RELIABILITY ANALYSIS OF RAINWATER HARVESTING IN THREE TEXAS CITIES

by

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-Dustin Lawrence, July 2014

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ABSTRACT

Population growth and a prolonged drought have raised concerns about the sustainability of water resources in Texas. Recent state legislation has made financial assistance available towards the development of water supplies. The purpose of this study is to inform decision makers at state and local levels, as well as property owners about the amount of water that can be supplied by rainwater harvesting systems in Texas so that it may be included in any future planning. Reliability of a rainwater tank is important because people want to know to what degree a source of water can be depended on. Performance analyses were conducted on 3 cities under different climate conditions and multiple scenarios to demonstrate the importance of optimizing rainwater tank design. This was accomplished using a daily water balance model and running simulations on a range of tank sizes appropriate for rainwater harvesting at the household level. Reliability curves were produced and reflect the percentage of days in a year that water can be supplied by a tank. Operational thresholds were reached in all scenarios and mark the point at which reliability increases by only 2% or less with an increase in tank size. Maximum thresholds were also reached in some scenarios and indicate a tank size that provides the maximum achievable reliability. Additional simulations considered several average years of rainfall for each city under a single scenario to determine an average optimal tank size. A payback period analysis was conducted on these tank sizes to estimate the amount of time it would take to recoup the cost of installing a rainwater harvesting system.

CHAPTER I

INTRODUCTION

Background

The availability of water resources in Texas continues to be a cause of great concern. A combination of severe drought in recent years and an increasing population has raised questions about sustainability and future growth. Decision makers will be faced with the challenge of maintaining an adequate supply of water for human consumption, industry, agriculture and the environment. This process should consider all available options including some innovative approaches. Established water provision methods such as reservoir construction, desalination and wastewater re-use will certainly be implemented whenever needed, but these projects are expensive and may take years to complete. A seemingly effective and simple alternative that should be explored is domestic rainwater harvesting.

When compared to other states, Texas has one of the fastest growing populations in the country. A warm, sunny climate is certainly a big draw for many of the incoming residents that are putting down roots. Even more attractive are the booming economic opportunities across the state in various fields: like oil production in the southwest, refineries along the gulf, auto and aircraft manufacturing in Dallas, and technology in Austin (CNN Money, 2013). According to the U.S. Census Bureau (2013), 8 of the 15 fastest growing cities in the country from July 2011 to July 2012 are in Texas and include Houston, San Antonio, Austin, Dallas, and Fort Worth. The area along the Interstate 35 corridor between San Antonio and Austin has experienced a notable influx of people with

San Marcos being recognized for the highest growth rate among U.S. cities with a population of at least 50,000.

The availability of water resources in the face of a rapidly growing population is further complicated by the fact that Texas has been suffering from several years of drought. In a United States Geological Survey report by Karl Winters (2013), the statewide drought conditions in 2011 are compared with those of 1951-1956. The drought of the 1950s is often used as a benchmark for water planners as the driest period in Texas history. However, this distinction is challenged by the lack of rainfall in recent years. The lowest record of average annual rainfall in the state was formerly held in 1956 when 13.91 inches was observed. The year 2011 proved to be even drier when only 11.27 inches fell. The drought seemed to hit its peak in early October that year when data from the University of Nebraska-Lincoln Drought Monitor showed that 97 percent of Texas was under extreme to exceptional drought conditions. The rainfall deficit has continued and prospects for the future may be bleak as well. John Nielsen-Gammon, a professor of atmospheric sciences at Texas A&M University and state climatologist, gave his opinion on the matter in 2013. He says that the current drought could last another 10-15 years based on long-term temperature patterns from the Pacific and Atlantic Oceans which look similar to those of the 1950s (Amarillo Globe News, 2013).

In an attempt to remedy the problem, lawmakers proposed an amendment to the Texas Constitution in early 2013 that would help develop state water projects by creating the State Water Implementation Fund for Texas (SWIFT). The law went before voters on the November 5th, 2013 ballot under the name Proposition 6 and passed by a wide margin (Texas Water Development Board, 2013). This landmark piece of legislation means that

2 billion dollars will be transferred from the Economic Stabilization Fund (appropriately dubbed the Rainy Day Fund) to SWIFT. The newly reformed Texas Water Development Board (TWDB) will determine which water projects are going to be financed by SWIFT dollars and will prioritize them based on public need. However, it is important to understand that the only projects eligible to receive monetary assistance are those already outlined in the 2012 State Water Plan. Many different approaches for obtaining water are included in this plan such as: desalinization plants, well development, reservoir construction, wastewater re-use and piping water in from other areas. One technique that is absent from the State Water Plan, and therefore ineligible for SWIFT funding, is rainwater harvesting. As it stands right now, a public water system that has interest in implementing a residential rainwater harvesting program would have to finance it on their own, which shows a clear disadvantage for this method of obtaining water and why it may be underutilized. A better understanding of the effectiveness of rainwater harvesting in Texas might illustrate that it is an option that deserves consideration in future state water planning along with other development strategies.

Some legislation in favor of residential rainwater harvesting has been passed in Texas in recent years (National Conference of State Legislatures, 2014). Texas Property Code §202.007 went into effect in 2003 and prevents homeowner's associations from enforcing rules against a property owner who installs a rainwater harvesting system. It does however allow restrictions on the location and size of tank. Requiring the placement of shielding and maintaining the aesthetic quality of a piece of property is also permitted whenever it is financially reasonable for a homeowner to do so. Texas Tax Code §151.355 also went into effect in 2003 and allows a sales tax exemption on the purchase of rainwater harvesting equipment and supplies that are used solely for the purpose of reducing or eliminating water use. In 2007, Texas Health and Safety Code §341.042 established standards relating to the domestic use of harvested rainwater. These included health and safety standards for treatment and collection of harvested rainwater intended for potable uses.

The state legislation passed Texas HB 3391 in 2011 and it stands as the most comprehensive law on rainwater harvesting to date. Among the many provisions, it allows financial institutions to issue loans for developments that rely solely on rainwater. Rules are also required for the installation of rainwater harvesting systems that connect to public water systems. The purpose of these is to ensure safe drinking water standards and to prevent a cross-connection that could contaminate the municipal water supply. Public water systems are also given liability protection in these situations. Another provision requires new state buildings that meet certain criteria to incorporate rainwater harvesting systems into their design and construction. Municipalities and counties are also prohibited from denying any building permit solely because the facility will implement rainwater catchment. Perhaps the most interesting piece of this legislation is that it encourages municipalities and counties to promote rainwater harvesting at the residential, commercial, and industrial levels by suggesting that these local governmental entities should offer up incentives such as discounts on rain barrels or rebates for water storage.

Problem Statement

In order to provide the growing population of Texas with an adequate supply of water, decision makers will need to consider all available options. Rainwater harvesting systems at the household level may be an important factor in meeting water resource demands, however more information is needed. The dependability of a water source is very important, and the amount of water that can be supplied by rainwater harvesting systems in the state is not fully understood. Information on tank size reliability, for instance, is an important step toward implementing rainwater harvesting systems as a viable management strategy.

Objectives

This study has the following objectives:

1) Explore the performance and design optimization of rainwater tanks in three different cities in Texas (San Antonio, Dallas, and Houston) using a daily water balance model.
2) Determine optimal tank sizes based on the local rainfall characteristics.
3) Improve understanding of how different site conditions can affect the reliability provided for by a rainwater tank.

Relevance of Study

Water is not only vital to life but necessary for the economic well-being of the state. According to a synthesis report by the Environmental Protection Agency (2013), the importance of water to the United States economy is abundantly clear, but the efficient use of it is often difficult to manage. This is due to the several factors that contribute to an inconsistent valuation of water resources. Among them is the quantity that a source can provide. The location that the water will be delivered to and the timing of that supply are also forces at work that determine its cost. Reliability is always a concern and the assurance that a supply will not be interrupted is invaluable. Another very important factor to consider is the water quality as it relates to its intended use. For instance, water sources obtained for domestic purposes should be free of contaminants. Complicating the issue of water valuation is the fact that much of it is subsidized by taxes paid towards public infrastructure, which means that the true cost of delivering water is not reflected in what is being paid to the public water systems by customers. Prices that are artificially low extend the amount of time it takes for homeowners to recoup the money paid for the installation of rainwater tanks. Therefore, payback period analyses like the ones featured in this study may be skewed enough to make rainwater harvesting appear unfavorable, when in reality it may be a fiscally sound decision for homeowners and public water systems alike.

The EPA report (2014) makes it clear that as economies grow, the competition for water will increase, driving up its value. The efficient use of water will become even more important over time and will rely upon good information that is currently limited. According to the report,

> "The path to making better choices in using and managing our water resources begins with a better understanding of the economic and environmental consequences of the options available to us…developing this understanding and generating the information necessary to make better decisions will require a collective effort."

Demand for this knowledge is growing and is most apparent in regions of the country that are experiencing water scarcity due to drought or population growth. Texas is a state that is familiar with both of these circumstances, and the application of rainwater harvesting is an intriguing possibility that could contribute to water resource sustainability.

A study conducted by the Electric Power Research Institute (2011) contained a map showing counties of the United States and their projected sustainability risk if current trends continued until the year 2030 (Figure 1). The sustainability risk index was based on five factors including: availability of renewable water resources, groundwater use, susceptibility to drought, growth in water demand, and increased need for storage. Thresholds were established for each of the criteria and counties were classified as low, moderate, high or extreme based on how many of these benchmarks were met. EPRI cautioned that the information was most appropriate as a general assessment since a county might only meet one or two of the established criteria but could be in a critical condition for those factors and therefore be unsustainable. The potential future of water resources in the 3 Texas cities selected for this study can be seen by the data. Houston's Harris County and San Antonio's Bexar County had water supply sustainability risks classified as extreme and high, respectively. Dallas County's sustainability risk was classified as moderate. Many other counties across the state show extreme and high sustainability risks. The outlook in this projection suggests that it would be wise for these areas to explore every option available in the development of water resources, including rainwater harvesting.

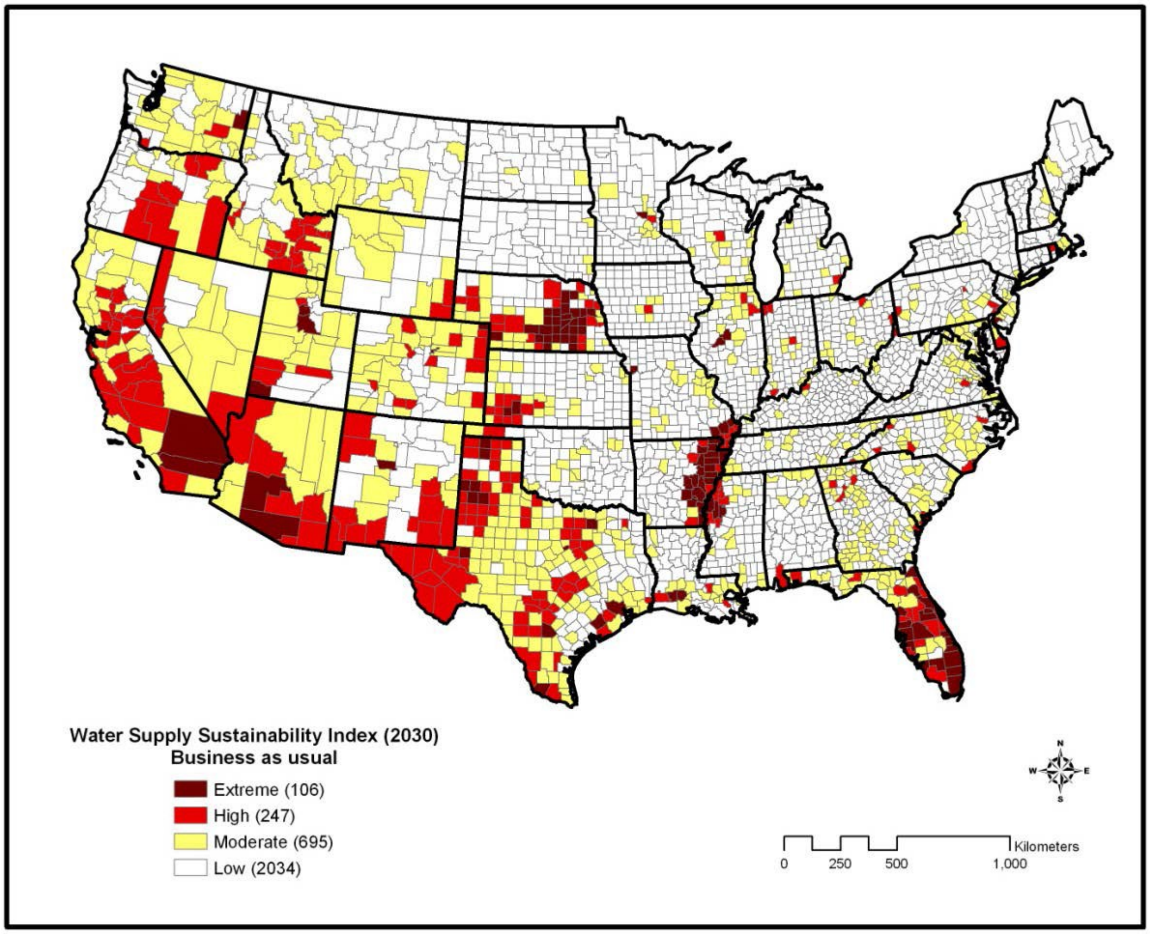

Fig. 1. Water Supply Sustainability Index (2030). Water supply sustainability risk index of U.S. counties in 2030 assuming current trends continue.

