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RELIABILITY ANALYSIS OF URBAN RAINWATER HARVESTING FOR THREE TEXAS CITIES

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Abstract: The purpose of this study was 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 that a source of water can be depended on. Performance analyses were conducted on rainwater harvesting tanks for three Texas cities under different rainfall conditions and multiple scenarios to demonstrate the importance of optimizing rainwater tank design. 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. A payback period analysis was conducted on tank sizes to estimate the amount of time it would take to recoup the cost of installing a rainwater harvesting system.

Keywords: Urban rainwater harvesting; reliability analysis; optimal tank size; operational threshold; payback period analysis

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INTRODUCTION

The availability of water resources in Texas is a great concern. A combination of severe drought in recent years and an increasing population has raised questions about 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. Managing water resources in the face of a rapidly growing population is complicated by the fact that Texas has been suffering from several years of drought.

Winters (2013) compared drought conditions in 2011 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 35.3 centimeters was observed. The year 2011 proved to be even drier when only 28.6 centimeters 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.

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 option that is absent from the State Water Plan, and therefore ineligible for SWIFT funding, is rainwater harvesting. Currently, 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 deserving consideration in future state water planning.

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. However, it does allow restrictions on the location and size of a 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 legislature passed Texas HB 3391 in 2011 and it stands as the most comprehensive law on rainwater harvesting to date in Texas. 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. A cross-connection is defined as a physical connection between potable water and any water of lesser or unknown quality. 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 incentives such as discounts on rain barrels or rebates for water storage.

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 a significant factor in meeting water resource demands, however more information is needed. The dependability of a water source is critical, 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. This study has the following objectives:

(a) Explore the performance and design optimization of rainwater tanks in three cities in Texas (San Antonio, Dallas, and Houston) using a daily water balance model.

(b) Determine optimal tank sizes based on the local rainfall characteristics.

(c) Improve understanding of how different site conditions can affect the reliability provided for by a rainwater tank.

Previous Studies

The design and implementation of rainwater tanks have been studied extensively. 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. It was 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) 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.

A case study conducted in Melbourne, Australia by Imteaz *et al.* (2011a) explored the optimization of rainwater tanks for large roofs under three different rainfall conditions (dry, average and wet years). They concluded that both tank sizes (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, rainfall 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. Imteaz *et al.* (2011b) defined reliability 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 rainfall 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 increases in 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 study 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. Their 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 study conducted in the United States, Steffen *et al.* (2013) examined 23 cities under seven climatic regions across the country. They were interested in how much water could be provided from harvesting rainfall at the level of a residential parcel. A daily water balance model was employed to estimate water saving efficiency for a range of rainwater tank sizes and determined that performance depends on rainfall 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. Although 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.

Although the performance of rainwater tanks has been investigated in many locations throughout the world by previous studies, there have not been any studies of this nature carried out with Texas cities despite the water resource problems befalling the state in recent years. Therefore, the aim of this study is to apply an established methodology to three major Texas cities to determine the reliability of rainwater tanks under multiple conditions based on local rainfall characteristics.

MATERIAL AND METHODS

Study Area and Data Sets

Historical daily rainfall data were obtained from the National Climatic Data Center (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 rainfall conditions: dry, average and wet years. Categorization of these rainfall conditions was based on the 10th, 50th and 90th percentiles for annual rainfall at each station. The reason the 10th and 90th percentiles represent dry and wet years respectively, is that this amount of rainfall has a higher probability of occurring when compared to the driest or wettest years on record. Extreme dry or wet conditions are rare within a normal distribution of 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 have the biggest potential impact if rainwater harvesting is implemented. They also vary enough geographically that the different rainfall characteristics of these locations provides examples for decision makers to compare with other parts of Texas. The data for San Antonio span 1948–2013, the data for Dallas span 1940–2013, and the data for Houston span 1941–2013. **Table 1** illustrates the outcome of the year selection and the amount of rainfall observed in dry, average and wet years for each city.

Water Balance

This study was conducted using a daily water balance model with the variables being daily rainfall, roof area, runoff coefficient, volume of storage tank, and water demand, following the approach used by Imteaz *et al.* (2012). Daily runoff was calculated by multiplying the amount of daily rainfall by a runoff coefficient for metal roofing and the roof area. Metal roofs were selected for this study because of their abundance in Texas and their high performance as a rainwater collector. Farreny *et al.* (2011) showed that the composition and slope of a roof influence the runoff generated. They reported an average runoff coefficient of 0.92 for metal roof.

