water consumptions. Future studies should also consider inclusion of different technological approaches for GWR and RWH for water treatment and how water quality from reuse affects payback time and environmental viability. Additionally, the effect of climate change on decentralized system should be investigated as well as how socio-economic factors affect public perception.

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