CHAPTER II

LITERATURE REVIEW

The design and implementation of rainwater tanks have been studied extensively in various parts of the world. In the United Kingdom, for example, Fewkes (1999) used the data from a field tested rainwater collection system to verify and refine a sizing model. This model produced a set of dimensionless design curves that give the ideal tank size to achieve a desired level of performance when roof area and demand for water are known. Vaes and Berlamont (2001) developed a conceptual model using long term historical rainfall data in northern Belgium to assess the effect of rainwater tanks on runoff. They determined that the variability of rainfall was an important factor for source control measures in combined sewer systems due to periods of antecedent storage. Villareal and Dixon (2005) explored the benefits of a rainwater collection system in Norrkoping, Sweden by utilizing a computer model to determine the water savings potential under different scenarios and provide suggested tank sizes.

In southeastern Brazil, Ghisi et al. (2007) evaluated the potential for water savings for 195 cities when using rainwater in the residential sector and found that the average savings ranged from 12% to 79%. They assessed the ideal tank capacities for specific cities and determined that it depended largely on location due to potable water demand and rainwater demand. Another study by Ghisi et al. (2009) looked at the potential water savings when using rainwater for washing vehicles in petrol stations in Brasilia. They considered rainfall data from two meteorological stations along with different rainwater collecting areas, tank capacities, number of washings, and potable and rainwater demands. Average potable water savings were 32.7% and the investment feasibility analysis included in the article was positive in most cases.

The city of Melbourne in southeastern Australia has been suffering from many years of drought which has forced its citizens to explore alternative water sources, including domestic rainwater harvesting. A case study by Muthukumaran et al. (2011) states that the use of rainwater inside the home can save up to 40% of potable water use. The importance of tank size selection is apparent in this part of the world as well. Khastagir and Jayasuriya (2010) highlight the fact that there is a large variation in average annual rainfall across Melbourne and that different tank sizes are necessary to provide the same supply reliability. Their research examines the relationship between annual rainfall at a geographic location, rainwater demand, roof area catchment, and the desired supply reliability to select optimum tank sizes with the use of a dimensionless curve.

Another case study conducted in Melbourne by Imteaz et al. (2011a) explored the optimization of rainwater tanks for large roofs under three different climate regimes (dry, average and wet years). A simple spreadsheet-based daily water balance model was developed with the inputs of daily rainfall data, roof area, rainfall loss factor, available storage volume, tank overflow, and water demand. They concluded that both tank sizes being studied (185 m^3 and 110 m^3) performed well in wet and average years but were less effective in dry years. A payback period analysis showed that tank construction costs could be recovered in 15-21 years depending on tank size, climate conditions, and the rate of future water price increases. Imteaz et al. (2011b) used a similar methodology in another paper that same year but this time included a reliability analysis. Reliability was defined as the percentage of days in a year that water demand could be satisfied by the rainwater tank supply. A number of reliability charts were produced for the three climate conditions (dry average and wet years) under different scenarios of roof size, number of people in a house, and percentage of total water demand to be satisfied by rainwater. This methodology was used again in a paper by Imteaz et al. (2012) to compare South-East and Central Melbourne due to the notably different topography and rainfall characteristics displayed by each region. There is also a greater emphasis placed on the threshold tank size, which is defined as the point when reliability becomes independent of an increasing tank size.

Farreny et al. (2011) examined the importance of roof selection for rainwater harvesting in Spain. Four roof types were assessed for water quality parameters and the volume of runoff provided. They discovered that the slope and roughness of a roof had a notable influence on its runoff coefficient. A smooth roof with a greater slope could harvest up to 50% more rainwater than one that is flat and rough. They also observed that rain collected from sloping roofs had better water quality for all parameters measured, except ammonia. Another article on rainwater harvesting in the Mediterranean was composed by Campisano and Modica (2012) for the island of Sicily. They carried out daily water balance simulations for 17 rainfall gauging stations and developed regressive models to estimate water savings and overflows for specific regions. Like many other studies, the goal was to determine the optimal tank size and results showed that the economic advantage of large tanks decreased as less rainwater was available. Rainwater collection systems that are appropriately designed should minimize overflows but not contain excess storage volume that is rarely utilized.

In a rainwater harvesting paper focused on the United States, Steffen et al. (2013) examined 23 cities that made up seven climate regions across the country. They were interested in how much water supply could be provided from harvesting rainfall at the level of a residential parcel. They employed a daily water balance method to estimate water saving efficiency for a range of rainwater tank sizes and determined that performance depends on climate patterns and tank size. Their results showed that a single rain barrel can provide about 50% water savings in cities of the East Coast, Southeast, Midwest, and Pacific Northwest for a demand scenario that represents non-potable indoor water use. Cities of the Mountain West, Southwest, and most of California, on the other hand, showed a water savings of <30%. Stormwater management benefits were also explored using a model developed by the U.S. Environmental Protection Agency. Even though Texas was covered under the southwest region in this study, no Texas cities were included in the analysis. The southwest was characterized by Albuquerque, Phoenix, and Las Vegas.

Using a daily water balance model to evaluate the performance of rainwater tanks has been investigated in many locations throughout the world as the cited literature shows. There hasn’t been any research of this nature carried out with Texas cities as the study area, despite the water resource problems befalling the state in recent years. The aim of this study is to apply an established methodology to locations in Texas and determine the reliability of rainwater tanks under multiple conditions based on the local rainfall characteristics.

CHAPTER III

METHODOLOGY

Study Area and Data Sets

Historical daily rainfall data was obtained from the National Weather Service (2013) for rainfall gaging stations at San Antonio International Airport, Dallas Love Field, and William P. Hobby Airport in Houston. The three locations represented their respective cities for daily amount and variability of rainfall for three different annual climate conditions: dry, average and wet years. Categorization of these climate conditions was based on the 10^{th}, 50^{th} and 90^{th} percentiles for total annual rainfall at each station for all years that precipitation data is available. The reason why 10^{th} and 90^{th} percentiles represent dry and wet years is due to the fact that this amount of rainfall has a higher probability of occurring when compared to the actual driest or wettest years on record. Extreme dry or wet conditions are very rare within a normal distribution of total annual rainfall. An "average year" is a qualitative term and is actually represented by the median instead of an arithmetic mean. The cities of San Antonio, Dallas, and Houston were selected because they have the highest populations in the state and therefore stand to make the biggest potential impact if rainwater harvesting is implemented. They also vary enough geographically that the different rainfall characteristics of these locations provides a good framework for decision makers to compare with other parts of Texas. The data set for San Antonio spans the years 1948-2013, the one for Dallas spans the years 1940-2013, and the one for Houston spans the years 1941-2013. Any years that had missing data were not included. Table 1 illustrates the outcome of the year selection and the amount of rainfall observed in dry, average and wet years for each city.

Table 1. Dry, Average, and Wet Year Selection. Selection of dry, average, and wet years for each city based on the 10th, 50th, and 90th percentile of total annual rainfall with rainfall amount listed in millimeters and inches.

	San Antonio			Dallas			Houston		
	Rain (mm)	Rain (in.)	Year	Rain (mm)	Rain (in.)	Year	Rain (mm)	Rain (in.)	Year
Dry Year	446.7	17.59	2011	619.1	24.37	1972	861.3	33.91	1950
Avg. Year	772.4	30.41	1968	938.6	36.95	2002	1207.7	47.55	1985
Wet Year	1086.6	42.78	1991	1218.5	47.97	1973	1769.6	69.67	1976

Model

This study was conducted using a spreadsheet-based daily water balance model with the inputs being daily rainfall, roof area, runoff coefficient, volume of storage tank, and water demand, following the approach used by Imteaz et al. (2012) in their comparison of South-East and Central Melbourne. The daily amount of runoff the storage tank collects was calculated by multiplying the rainfall amount by the roof area and then factoring in the runoff coefficient for metal roofing. Metal roofs were selected for this study due to their abundance in Texas and the fact that they are the construction material that performs best as a rainwater catchment area. Fieldwork by Farreny et al. (2011) shows that the composition and slope of a roof has a notable effect on the amount of runoff that makes it into the storage tank and the average runoff coefficient for metal roofs was found to be 0.92.

Using the daily water balance model, calculated runoff from each rainfall event was deposited into the theoretical storage tank with any accumulated storage. If runoff was greater than available storage volume, excess water was deducted from runoff as overflow. Water demand was deducted from accumulated storage every day as long as there was water present. In the event that the tank was empty, the model assumed that the remaining water demand is met by a municipal water source. The model calculated daily rainwater use, daily water storage in the tank, daily overflow, and daily municipal water use. All volumes are displayed as liters (L). Additionally, the model calculated annual rainwater use, accumulated annual overflow and accumulated annual municipal water use. The overall procedure can be mathematically described as:

Cumulative water storage equation:

$$S_t = V_t + S_{t-1} - D \quad (1)$$

where,

$$S_t = 0, \text{ for } S_t < 0 \quad (2)$$

$$S_t = C, \text{ for } S_t > C \quad (3)$$

where S_t is the cumulative water stored in the rainwater tank (L) after the end of the *t*th day; V_t is the harvested rainwater (L) on the *t*th day; S_{t-1} is the storage in the tank (L) at the beginning of the *t*th day; D is the daily rainwater demand (L) and C is the capacity of the rainwater tank (L).

Municipal water use equation:

$$MW = D - S_t, \text{ for } S_t < D \quad (4)$$

where MW is the municipal water use on the *t*th day (L).

Overflow equation:

$$OF = S_t - C, \text{ for } S_t > C \quad (5)$$

where OF is overflow on the *t*th day (L).

Reliability was calculated with the following equation:

$$R_e = [(N - U) / N] \times 100$$

where R_e is the reliability of the tank to be able to provide sufficient water to satisfy demand as a percentage; U is the number of days in a given year the tank was unable to meet demand; and N is the total number of days in that year.

The daily water balance model ran simulations with the daily rainfall data from the three selected locations for a dry, average, and wet year. Ten different tank sizes were analyzed under these climate conditions and a percentage of total water demand that can be fulfilled by the rainwater tank was determined. This percentage is called reliability. Tank volumes and water demand are displayed in liters (L) with gallons (gal) in parentheses. The tank sizes ranged from 946-9464 L (250-2500 gal) and increased in increments of 946.4 L (250 gal) which corresponds well with the selection of tanks available for sale. A company that sells large plastic water tanks in Texas provided the information for the tank sizes (Tank Depot, 2014).

To show the effects of other parameters, two roof areas were considered along with two water demand scenarios. According to a 2009 survey by the U.S. Energy Information Administration (2014), the average area inside Texas homes is 163 m^2 (1757 ft^2). A one-story home should have about the same size roof area as the area within, so this number served as one variable in the water balance simulations. To represent two-story homes (as well as smaller homes) 163 m^2 was multiplied by 0.667 which produced the other variable of 109 m^2 (1172 ft^2). Since the upper story of homes is often not as large as the lower story is, the average area was only reduced by 2/3 instead of 1/2.

The demand scenarios were based on a publication by Mayer et al. (1999) on behalf of the American Water Works Association that estimated residential use of water in North America. Toilet flushing and laundry washing were chosen for rainwater application in our study because of their high demand compared to other indoor water uses. Additionally, this non-potable water would require no treatment. The AWWA found that the average amount of water used per day for toilet flushing was 70 L (18.5 gal) per person, and the average amount of water used per day for laundry was 56.7 L (15 gal) per person. They reported a striking similarity in appliance and water fixture use across multiple locations indicating that indoor water consumption does not vary much by region, so these per capita amounts should serve well for Texas. According to the U.S. Census Bureau (2013), the average persons-per-household for Texas in 2008-2012 was 2.8. The number was simply rounded up to 3 for this study. Therefore, the first demand scenario was 210 L (55.5 gal) per day which represents 3 people's use of water for toilet flushing. The second demand scenario was 380 L (100.5 gal) per day which represents 3 people's use of water for toilet flushing and laundry combined. Coincidentally, this AWWA study found that average outdoor water use for a household was 382 L (100.8 gal) per day, so the second demand scenario also serves as an example of rainwater harvesting for outdoor use only. Some might even argue that this is the most practical application of rainwater since no additional indoor plumbing would be needed for household fixtures.

With the variables listed above, a total of 360 water balance simulations were run with 12 reliability charts produced. Each chart displays the 10 tank sizes on the X axis and reliability percentage on the Y axis. Relationship curves illustrate how selected variables can influence rainwater tank reliability under the three climate conditions (dry, average, and wet years). Optimal tank sizes are apparent for each scenario in the cities examined due to reliability thresholds where installing larger tanks will cost more but provide little additional benefit. This is a slight departure from the methods in the cited literature that state threshold tank sizes as the point where maximum achievable reliability is reached. Due to the differences in rainfall and water demand in this Texas study, maximum achievable reliability was not observed in the majority of the scenarios considered. Therefore, an additional threshold (distinguished from a maximum threshold) will be defined here as a leveling-off effect where the added benefit from an increasing tank size stabilizes to a small amount before it reaches maximum reliability. This can be referred to as an operational threshold and occurs when there is a 2% increase in reliability or less for the next tank size increment. To look at it another way, 2% of 365 days is 7.3 days, so a larger tank size after the operational threshold is reached might yield a week's worth of water or less during the year for every added 946 L (250 gal) of capacity. The mean retail cost of this increasing tank size increment is $108 USD and was determined by comparing tanks available for sale (Tank Depot, 2014). In addition to financial savings during installation, the distinction between an operational threshold and a maximum threshold is important because space is usually limited in urban areas and squeezing the last few drops of reliability out of a rainwater collection system at the expense of precious real estate might not be desirable. The footprint of a vertical water tank can range from 0.79 m (2.58 ft.) to 2.59 m (8.50 ft.) in diameter for 946 L (250 gal) and 9464 L (2500 gal) storage capacities respectively. An image of a typical rainwater tank installed at a household was obtained from Texas A&M Agrilife Extension (2014) and can be seen in Figure 2 below.


Fig. 2. Image of a Residential Rainwater Harvesting Tank.

CHAPTER IV

RESULTS

The following section contains 12 reliability charts along with an explanation of the results. More detailed information can be found by looking at the corresponding tables in the appendix. A secondary analysis was also conducted on each city to explore the effects of rainfall variability in the 5 most average years. These 3 additional reliability charts can be found in the section titled Additional Simulations.

San Antonio Results

Fig. 3 shows the reliability curves for the city of San Antonio under different climate conditions (dry, average, and wet years) and different tank sizes when the roof catchment in place is 109 m^2 (1172 ft^2) and rainwater demand is 210 L (55.5 gal) per day. In a dry year, reliability increases with tank size until the operational threshold is reached at 4732 L (1250 gal) with a reliability of 45%. Reliability continues to go up very slowly after that point until a maximum reliability of 50% is met with a tank size of 8517 L (2250 gal). A larger tank would provide no additional benefit beyond that size. In an average year, reliability increases to 76% when the operational threshold is reached with a 4732 L (1250 gal) tank. In a wet year, reliability follows a similar upward trend as the average year, but the operational threshold is not reached until a 7571 L (2000 gal) tank size is used and 84% reliability is met. The previous 4 tank sizes only make reliability go up by 3% for each increment, which is just shy of the criteria for an operational threshold set at 2%. This makes the optimal tank size quite large for this climate condition in the scenario.

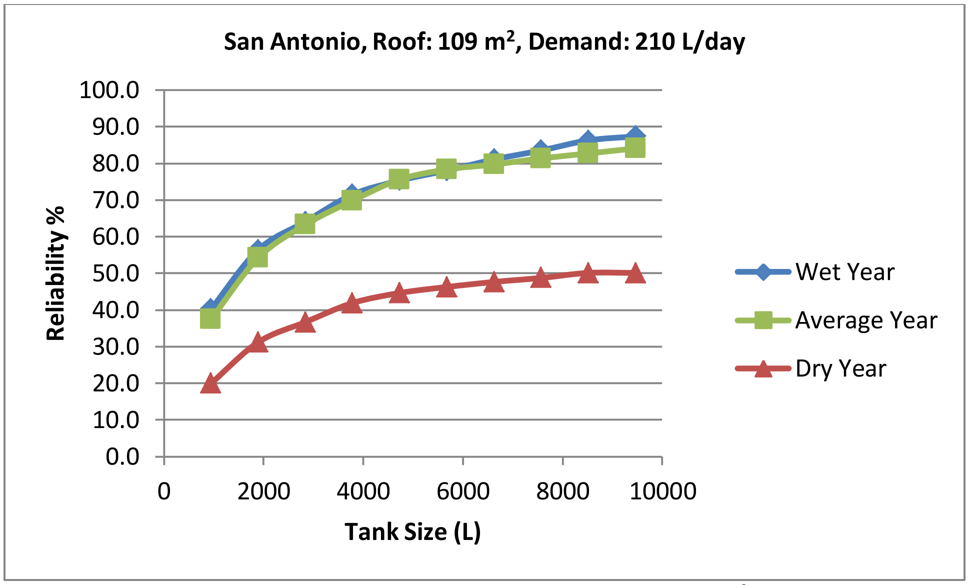

Fig. 3. Reliability Chart for San Antonio, Roof: 109 m^2, Demand: 210 L/day. Reliability curves for San Antonio under three climate conditions with a roof size of 109 m^2 (1172 ft^2) and a rainwater demand of 210 L (55.5 gal) per day.

Fig. 4 shows the reliability curves for San Antonio under a similar scenario to the previous one with the difference being a rainwater demand of 380 L (100.5 gal). In a dry year, reliability increases with tank size until the operational threshold is reached at 3785 L (1000 gal) with a reliability of 24%. Reliability continues to go up very slowly after that point until a maximum reliability of 29% is met with a tank size of 7571 L (2000 gal). The operational threshold and maximum threshold tank sizes are one size smaller than the previous dry year scenario, but the increased demand results in a lower reliability percentage. In an average year, reliability increases to 37% when the operational threshold is reached with a 3785 L (1000 gal) tank. In a wet year, reliability is nearly the same as an average year at the smallest tank size but increases steadily with larger tanks until the operational threshold is reached at 6624 L (1750 gal) with a reliability of 51%.

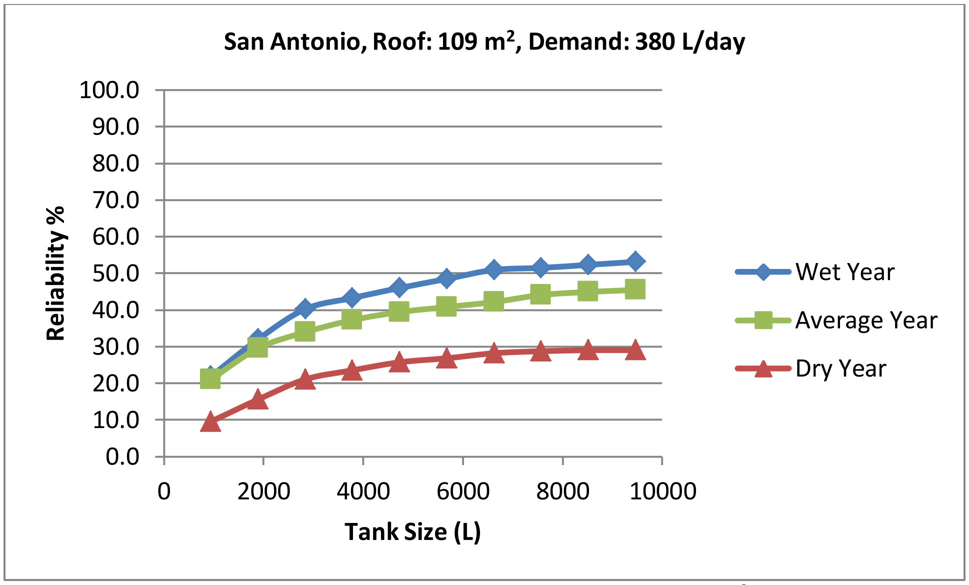

Fig. 4. Reliability Chart for San Antonio, Roof: 109 m^2, Demand: 380 L/day. Reliability curves for San Antonio under three climate conditions with a roof size of 109 m^2 (1172 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Fig. 5 shows the reliability curves for the city of San Antonio under different climate conditions (dry, average, and wet years) and different tank sizes when the roof catchment in place is 163 m^2 (1757 ft^2) and rainwater demand is 210 L (55.5 gal) per day. In a dry year, reliability increases with tank size until the operational threshold is reached at 6624 L (1750 gal) with a reliability of 59%. The maximum threshold is reached two tank sizes larger at 8517 L (2250 gal) with a reliability of 62%. An average year for San Antonio in this scenario has larger threshold tank sizes than a dry year but also displays higher reliability. In an average year, the operational threshold is reached at 7571 (2000 gal) with a reliability of 98%. The maximum threshold is reached on the next tank size of 8517 L (2250 gal) with a reliability of 99%. In a wet year, reliability follows a similar trend as the average year but unexpectedly achieves less reliability after the first two tank sizes. Reliability increases with tank size until the operational threshold is reached at 5678 L (1500 gal) with 90% reliability.

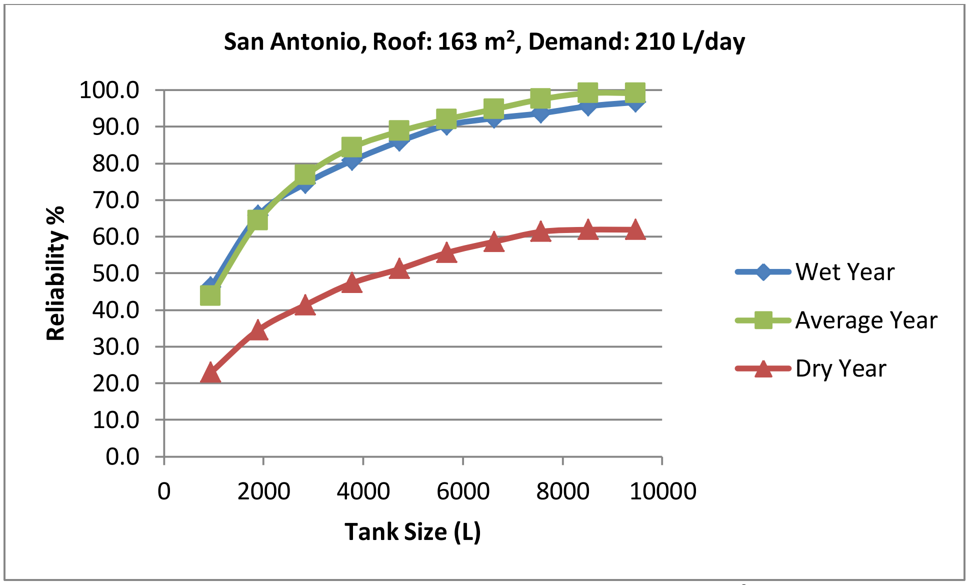

Fig. 5. Reliability Chart for San Antonio, Roof: 163 m^2, Demand: 210 L/day. Reliability curves for San Antonio under three climate conditions with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 210 L (55.5 gal) per day.

Fig. 6 shows the reliability curves for San Antonio under a similar scenario to the previous one with the difference being a rainwater demand of 380 L (100.5 gal). In a dry year, reliability increases with tank size until the operational threshold is reached at 4732 L (1250 gal) with a reliability of 34%. In an average year, reliability increases to 54% when the operational threshold is reached with a 4732 L (1250 gal) tank also. The operational threshold tank size is identical in dry and average climate conditions with only a difference in reliability. In a wet year, the curve follows closely with that of an average year but with slightly higher reliability achieved for each tank size after the first. The operational threshold is reached with a 6624 L (2000 gal) tank and 65% reliability.

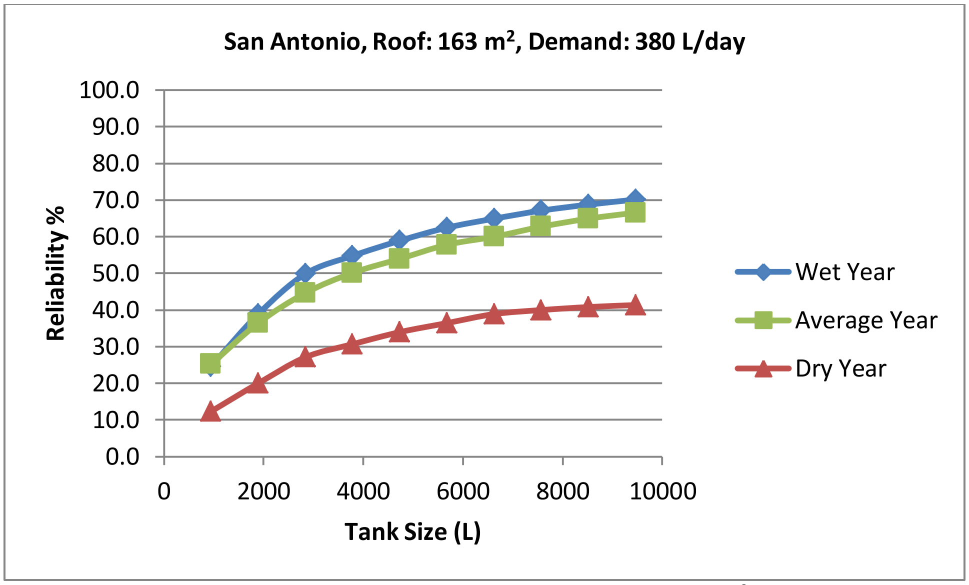

Fig. 6. Reliability Chart for San Antonio, Roof: 163 m^2, Demand: 380 L/day. Reliability curves for San Antonio under three climate conditions with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Dallas Results

Fig. 7 shows the reliability curves for the city of Dallas under different climate conditions (dry, average, and wet years) and different tank sizes when the roof catchment in place is 109 m^2 (1172 ft^2) and rainwater demand is 210 L (55.5 gal) per day. In a dry year, reliability increases with tank size until the operational threshold is reached at 5678 L (1500 gal) with a reliability of 62%. Reliability goes up very slowly for the next two tank sizes until a maximum reliability of 66% is met at 7571 L (2000 gal). A larger tank would provide no additional benefit beyond that size. In an average year, the operational threshold isn't reached until a 7571 L (2000 gal) tank is used, and reliability at this capacity would be 84%. In a wet year, reliability increases greatly over the first few tank sizes until an operational threshold is reached at 5678 L (1500 gal) with 99% reliability. The very next tank size of 6624 L (1750 gal) displays the maximum threshold with 100% reliability.

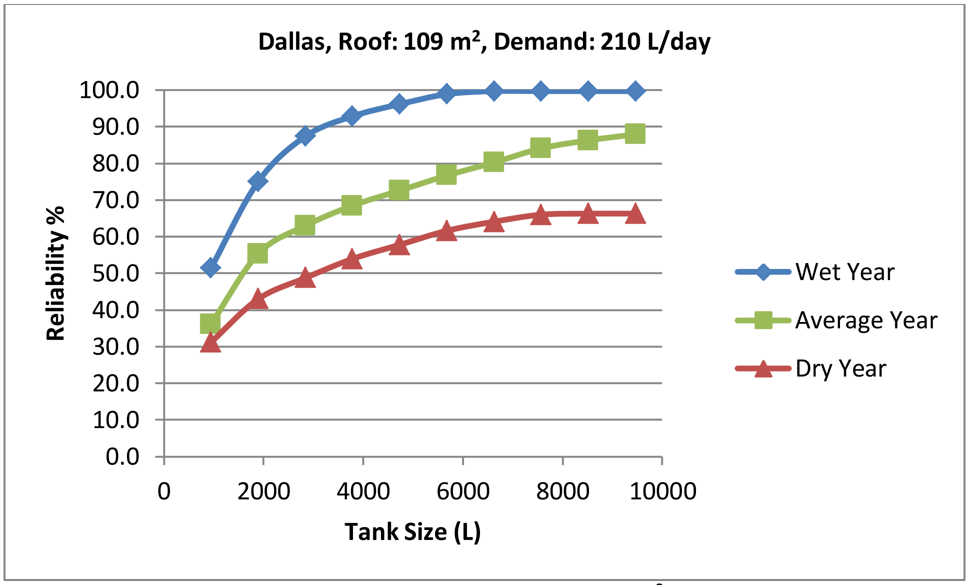

Fig. 7. Reliability Chart for Dallas, Roof: 109 m^2, Demand: 210 L/day. Reliability curves for Dallas under three climate conditions with a roof size of 109 m^2 (1172 ft^2) and a rainwater demand of 210 L (55.5 gal) per day.

Fig. 8 shows the reliability curves for Dallas under a similar scenario to the previous one with the difference being a rainwater demand of 380 L (100.5 gal). In a dry year, reliability increases with tank size gradually until the operational threshold is reached at 4732 L (1250 gal) with a reliability of 33%. In an average year, reliability increases to 48% when the operational threshold is also reached with a 4732 L (1250 gal) tank. In a wet year, reliability increases steadily until the operational threshold is reached at 5678 L (1500 gal) with a reliability of 72%. It should be noted that the maximum threshold was not reached for any of the three climate conditions in this scenario within this range of tank sizes.

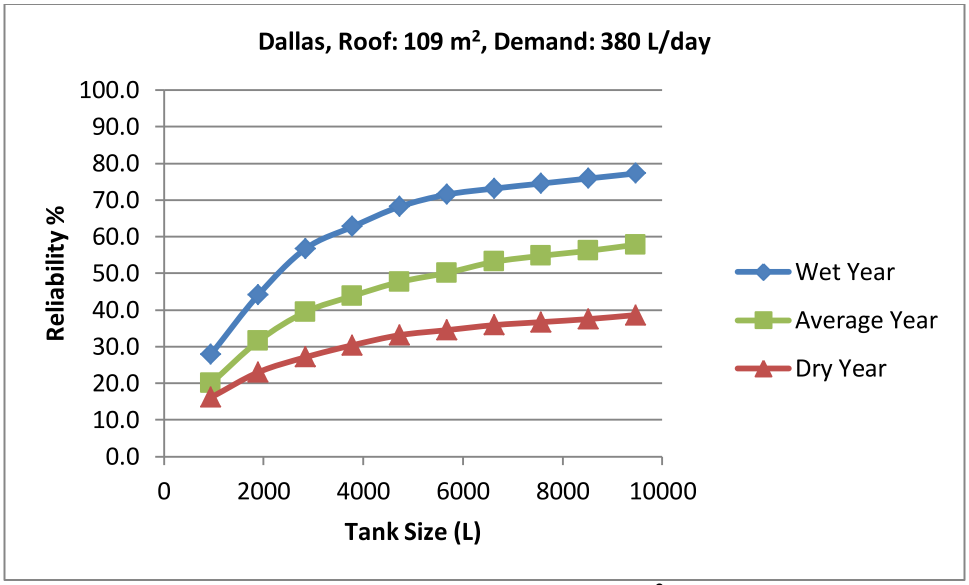

Fig. 8. Reliability Chart for Dallas, Roof: 109 m^2, Demand: 380 L/day. Reliability curves for Dallas under three climate conditions with a roof size of 109 m^2 (1172 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Fig. 9 shows the reliability curves for the city of Dallas under different climate conditions (dry, average, and wet years) and different tank sizes when the roof catchment in place is 163 m^2 (1757 ft^2) and rainwater demand is 210 L (55.5 gal) per day. In a dry year, reliability increases with tank size until the operational threshold is reached at 6624 L (2000 gal) with a reliability of 76%. The maximum threshold is reached on the very next tank size of 7571 L (2000 gal) with a reliability of 77%. In an average year, reliability increases at a slow pace after the first few tank sizes until the operational threshold is finally reached at 7571 L (2000 gal) with a 91% reliability. In a wet year, reliability increases greatly over the first three tank sizes until the operational threshold is reached at 3785 L (1000 gal) with 98% reliability. The maximum threshold is then reached on the next tank size of 4732 L (1250 gal) with a reliability of 100%.

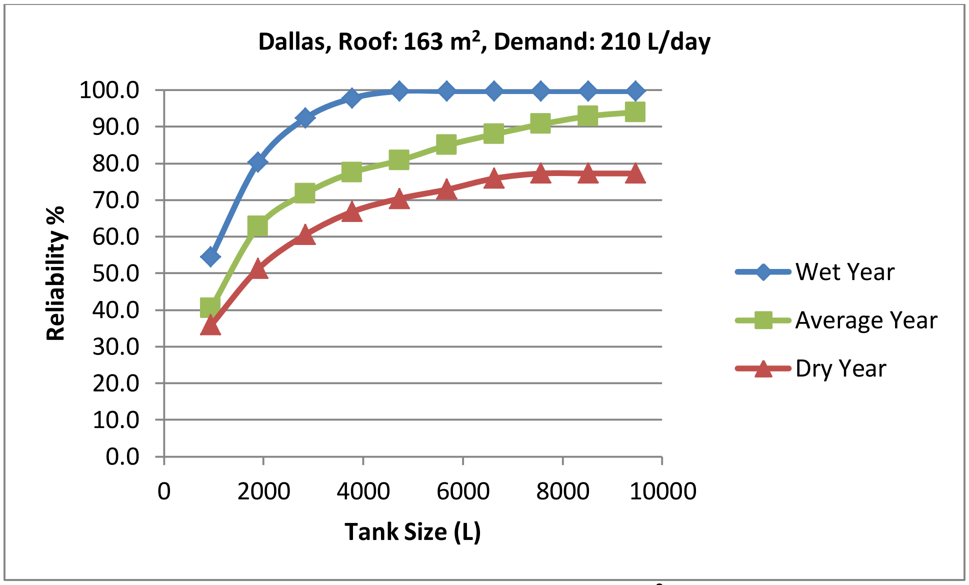

Fig. 9. Reliability Chart for Dallas, Roof: 163 m^2, Demand: 210 L/day. Reliability curves for Dallas under three climate conditions with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 210 L (55.5 gal) per day.

Fig. 10 shows the reliability curves for Dallas under a similar scenario to the previous one with the difference being a rainwater demand of 380 L (100.5 gal). In a dry year, reliability increases with tank size until the operational threshold is reached at 6624 L (1750 gal) with a reliability of 49%. In an average year, reliability increases to 61% when the operational threshold is reached with a 5678 L (1500 gal) tank. In a wet year, reliability increases greatly over the first few tank sizes until the operational threshold is reached at 6624 L (1750 gal) with a reliability of 88%. It should be noted that the maximum threshold was not reached for any of the three climate conditions in this scenario within the range of tank sizes under consideration.

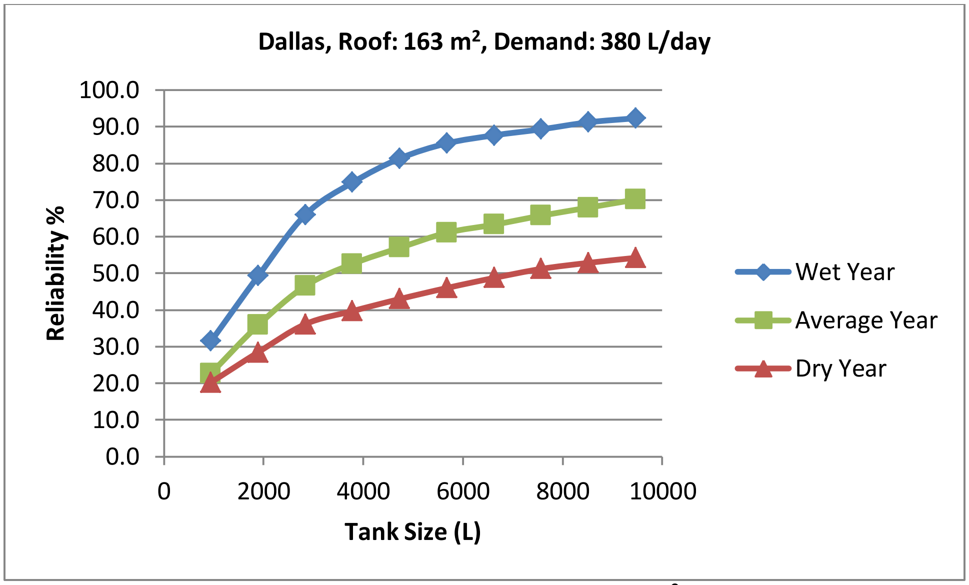

Fig. 10. Reliability Chart for Dallas, Roof: 163 m^2, Demand: 380 L/day. Reliability curves for Dallas under three climate conditions with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Houston Results

Fig. 11 shows the reliability curves for the city of Houston under different climate conditions (dry, average, and wet years) and different tank sizes when the roof catchment in place is 109 m^2 (1172 ft^2) and rainwater demand is 210 L (55.5 gal) per day. In a dry year, reliability increases with tank size until the operational threshold is reached at 5678 L (1500 gal) with a reliability of 76%. In an average year, reliability increases to 91% when the operational threshold is reached with a 5678 L (1500 gal) tank. The curves in a dry and average year have a similar shape with different percentages of reliability attained. They also share the same operational threshold tank size. In a wet year, the reliability curve looks quite different. It reaches an operational threshold very quickly with a capacity of 2839 L (750 gal) and 88% reliability. Reliability goes up only slightly for the next two tank sizes until a maximum reliability of 90% is met at 4732 L (1250 gal). A larger tank would provide no additional benefit beyond that size. It’s interesting to point out that more reliability can be attained in an average year than in a wet year. After the operational threshold is reached in an average year, reliability increases very slowly up to 96% with the largest tank size. No maximum threshold is reached under this climate condition.

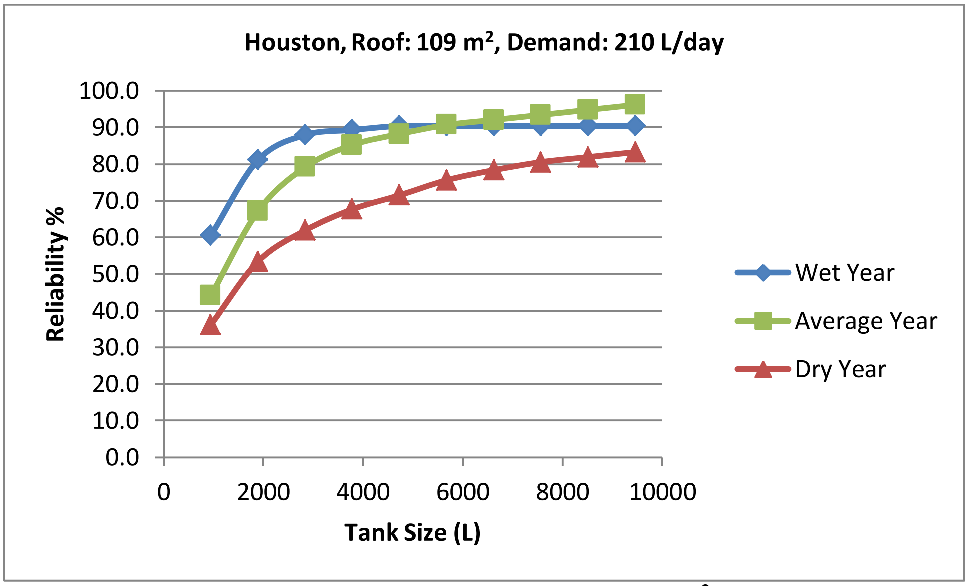

Fig. 11. Reliability Chart for Houston, Roof: 109 m^2, Demand: 210 L/day. Reliability curves for Houston under three climate conditions with a roof size of 109 m^2 (1172 ft^2) and a rainwater demand of 210 L (55.5 gal) per day.

Fig. 12 shows the reliability curves for Houston under a similar scenario to the previous one with the difference being a rainwater demand of 380 L (100.5 gal). In a dry year, reliability increases gradually with tank size until the operational threshold is reached at 7571 L (2000 gal) with a reliability of 57%. In an average year, reliability increases to 65% when the operational threshold is reached with a 5678 L (1500 gal) tank. In a wet year, reliability increases with tank size until the operational threshold is also reached at 5678 L (1500 gal) with a reliability of 76%. Reliability goes up only slightly for the next two tank sizes until a maximum reliability of 78% is met at 7571 L (2000 gal). A larger tank would provide no additional benefit beyond that size. The operational threshold tank size is the same with average and wet climate conditions in this scenario.

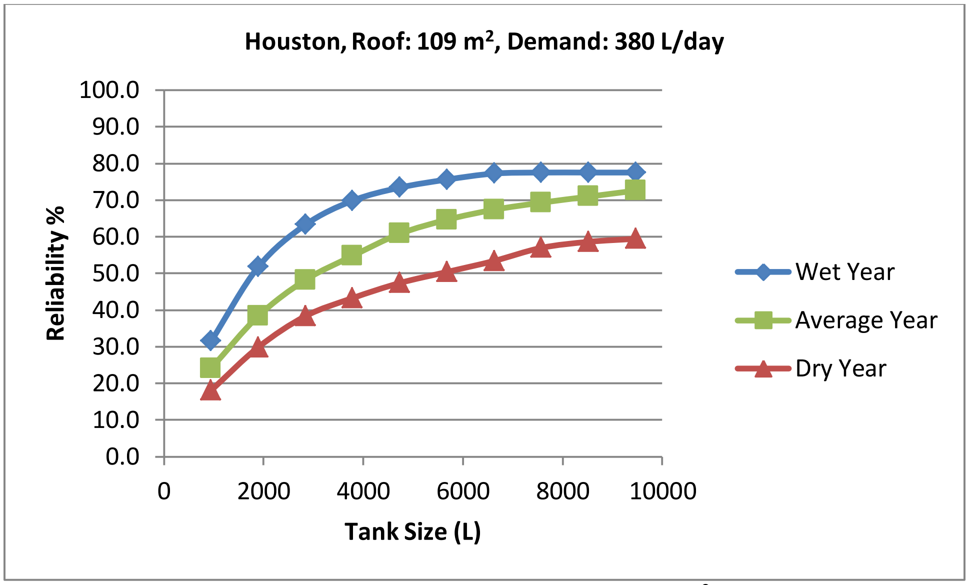

Fig. 12. Reliability Chart for Houston, Roof: 109 m^2, Demand: 380 L/day. Reliability curves for Houston under three climate conditions with a roof size of 109 m^2 (1172 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Fig. 13 shows the reliability curves for the city of Houston under different climate conditions (dry, average, and wet years) and different tank sizes when the roof catchment in place is 163 m^2 (1757 ft^2) and rainwater demand is 210 L (55.5 gal) per day. In a dry year, reliability increases greatly with tank size until the operational threshold is reached at 5678 L (1500 gal) with a reliability of 86%. In an average year, reliability increases to 95% when the operational threshold is reached with a 3785 L (1000 gal) tank. Reliability goes up a bit for the next three tank sizes before the maximum threshold is reached with a 6624 L (1750 gal) tank and reliability of 100%. In a wet year, the reliability increases greatly with tank size until an operational threshold is reached with a capacity of 2839 L (750 gal) and 93% reliability. Reliability goes up slightly for the next tank size when a maximum reliability of 95% is met at 4732 L (1250 gal). A larger tank would provide no additional benefit beyond that size. The same interesting situation that occurred in a previous Houston scenario happens again here, where more reliability can be attained in an average year than in a wet year. Of course, it takes a larger tank size in an average year to attain that level.

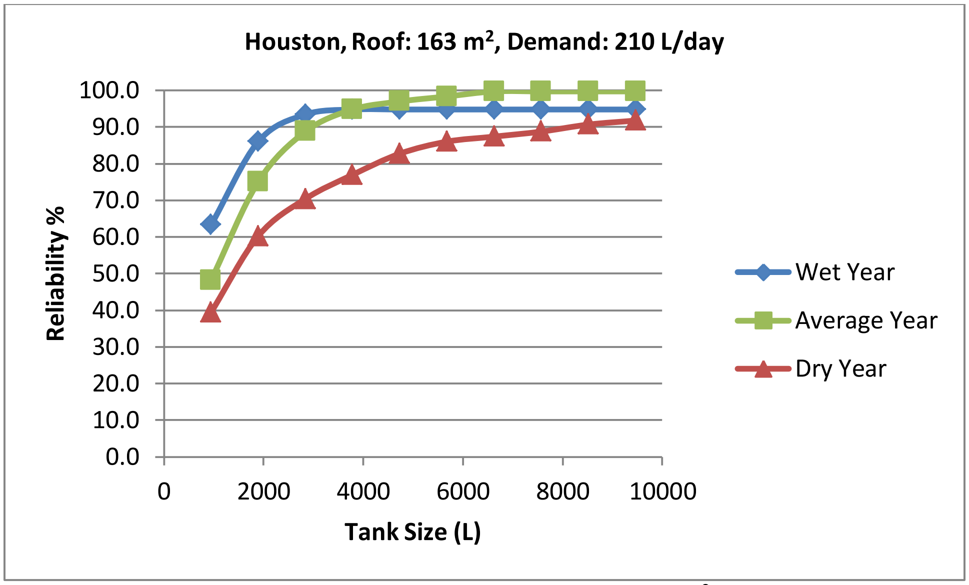

Fig. 13. Reliability Chart for Houston, Roof: 163 m^2, Demand: 210 L/day. Reliability curves for Houston under three climate conditions with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 210 L (55.5 gal) per day.

Fig. 14 shows the reliability curves for Houston under a similar scenario to the previous one with the difference being a rainwater demand of 380 L (100.5 gal). In a dry year, reliability increases with tank size until the operational threshold is reached at 6624 L (1750 gal) with a reliability of 63%. In an average year, reliability increases to 75% when the operational threshold is reached with a 5678 L (1500 gal) tank. In a wet year, reliability increases with tank size until the operational threshold is also reached at 5678 L (1500 gal) with a reliability of 86%. This tank size also happens to be the maximum threshold, so a larger tank would provide no additional benefit. It's worth mentioning that the shapes of the reliability curves in this scenario are almost identical to a previous scenario that also had a 380 L (100.5 gal) demand but a 109 m^2 (1172 ft^2) roof size. The threshold tank capacities are very similar, but the larger catchment area provides more reliability, as would be expected.

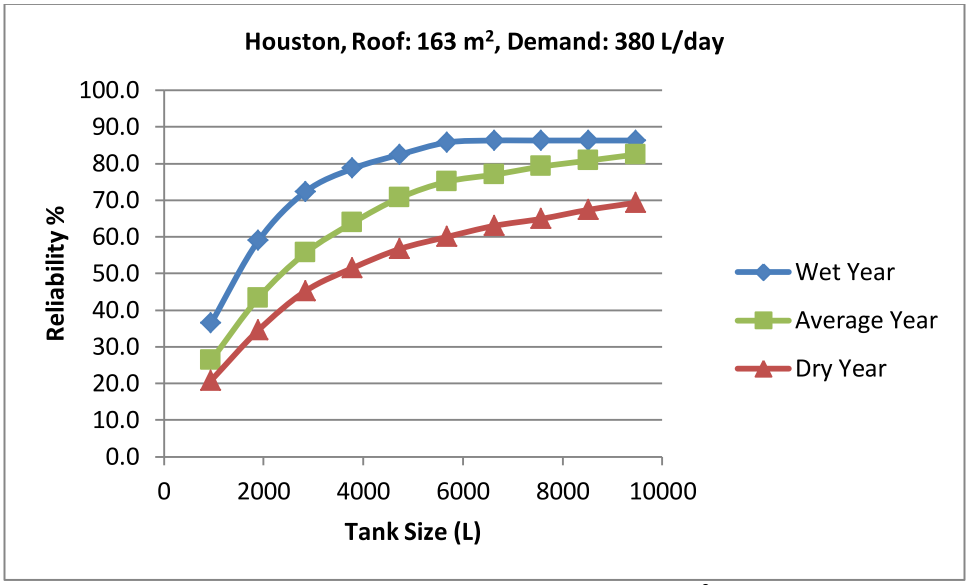

Fig. 14. Reliability Chart for Houston, Roof: 163 m^2, Demand: 380 L/day. Reliability curves for Houston under three climate conditions with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Summary of Results

Table 2 contains a summary of the operational threshold tank sizes for each scenario in all 3 cities under different climate conditions. With the information provided by these results, decision makers can be informed on what to expect from implementing a rainwater harvesting program in the cities of San Antonio, Dallas, and Houston. The different scenarios give an understanding about how a rainwater tank's reliability can be influenced by factors like roof size and demand provided for. The three climate scenarios show how the variability of precipitation from year to year might affect a tank's performance.

Table 2. Operational Threshold Tank Size Summary for 3 Climate Conditions. Summary table showing operational threshold tank sizes for each scenario in all 3 cities under different climate conditions. Operational tank sizes are displayed in liters with the reliability provided as a percent in parentheses. Roof catchment area and demand per day (dpd) also shown.

		Operational Threshold Tank Size (% Reliability)					
		Dry Year		Average Year		Wet Year	
		210 L dpd	380 L dpd	210 L dpd	380 L dpd	210 L dpd	380 L dpd
San Antonio	109 m^2 Roof	4732 L (45%)	3785 L (24%)	4732 L (76%)	3785 L (37%)	7571 L (84%)	6624 L (51%)
	163 m^2 Roof	6624 L (59%)	4732 L (34%)	7571 L (98%)	4732 L (54%)	5678 L (90%)	6624 L (65%)
Dallas	109 m^2 Roof	5678 L (62%)	4732 L (33%)	7571 L (84%)	4732 L (48%)	5678 L (99%)	5678 L (72%)
	163 m^2 Roof	6624 L (76%)	6624 L (49%)	7571 L (91%)	5678 L (61%)	3785 L (98 %)	6624 L (88%)
Houston	109 m^2 Roof	5678 L (76%)	7571 L (57%)	5678 L (91%)	5678 L (65%)	2839 L (88%)	5678 L (76%)
	163 m^2 Roof	5678 L (86%)	6624 L (63%)	3785 L (95%)	5678 L (75%)	2839 L (93%)	5678 L (86%)

<u>Rainfall Variability</u>

For the most part, the results in this study were as expected. It's logical to assume that a wet year would provide more reliability than an average year because more rainfall would keep a tank full. This was true for the majority of the scenarios under consideration. All four of the Dallas scenarios looked normal in this respect. However, San Antonio and Houston both had some unusual reliability curves in a couple of scenarios.

In the city of San Antonio, when the roof catchment in place is 109 m^2 (1172 ft^2) and rainwater demand is 210 L (55.5 gal) per day, the reliability curves for an average and wet year overlap almost exactly. The reliability in a wet year is never more than 3% higher than an average year for any tank size and happens to actually be slightly lower for a 4732 L (1250 gal) tank size. Reliability is identical at 78% in an average and wet year for the tank size 5678 L (1500 gal). A similar situation occurs in another San Antonio scenario when the roof catchment in place is 163 m^2 (1757 ft^2) and rainwater demand is 210 L (55.5 gal) per day. The reliability curves again almost overlap in average and wet years, never being more than 4% apart for any tank size. The reliability in an average year overtakes that in a wet year with a 2839 L (750 gal) tank and remains higher for all subsequent tank sizes. The reason for these phenomena becomes apparent after referring to the water balance calculations. The accumulated annual overflow is very high in a wet year in both scenarios when compared to an average year. This must be due to rainwater demand being so low at 210 L (55.5 gal) per day and not depleting the water reserves enough to free up storage space and catch the infrequent but heavy rains. It's important to remember that being classified as a wet year has nothing to do with the distribution of rain throughout that year. If the majority of rain comes in too few events, the reliability of a rainwater tank can certainly be negatively affected.

In the city of Houston, when the roof catchment in place is 109 m^2 (1172 ft^2) and rainwater demand is 210 L (55.5 gal) per day, the maximum achievable reliability in a wet year is 90% reliability with a 4732 L (1250gal) tank, while reliability in an average year surpasses that mark with a 5678 L (1500 gal) tank and continues to go up slowly until 96% reliability is reached with the largest tank size. A similar situation occurs in another Houston scenario when the roof catchment in place is 163 m^2 (1757 ft^2) and rainwater demand is 210 L (55.5 gal) per day. The maximum achievable reliability in a wet year is 95% and is again reached with a small tank size of 3785 L (1000 gal). Reliability in an average year is also 95% with a 3785 L (1000 gal) tank but continues to increase slightly over the next three tank sizes until 100% reliability is met with a 6624 L (1750 gal) tank size. The reason that an average year was able to outperform a wet year in these scenarios was again due to the distribution of rain during the year. Referring to the water balance calculations, there is a period of time during the representative wet year

(1976) that rain didn't fall for 26 days. This means that the rainwater tank was empty for a long stretch which puts an upward limit on the reliability that can be attained. Reliability is a percentage of days during the year that rainwater demand can be satisfied by the tank. Therefore, 347 days of rainwater use results in a reliability of 95% and 18 days of an empty tank when municipal water must be used.

<u>Additional Simulations</u>

In light of the consequences that rainfall variability can have on the performance of rainwater tanks, a few more water balance simulations were run to give this study more examples to draw from. Focus was placed on average rainfall years instead of dry and wet years because they are more likely to occur statistically, assuming a normal distribution of total annual rainfall. An average year has already been investigated for San Antonio, Dallas, and Houston under a few different scenarios and is represented by the 50^{th} percentile of total annual rainfall for all the years that rainfall data is available at an airport location within each city. Four more average years were selected for each city by simply including the two closest years on opposite sides of the median. These years are slightly wetter or drier than the original average representative but will provide additional examples of the reliability that can be expected under normal conditions. The 5 average years are referred to as A through E, descending from the driest to the wettest. The median will therefore be designated as Average C. Table 3 shows the year selection and the amount of rainfall observed in 5 average years for each city. The operational threshold tank sizes from each of these 5 years can be averaged together and compared to the list of 10 tank sizes. The nearest tank capacity will be selected as the average optimal tank size. Furthermore, a mean and standard deviation can be calculated from the reliability provided by the tank size in these years. To simplify this additional analysis, only 1 of the initial 4 scenarios was explored. The larger roof catchment area of 163 m^2 (1757 ft^2) was selected because it is reflects the average size for homes in Texas. The greater demand of 380 L (100.5 gal) was chosen because of its dual representation for indoor use (toilet flushing and laundry) as well as irrigation.

Table 3. Five Average Years Selection. Selection of 5 average years for total annual rainfall with amount listed in millimeters and inches. Average C is the median for total annual rainfall.

	San Antonio			Dallas			Houston		
	Rain (mm)	Rain (in.)	Year	Rain (mm)	Rain (in.)	Year	Rain (mm)	Rain (in.)	Year
Average A	753.3	29.66	1977	904.8	35.62	1995	1179.0	46.42	1982
Average B	756.9	29.80	1960	919.6	36.20	1968	1194.3	47.02	2010
Average C	772.4	30.41	1968	938.6	36.95	2002	1207.7	47.55	1985
Average D	780.1	30.71	2009	952.3	37.49	1964	1247.2	49.10	1975
Average E	798.5	31.44	1969	960.1	37.80	1976	1263.3	49.74	1984

Fig. 15 shows the reliability curves for the city of San Antonio under different tank sizes in 5 average years when the roof catchment in place is 163 m^2 (1757 ft^2) and rainwater demand is 380 L (100.5 gal) per day. In the Average A year, reliability increases with tank size until the operational threshold is reached at 6624 L (1750 gal) with a reliability of 48%. In the Average B year, reliability increases to 52% when the operational threshold is reached with the same tank size. In the Average C year, reliability increases with tank size until the operational threshold is also reached at 7571 L (2000 gal) with a reliability of 63%. In the Average D year, reliability increases to 45% when the operational threshold is reached with a tank size of 4732 L (1250 gal). In the Average E year, reliability increases with tank size until the operational threshold is reached at 6624 L (1750 gal) with a reliability 67%. A maximum threshold was not reached in any of the average years in this scenario. It's interesting to note that that the operational threshold was the same in 3 of the 5 years with a 6624 L (1750 gal) tank. The reliability achieved at that capacity varied quite a bit, as it did for all the years. The wettest of these years expectedly displayed the highest reliability, but the second wettest displayed the lowest reliability. The average operational tank capacity for San Antonio is 6435 L (1700 gal) which makes the average optimal tank size 6624 L (1750 gal). Mean reliability provided would be 55.0% with a standard deviation of 8.1%.

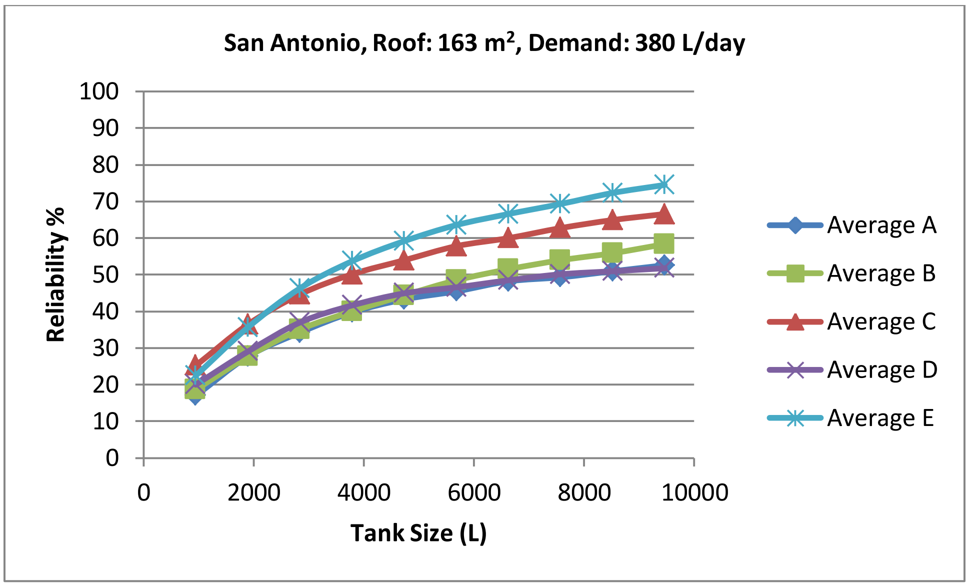

Fig. 15. Reliability Chart for 5 average years in San Antonio. Reliability curves for San Antonio in five average years with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Fig. 16 shows the reliability curves for the city of Dallas under different tank sizes in 5 average years when the roof catchment in place is 163 m^2 (1757 ft^2) and rainwater demand is 210 L (55.5 gal) per day. In the Average A year, reliability increases with tank size until the operational threshold is reached at 5678 L (1500 gal) with a reliability of 62%. In the Average B year, the operational threshold is never reached and reliability increases to 87% with the largest tank size of 9464 L (2500 gal). In the Average C year, reliability increases with tank size until the operational threshold is also reached at 5678 L (1500 gal) with a reliability of 61%. In the Average D year, reliability increases to 75% on the largest tank size without reaching the operational threshold either. In the Average E year, reliability increases with tank size until the operational threshold is reached at 6624 L (1750 gal) with a reliability 72%. A maximum threshold was not reached in any of the average years in this scenario. The operational threshold was the same in two of these average years with the reliability achieved being almost identical. The two years that an operational threshold wasn't reached had small increases in reliability for the largest tank, but the established criteria of 2% between tanks never occurred. Nevertheless, a 9464 L (2500 gal) capacity will serve as the operational tank size for these two years. The average operational tank capacity for Dallas is 7382 L (1950 gal) which makes the average optimal tank size 7571 L (2000 gal). Mean reliability provided would be 71.0% with a standard deviation of 6.2%.

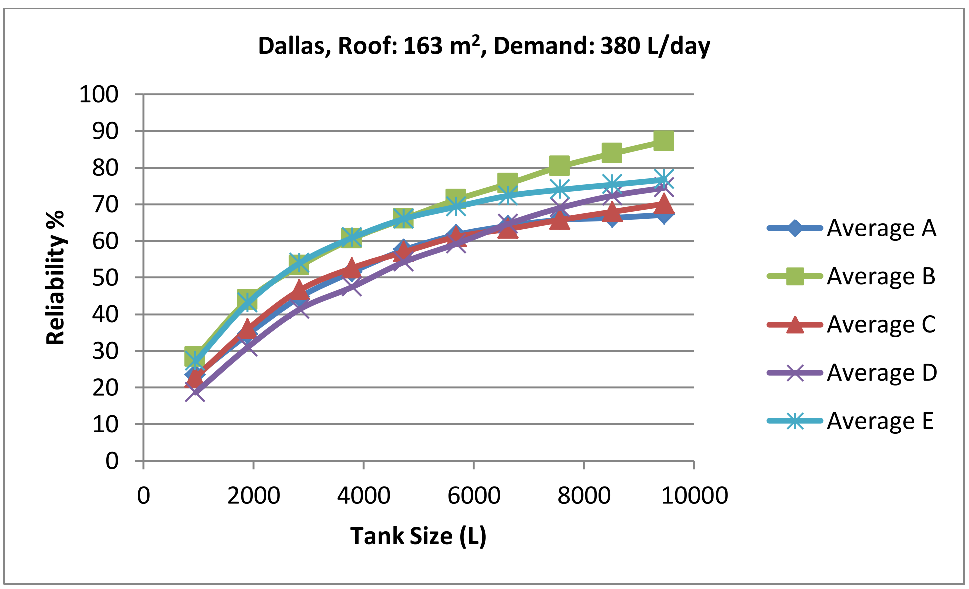

Fig. 16. Reliability Chart for 5 average years in Dallas. Reliability curves for Dallas in five average years with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Fig. 17 shows the reliability curves for the city of Houston under different tank sizes in 5 average years when the roof catchment in place is 163 m^2 (1757 ft^2) and rainwater demand is 380 L (100.5 gal) per day. In the Average A year, reliability increases with tank size until the operational threshold is reached at 8517 L (2250 gal) with a reliability of 83%. In the Average B year, reliability increases to 74% on the largest tank size without reaching the operational threshold. In the Average C year, reliability increases with tank size until the operational threshold is also reached at 6624 L (1750 gal) with a reliability of 77%. In the Average D year, reliability increases to 78% when the operational threshold is reached with a tank size of 6624 L (1750 gal) as well. In the Average E year, reliability increases with tank size until the operational threshold is reached at 7571 L (2000 gal) with a reliability 79%. A maximum threshold was not reached in any of the average years in this scenario. Houston showed the most similarity among average years when compared to the other two cities. The operational threshold was the same in 2 of the 5 years with a 6624 L (1750 gal) tank and the reliability achieved was only different by 1%. Another year's operational threshold was one tank larger with a slight increase in reliability achieved. Looking at the chart, the reliability curves overlap almost perfectly with the one exception being the Average B year which didn't reach an operational threshold. A 9464 L (2500 gal) capacity will serve as the operational tank size for this year. The average operational tank capacity for Houston is 7760 L (2050 gal) which makes the average optimal tank size 7571 L (2000 gal). Mean reliability provided would be 77.2% with a standard deviation of 5.2%.

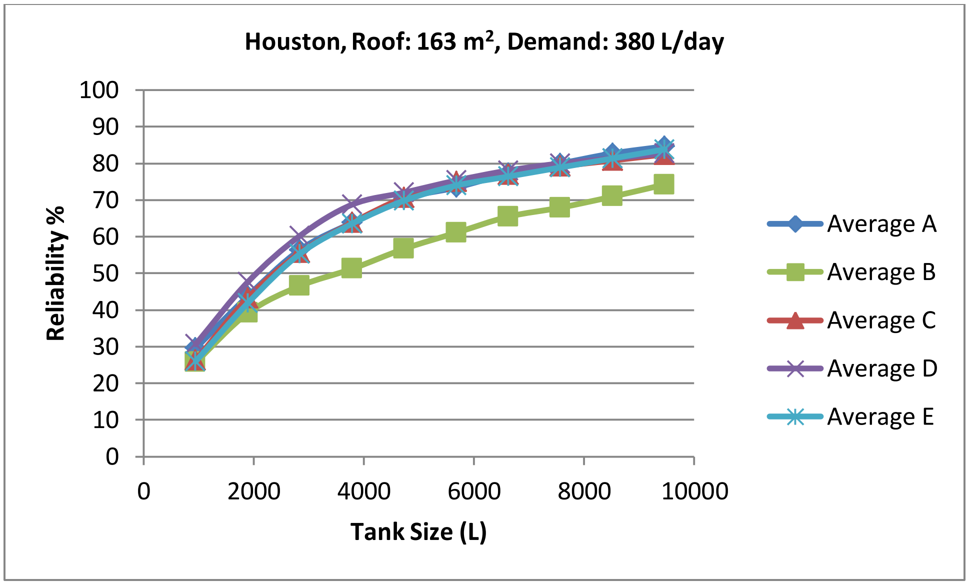

Fig. 17. Reliability Chart for 5 average years in Houston. Reliability curves for Houston in five average years with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Table 4 contains a summary of the operational threshold tank sizes in 5 average years for each city when the roof size is 163 m^2 (1757 ft^2) and the rainwater demand is 380 L (100.5 gal) per day. This information shows how reliability can fluctuate in average years due to rainfall variability. The operational threshold tank sizes may also differ by several tank size increments, as can be seen for Dallas.

Table 4. Operational Threshold Tank Size Summary for 5 Average Year. Summary table showing operational threshold tank sizes for all 3 cities in five average years with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 380 L (100.5 gal) per day. Operational tank sizes are displayed in liters with the reliability provided as a percent in parentheses.

	Operational Threshold Tank Size (% Reliability)				
	Average A	Average B	Average C	Average D	Average E
San Antonio	6624 L (48%)	6624 L (52%)	7571 L (63%)	4732 L (45%)	6624 L (67%)
Dallas	5678 L (62%)	9464 L (87%)	5678 L (61%)	9464 L (75%)	6624 L (72%)
Houston	8517 L (83%)	9464 L (74%)	6624 L (77%)	6624 L (78%)	7571 L (79 %)

CHAPTER V

DISCUSSION

Decision makers at the state or local level can use the information provided by this study to implement cost-effective rainwater collection systems in residential areas to address water shortage issues in the 3 cities and surrounding areas that share similar rainfall patterns. Of course, any homeowner that is interested in installing a system at their house could benefit from the information, even without state or local support. This study introduced an operational threshold tank size to consider along with the maximum threshold tank size, and it is defined as the point where the following tank size increase only provides an additional 2% or less of reliability. The idea here is to determine optimal tank sizes to increase the effectiveness of rainwater harvesting systems. It would depend on the discretion of the individual to decide if the small amount of added reliability supplied by the maximum threshold tank is worth the added financial cost and need for space. The results could also serve as a reference point for any future analysis of rainwater harvesting in other parts of the state with different rainfall characteristics.

Payback Period Analysis

A payback period analysis was conducted to estimate the amount of time it would take for a homeowner to recover the financial cost of installing a rainwater harvesting tank. The analysis is based on current water rates made available on the website of each city's public water system. Water meter charges and other additional fees were included to provide the best representation of a monthly bill. However, wastewater rates were not included even though they are generally derived from water use on a customer's account.

Water usage was determined by referring to the AWWA (1999) study previously cited. Average daily indoor use for 3 people is 787 L (207.9 gal) and was combined with the daily outdoor use of 382 L (100.8 gal), which results in 35057 L (9261 gal) total use for the month. A 5/8 inch water meter was assumed since it is the most common size installed in single family residences. No rainwater catchment rebates are offered by the public water systems of the three cities, otherwise they would be factored into the payback period. The scenario used to estimate monthly water savings for all cities was with a roof catchment size of 163 m^2 (1757 ft^2) and rainwater demand of 380 L (100.5 gal) per day. An average optimal tank size and the mean reliability provided have already been determined under this scenario for each city. The cost of tank sizes was obtained by referring to the prices of plastic rainwater tanks available for sale by Tank Depot (2014). Since tank dimensions can vary substantially, the importance of space was assumed. The lowest price of the tank with the smallest footprint at a given capacity was selected.

It's important to remember that this payback period analysis only covers the purchase of a tank and does not include some of the other costs associated with harvesting rainwater such as plumbing, gutters, or pumps. Retrofitting the indoor plumbing of existing homes could be especially expensive. Houses with pier and beam foundations are more manageable than ones with slab foundations in this respect due to easier access to pipes. The cost of including additional plumbing for a rainwater system in newly constructed homes should be negligible however. Water pressure can either be provided by a pump or by elevating the storage tank above the plumbing system. Elevated water storage allows gravity to do the work of a pump but is probably not feasible in supplying water to the upper level of two-story homes. These additional expenses mostly apply if rainwater is expected to meet the indoor demands of the household. As mentioned previously, the demand scenario of 380 L (100.5 gal) per day can represent either outdoor use or the combined use of toilet flushing and laundry. Collecting rainwater for irrigation purposes might be the simplest and most affordable application. Due to these many variables that can be associated with the cost of installing a rainwater harvesting system, this payback period analysis will only cover the price of the tank itself.

The monthly water bill for San Antonio normally costs $37.29 USD (San Antonio Water System, 2014) when usage is 35057 L (9261 gal). If the optimal tank size of 6624 L (1750 gal) is installed, 6270 L (1656 gal) of rainwater is provided each month for toilet flushing and laundry. With 55% reliability for this demand met, the adjusted monthly use would be 28787 L (7605 gal) at a cost of $31.49 USD. The savings would therefore be $5.80 USD, and it would take 11.2 years for a homeowner to pay off a tank at a cost of $779 USD.

The monthly water bill for Dallas normally costs $37.29 USD (City of Dallas, 2014) when usage is 35057 L (9261 gal). If the optimal tank size of 7571 L (2000 gal) is installed, 8094 L (2138 gal) of rainwater is provided each month for toilet flushing and laundry. With 71% reliability for this demand met, the adjusted monthly use would be 26963 L (7123 gal) at a cost of $26.93 USD. The savings would therefore be $7.54 USD, and it would take 11.0 years for a homeowner to pay off a tank at a cost of $999 USD.

The monthly water bill for Houston normally costs $49.50 USD (City of Houston, 2014) when usage is 35057 L (9261 gal). If the optimal tank size of 7571 L (2000 gal) is installed, 8778 L (2319 gal) of rainwater is provided each month for toilet flushing and laundry. With 77% reliability for this demand met, the adjusted monthly use would be 26279 L (6942 gal) at a cost of $35.34 USD. The savings would therefore be $14.16 USD, and it would take 5.9 years for a homeowner to pay off a tank at a cost of $999 USD.

The payback periods for San Antonio and Dallas are both over 10 years which certainly seems like a long time for financial benefits to be realized from installation of a rainwater tank. Houston's payback period seems more manageable coming in at just under 6 years but could also be a deterrent for an otherwise interested homeowner. It needs to be emphasized, however, that none of these 3 cities offer rebates to make rainwater harvesting more affordable like some other municipalities in Texas do. For example, the City of Austin (2014) provides a rebate of $0.50 USD per gallon (non-pressurized) and $1.00 USD per gallon (pressurized) to its customers towards the cost of new rainwater catchment systems, not to exceed 50% of the project costs or $5000 USD. This type of incentive effectively cuts the above payback periods in half. Many small towns provide similar rebates but have lower limits on the maximum amount paid toward the project.

It could be in the best interest of future growth for a city to incentivize residential rainwater harvesting, as it will relieve some of the pressure of developing water resources for a booming population in the middle of a long drought. The more people that use rainwater, the less a city will have to plan and provide for. At present, each of these cities do encourage rainwater harvesting through community education and information posted on their websites. However, a rainwater harvesting program that provides financial incentive would promote wider implementation by reducing the amount of time for a payback period. Aside from rebates, decision makers could also offer no-interest loans on tank installation and property tax exemptions.

At the state level, decision makers have already attempted to tackle some of the water issues plaguing Texas by creating SWIFT to fund water projects. Unfortunately, the only projects to receive funding are those outlined in the 2012 State Water Plan and include many large-scale water development strategies like reservoir construction, desalination, and wastewater re-use. No assistance towards rainwater harvesting projects was included, which is unfortunate because it can be demonstrated as a viable option. With a huge amount of money being contributed to acquiring water resources, it may be in the state's interest to direct some of that funding towards public water systems who are implementing domestic rainwater harvesting programs. Financial support for rainwater harvesting will shorten payback periods and encourage the installation of tanks throughout the state, which could help in alleviating water concerns and safeguarding projections of future growth.

Environmental Impacts

Along with the water resource capabilities of rainwater harvesting, environmental implications should also be considered. The act of collecting rainwater from rooftops and storing it for future use is an interference of the natural process of the water cycle. During a precipitation event, rainfall produces soil moisture, groundwater recharge, subsurface flow and runoff. The amount of water that is contributed to these mechanisms obviously has to do with the duration and intensity of the rain, but rainwater harvesting intercepts some portion that would normally be applied directly to the environment. It's logical to assume that the biggest impact would occur in times of drought when the soil and terrestrial life are starved for moisture. Withholding any amount of rainwater in these situations would likely have the biggest consequences. Whenever a lot of rain is falling, on the other hand, the subsurface eventually becomes inundated and additional precipitation is carried downstream as runoff. During these events, the amount of rainwater collected in tanks would be disproportionately small compared to the water being received by the land. Once the capacity of a collection system has been met, further rainfall upon a roof will overflow into the environment. The impacts on either side of the dry/wet spectrum would depend on what scale rainwater harvesting is implemented and the capacities of storage tanks in place.

To be fair, the rain that is captured by a collection system may not be lost to streamflow but merely delayed and will take a different path to a nearby stream. With the application of rainwater for toilet flushing and laundry in urban areas, the used water will be carried away by a municipal sewer to a nearby wastewater treatment plant. There it will be treated with other wastewater and deposited as effluent into a receiving stream. It's possible that the usual paths for runoff and subsurface flows will carry less water from areas that practice rainwater harvesting though. For houses that aren't connected to a municipal sewer, used rainwater will be carried to a septic tank before eventually flowing into a septic drain field. This water will either percolate into the ground or be released into the atmosphere as transpiration by overlying plants. In the case of using harvested rainwater for irrigation, a similar fate will befall the water. A rainwater tank will contain a portion of precipitation to be applied to household vegetation during dry periods. Most of this water will end up as evapotranspiration which is beneficial to the plants cared for at home, but will not contribute to streamflow.

A hydrologic impact assessment of rainwater harvesting in the Texas Hill Country was included in a report by Venhuizen et al. (2013) completed on behalf of the Texas Water Development Board. The goal was to determine how the practice of capturing rainfall from rooftops instead of allowing it to runoff would affect the amount of overland flow, resulting in hydrologic degradation and reduced water available for instream flow. Their assessment involves two analyses at different levels. One was conducted on the roofprint area only and compared the amount of tank overflow expected from a basic rainwater system model with the amount of runoff produced on an undeveloped site of the same size. The other analysis used complex watershed modeling to explore the effects of a full-size development on hydrologic conditions when rainwater harvesting is employed on a wide scale. The native site was compared with a developed site that captured rainwater as well as a traditional development that did not. The findings of this assessment indicate that residential rainwater harvesting implemented by entire developments across a watershed would not result in a net loss of runoff, unless the native site is very hydrologically degraded, which is another way of saying that the landscape has been altered from its natural state. The case is even made, that widespread rainwater harvesting could improve a watershed that is in this degraded condition by preventing flash hydrology and withholding water that will be discharged by wastewater treatment facilities at a more uniform rate. The consequence of impervious cover that comes along with urban development is extreme runoff that can further degrade the hydrology of a watershed. Rainwater harvesting can mitigate this problem by releasing water steadily to maintain baseflow within a stream instead of allowing quickflow that can damage the environment. Indeed, disrupting the water cycle by collecting rainfall for future use might restore normal conditions to a watershed after a previous disruption from the placement of impervious cover.

Flood Control

The additional benefit of rainwater harvesting to prevent flooding is another factor that should be considered when discussing environmental impacts. The variability of rainfall in Texas usually leads to feast or famine scenarios regarding water. Even though the state is currently experiencing a drought, wet climate conditions will eventually return and drop large amounts of rain on the landscape. The ability to impound some volume of this rainfall in residential collection systems could lower flood waters, protecting life and personal property. This would only be possible if rainwater harvesting was implemented on a wide scale within a watershed.

To provide an example, a rough calculation was made for San Antonio by imagining that 1 in 20 households in the city maintained a rainwater harvesting capacity of 6624 L (1750 gal) which is the average optimal tank size based on this study. This is a conservative estimate of participation in rainwater collection, and San Antonio was chosen because it has the driest climate of the 3 Texas cities investigated and therefore might be most likely to implement a large program. The total number of 2008-2012 households in San Antonio was 471,742 (U.S. Census, 2014). If we assume that 5% of these houses have rainwater tanks that are half full, then 78,000 kiloliters (20.6 million gal) of rain could be captured citywide from a heavy precipitation event. This volume was compared to the peak flow during the October 1998 flood at a USGS gaging station called San Antonio River near Elmendorf (U.S. Geological Survey, 2014). The drainage basin was chosen due to its large area of 4514 km^2 (1743 mi^2) and because it is immediately downstream of the San Antonio city limits. The peak flow at this station was measured as 2124 kiloliters/s (0.561 million gal/s) which in that moment was only 2.72% of the total volume of captured rainwater. Despite this crude estimate, it would appear that rainwater harvesting might significantly decrease the amount of peak flow during a flood event. A more conclusive assessment would need to be provided by watershed modeling however.

A paper published by Steffen et al. (2013) highlights the performance of rainwater harvesting systems in the United States for their ability to reduce stormwater runoff from a residential drainage catchment. Seven regions across the country with varying climates were analyzed and the findings showed that up to 20% of stormwater could be reduced in semi-arid regions if a rainwater harvesting device was in place. Results were less favorable in regions that received more average annual rainfall, but performance in all locations was dependent on tank size as well as demand. If water usage was not enough to deplete water reserves on a regular basis, then the potential for rainwater capture was lower. Their paper provides evidence that rainwater tanks can be employed for the benefits of flood protection in addition to a source of water. From an urban planning perspective, the more rainwater harvesting capacity that is installed in residential areas, the less stormwater control structures will need to be built in a city.

CHAPTER VI

CONCLUSIONS

This study presents findings on the amount of water that can be expected from harvesting rainwater in 3 Texas cities. Different climate conditions and scenarios are investigated and optimal tank sizes are apparent in many situations by referring to the reliability curves produced. Understanding reliability is important because it informs decision makers and households of how many days throughout the year a rainwater collection system can satisfy water demand. Operational thresholds allow property owners to achieve most of a system's reliability while minimizing installation costs. If more reliability is desired, larger tank sizes can be chosen up to the maximum threshold. In addition to optimizing rainwater collection design in this way, a tank's reliability could be increased through water conservation methods. The demand scenarios explored here were based on nationwide averages of water use in a 1999 AWWA report and doesn't account for efficient fixtures and strategies to reduce water consumption within the household.

Application of this study's results to other locations in Texas may be accomplished by comparing the average annual rainfall of San Antonio's Bexar County, Dallas County, and Houston's Harris County with another county in question. Average annual precipitation in the state follows the general pattern of becoming more abundant as you move from west to east. Maps that illustrate this phenomenon are available from a number of sources. One of them generated by the PRISM Climate Group of Oregon State University (2014) can be found in Figure 18. The 3 cities investigated in this study can actually be seen easily on the map by looking for the 3 odd shaped polygons in their resident counties. San Antonio lies right in the middle of an isopleth dividing rainfall amounts of 26-30 in and 30-34 in which corresponds well with our study average of 30.4 in (77.1 cm). Dallas lies within the rainfall category of 34-38 in. The average for Dallas was 36.1 in (91.8 cm). Houston also lies along an isopleth dividing rainfall amounts of 46-50 in and 50-54 in. This corresponds well with the average of 50.4 in (127.9 cm). Any areas in Texas that fall within one of these categories should expect to have similar rainfall characteristics to the corresponding locations. The counties that lie along isopleths that run through San Antonio and Houston may benefit from more precise comparisons due to the higher resolution that a line embodies. It should be noted that these associations would assume that the distribution of rainfall during the year is similar within each category which might not be the case.

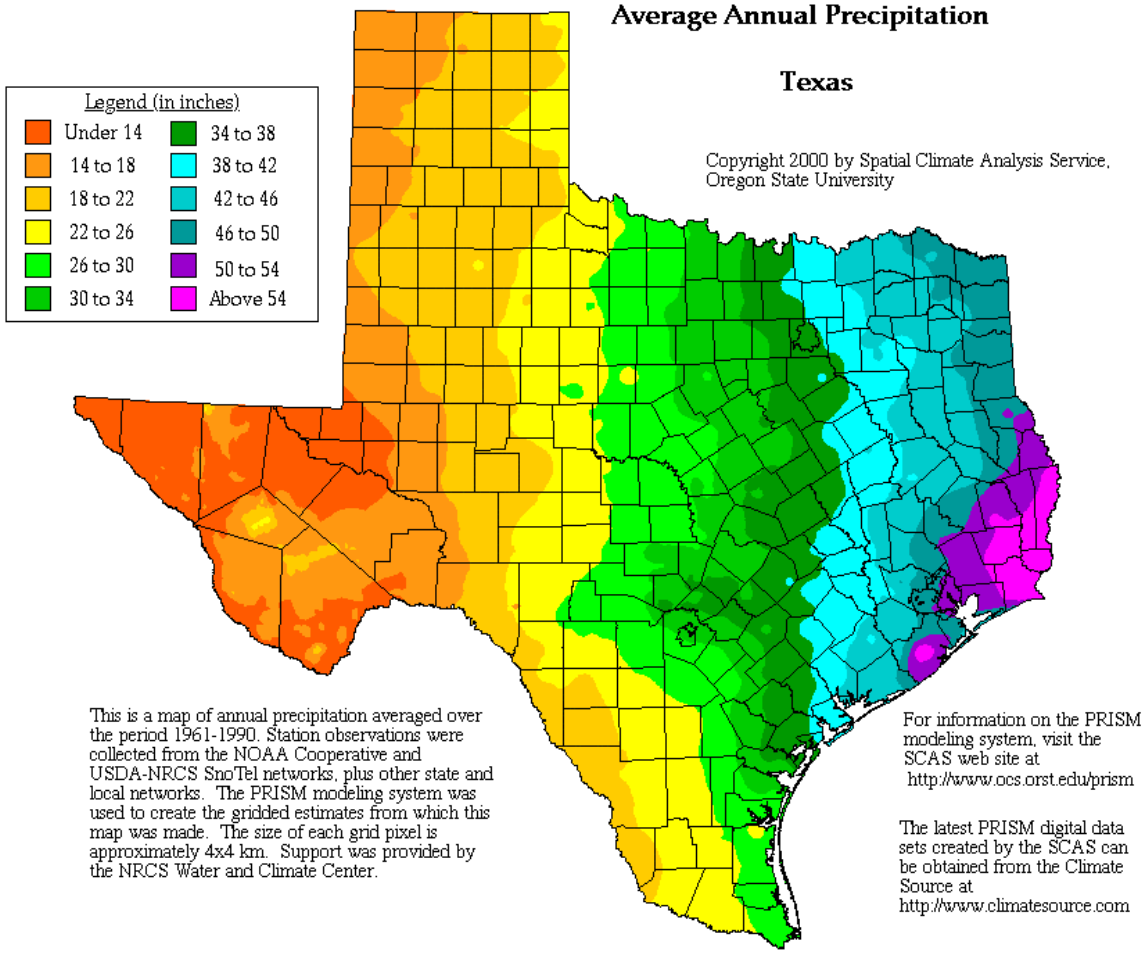

Fig. 18. Average Annual Precipitation for Texas Estimated by PRISM Modeling

The methods used in this study could also be repeated for any municipality or household that desired more accurate results reflecting their unique situation. The variables used in the daily water balance model simulation are: roof area, runoff coefficient, volume of storage tank, and water demand. Combined with the rainfall data of a local gaging station, these inputs could be estimated directly which would provide the most representative performance analysis of rainwater tank sizes for a particular area.

APPENDIX

The following list of tables contains the detailed results produced by all the daily water balance simulations that were run for this study. Reliability charts were created using these data. The reliability percentages are displayed with more precision here and can be read to the nearest tenth. Multiplying a percentage by 365 days will give the number of days in a year that a rainwater tank size will provide enough water to satisfy demand under a given scenario.

A1. Reliability for San Antonio under three climate conditions with a roof size of 109 m^2 (1172 ft^2) and a rainwater demand of 210 L (55.5 gal) per day.

Tank Size (L)	Tank Size (gal)	Wet Year %	Avg. Year %	Dry Year %
946	250	40.3	37.5	20.0
1893	500	56.4	54.2	31.2
2839	750	64.1	63.3	36.7
3785	1000	71.5	69.9	41.9
4732	1250	75.3	75.6	44.7
5678	1500	78.1	78.4	46.3
6624	1750	81.1	79.7	47.7
7571	2000	83.6	81.4	48.8
8517	2250	86.3	82.7	50.1
9464	2500	87.4	84.1	50.1

A2. Reliability for San Antonio under three climate conditions with a roof size of 109 m^2 (1172 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Tank Size (L)	Tank Size (gal)	Wet Year %	Avg. Year %	Dry Year %
946	250	21.9	21.1	9.6
1893	500	32.1	29.6	15.6
2839	750	40.3	34.0	21.1
3785	1000	43.3	37.3	23.6
4732	1250	46.0	39.5	25.8
5678	1500	48.5	40.8	26.8
6624	1750	51.0	42.2	28.2
7571	2000	51.5	44.1	28.8
8517	2250	52.3	44.9	29.0
9464	2500	53.2	45.5	29.0

A3. Reliability for San Antonio under three climate conditions with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 210 L (55.5 gal) per day.

Tank Size (L)	Tank Size (gal)	Wet Year %	Avg. Year %	Dry Year %
946	250	46.3	43.8	23.0
1893	500	65.8	64.4	34.5
2839	750	74.5	76.7	41.4
3785	1000	80.8	84.4	47.4
4732	1250	86.0	88.8	51.2
5678	1500	90.4	92.1	55.6
6624	1750	92.3	94.8	58.6
7571	2000	93.7	97.5	61.4
8517	2250	95.6	99.2	61.9
9464	2500	96.7	99.2	61.9

A4. Reliability for San Antonio under three climate conditions with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Tank Size (L)	Tank Size (gal)	Wet Year %	Avg. Year %	Dry Year %
946	250	24.7	25.2	12.3
1893	500	38.9	36.4	20.0
2839	750	49.9	44.7	27.1
3785	1000	54.8	50.1	30.7
4732	1250	58.9	54.0	34.0
5678	1500	62.5	57.8	36.4
6624	1750	64.9	60.0	38.9
7571	2000	67.1	62.7	40.0
8517	2250	68.8	64.9	40.8
9464	2500	70.1	66.6	41.4

A5. Reliability for Dallas under three climate conditions with a roof size of 109 m^2 (1172 ft^2) and a rainwater demand of 210 L (55.5 gal) per day.

Tank Size (L)	Tank Size (gal)	Wet Year %	Avg. Year %	Dry Year %
946	250	51.5	36.2	31.2
1893	500	75.1	55.3	43.0
2839	750	87.4	63.0	48.8
3785	1000	92.9	68.5	54.0
4732	1250	96.2	72.6	57.8
5678	1500	98.9	76.7	61.6
6624	1750	99.7	80.3	64.1
7571	2000	99.7	84.1	66.0
8517	2250	99.7	86.3	66.3
9464	2500	99.7	87.9	66.3

A6. Reliability for Dallas under three climate conditions with a roof size of 109 m^2 (1172 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Tank Size (L)	Tank Size (gal)	Wet Year %	Avg. Year %	Dry Year %
946	250	27.9	20.0	16.2
1893	500	44.1	31.5	23.0
2839	750	56.7	39.5	27.1
3785	1000	62.7	43.8	30.4
4732	1250	68.2	47.7	33.2
5678	1500	71.5	50.1	34.5
6624	1750	73.2	53.2	35.9
7571	2000	74.5	54.8	36.7
8517	2250	75.9	56.2	37.5
9464	2500	77.3	57.8	38.6

A7. Reliability for Dallas under three climate conditions with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 210 L (55.5 gal) per day.

Tank Size (L)	Tank Size (gal)	Wet Year %	Avg. Year %	Dry Year %
946	250	54.5	40.5	35.9
1893	500	80.3	62.7	51.2
2839	750	92.3	71.8	60.5
3785	1000	97.8	77.5	66.8
4732	1250	99.7	80.8	70.4
5678	1500	99.7	84.9	72.9
6624	1750	99.7	87.9	75.9
7571	2000	99.7	90.7	77.3
8517	2250	99.7	92.9	77.3
9464	2500	99.7	94.0	77.3

A8. Reliability for Dallas under three climate conditions with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Tank Size (L)	Tank Size (gal)	Wet Year %	Avg. Year %	Dry Year %
946	250	31.5	22.7	20.3
1893	500	49.3	35.9	28.5
2839	750	66.0	46.6	36.2
3785	1000	74.8	52.6	39.7
4732	1250	81.4	57.0	43.0
5678	1500	85.5	61.1	46.0
6624	1750	87.7	63.3	48.8
7571	2000	89.3	65.8	51.2
8517	2250	91.2	67.9	52.9
9464	2500	92.3	70.1	54.2

A9. Reliability for Houston under three climate conditions with a roof size of 109 m^2 (1172 ft^2) and a rainwater demand of 210 L (55.5 gal) per day.

Tank Size (L)	Tank Size (gal)	Wet Year %	Avg. Year %	Dry Year %
946	250	60.5	44.1	36.2
1893	500	81.1	67.1	53.4
2839	750	87.9	79.2	61.9
3785	1000	89.3	85.2	67.7
4732	1250	90.4	88.2	71.5
5678	1500	90.4	90.7	75.6
6624	1750	90.4	92.1	78.4
7571	2000	90.4	93.4	80.5
8517	2250	90.4	94.8	81.9
9464	2500	90.4	96.2	83.3

A10. Reliability for Houston under three climate conditions with a roof size of 109 m^2 (1172 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Tank Size (L)	Tank Size (gal)	Wet Year %	Avg. Year %	Dry Year %
946	250	31.5	24.1	18.1
1893	500	51.8	38.4	29.9
2839	750	63.3	48.2	38.4
3785	1000	69.9	54.8	43.3
4732	1250	73.4	60.8	47.4
5678	1500	75.6	64.7	50.4
6624	1750	77.3	67.4	53.4
7571	2000	77.5	69.3	57.0
8517	2250	77.5	71.0	58.6
9464	2500	77.5	72.6	59.5

A11. Reliability for Houston under three climate conditions with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 210 L (55.5 gal) per day.

Tank Size (L)	Tank Size (gal)	Wet Year %	Avg. Year %	Dry Year %
946	250	63.3	48.2	39.5
1893	500	86.0	75.1	60.3
2839	750	93.4	88.8	70.4
3785	1000	94.8	94.8	77.0
4732	1250	94.8	97.0	82.7
5678	1500	94.8	98.4	86.0
6624	1750	94.8	99.7	87.4
7571	2000	94.8	99.7	88.8
8517	2250	94.8	99.7	90.7
9464	2500	94.8	99.7	91.8

A12. Reliability for Houston under three climate conditions with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Tank Size (L)	Tank Size (gal)	Wet Year %	Avg. Year %	Dry Year %
946	250	36.4	26.3	20.8
1893	500	58.9	43.3	34.5
2839	750	72.3	55.6	45.2
3785	1000	78.6	63.8	51.5
4732	1250	82.5	70.7	56.7
5678	1500	85.8	75.1	60.0
6624	1750	86.3	77.0	63.0
7571	2000	86.3	79.2	64.9
8517	2250	86.3	80.8	67.4
9464	2500	86.3	82.5	69.3

A13. Reliability for San Antonio in five average years with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Tank Size (L)	Tank Size (gal)	Avg. A %	Avg. B %	Avg. C %	Avg. D %	Avg. E %
946	250	17.0	18.6	25.2	20.0	22.5
1893	500	27.7	27.7	36.4	29.0	35.6
2839	750	34.2	35.1	44.7	37.0	46.3
3785	1000	39.7	40.0	50.1	41.6	53.7
4732	1250	43.3	44.4	54.0	44.9	59.2
5678	1500	45.5	48.5	57.8	46.6	63.6
6624	1750	48.2	51.5	60.0	48.5	66.6
7571	2000	49.3	54.0	62.7	50.1	69.3
8517	2250	51.0	55.9	64.9	51.0	72.3
9464	2500	52.6	58.4	66.6	51.8	74.5

A14. Reliability for Dallas in five average years with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Tank Size (L)	Tank Size (gal)	Avg. A %	Avg. B %	Avg. C %	Avg. D %	Avg. E %
946	250	23.3	28.2	22.7	18.6	27.1
1893	500	34.5	43.8	35.9	31.0	43.0
2839	750	44.7	53.2	46.6	41.4	54.0
3785	1000	51.5	60.5	52.6	47.4	60.8
4732	1250	57.5	66.0	57.0	54.2	66.0
5678	1500	61.6	71.2	61.1	59.2	69.3
6624	1750	64.1	75.6	63.3	64.7	72.3
7571	2000	65.8	80.3	65.8	69.0	74.0
8517	2250	66.3	83.8	67.9	72.3	75.3
9464	2500	67.1	87.1	70.1	74.5	76.7

A15. Reliability for Houston in five average years with a roof size of 163 m^2 (1757 ft^2) and a rainwater demand of 380 L (100.5 gal) per day.

Tank Size (L)	Tank Size (gal)	Avg. A %	Avg. B %	Avg. C %	Avg. D %	Avg. E %
946	250	29.6	25.8	26.3	30.7	26.0
1893	500	43.8	39.2	43.3	47.7	41.9
2839	750	56.4	46.6	55.6	60.3	55.3
3785	1000	63.8	51.2	63.8	68.8	63.6
4732	1250	70.4	56.7	70.7	72.1	69.9
5678	1500	73.4	61.1	75.1	75.3	74.0
6624	1750	77.3	65.5	77.0	78.1	76.4
7571	2000	80.0	67.9	79.2	80.0	78.9
8517	2250	82.7	71.0	80.8	81.4	81.4
9464	2500	84.7	74.2	82.5	82.7	83.8

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