Calculated runoff from each rainfall event was deposited into the theoretical storage tank of a given size. If the amount of runoff was greater than the available storage volume, excess water was deducted from runoff as overflow. Daily water demand was deducted from accumulated storage as long as there was water in the tank. In the event that the tank was empty, the model assumed that the remaining water demand was met by a municipal water source. The model calculated daily rainwater use, daily water storage, daily overflow, and daily municipal water use. All volumes were displayed as liters (L). Additionally, the model calculated annual rainwater use, accumulated annual overflow and accumulated annual municipal water use. The overall computational procedure can be described as follows:

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

Table 1. Dry, average, and wet year conditions for each city based on the 10th, 50th, and 90th percentile of total annual rainfall 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

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:

$$R_e = [(N – U) / N] \times 100 \quad (6)$$

where R_e is the reliability of the tank 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.

Daily water balance calculations were performed for the three selected locations for a dry, average, and wet year. Ten different tank sizes were analyzed under these conditions and the percentage of water demand fulfilled by rainwater harvesting was calculated. This percentage is considered to be the tank reliability. Tank sizes ranged from 946–9464 L and increased in increments of 946.4 L which corresponds to standard commercial tank sizes in Texas (Tank Depot, 2014).

Two roof areas were selected 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. 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. Since the upper story of homes is often not as large as the lower story, it was assumed that the upper story accounted for 1/3 of the inside area and should not be included in the roof area.

The demand scenarios were based on a publication by Mayer *et al.* (1999) on behalf of the American Water Works Association (AWWA) that estimated residential use of water in North America. Toilet flushing and laundry washing were chosen for rainwater application because of their high demand compared to other indoor water uses. Additionally, this non-potable water would require very little or no treatment. The AWWA found that the average amount of water used per day for toilet flushing was 70 L per person, and the average amount of water used per day for laundry was 56.7 L 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 rounded up to 3 for this study. Therefore, the first demand scenario was 210 L per day which represents three people’s use of water for toilet flushing. The second demand scenario was 380 L per day which represents three 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 per day, so the second demand scenario also served 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.

A total of 360 simulations were performed resulting in 12 reliability charts produced. The results section shows six of these charts, however all scenarios are summarized in **Table 2**. Each chart displays reliability percentage versus tank size. Relationship curves illustrate how selected variables can influence rainwater tank reliability under the three rainfall conditions (dry, average, and wet years). Optimal tank sizes were apparent for each scenario due to reliability thresholds above which installing larger tanks would provide little additional benefit. This approach represents a slight departure from previous studies where threshold tank sizes were used as the point of maximum achievable reliability. Due to the differences in rainfall and water demand in Texas, maximum achievable reliability was not observed for most of the scenarios considered. Therefore, an additional threshold, distinguished from a maximum threshold, was 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 threshold was referred to here as an operational threshold, which occurs when there is a 2% increase or less in reliability for the next available tank size increment. In other words, 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 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 to 2.59 m in diameter for 946 L and 9464 L storage capacities, respectively.

RESULTS AND DISCUSSION

San Antonio

Figure 1 shows the reliability curves for the city of San Antonio under different rainfall conditions (dry, average, and wet years) and different tank sizes for a roof catchment of 163 m^2 and rainwater demand of 210 L per day. For a dry year, reliability increases with tank size until the operational threshold is reached at 6624 L with a reliability of 59%. The maximum threshold is reached two tank sizes larger at 8517 L with a reliability of 62%. An average year for San Antonio in this scenario has larger threshold tank sizes than those for a dry year but also displays higher reliability. For an average year, the operational threshold is reached at 7571 with a reliability of 98%. The maximum threshold is reached on the next tank size of 8517 L with a reliability of 99%. For 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 with 90% reliability.

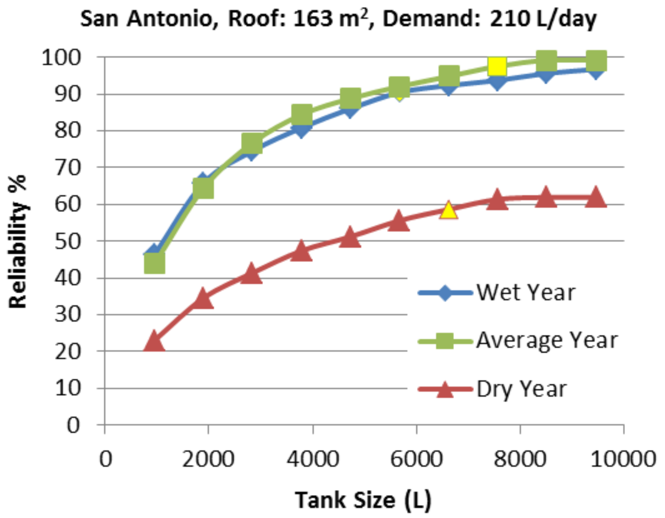

Fig. 1 Reliability curves for San Antonio under three rainfall conditions for a roof size of 163 m^2 and a rainwater demand of 210 L per day. Operational threshold tank sizes marked in yellow.

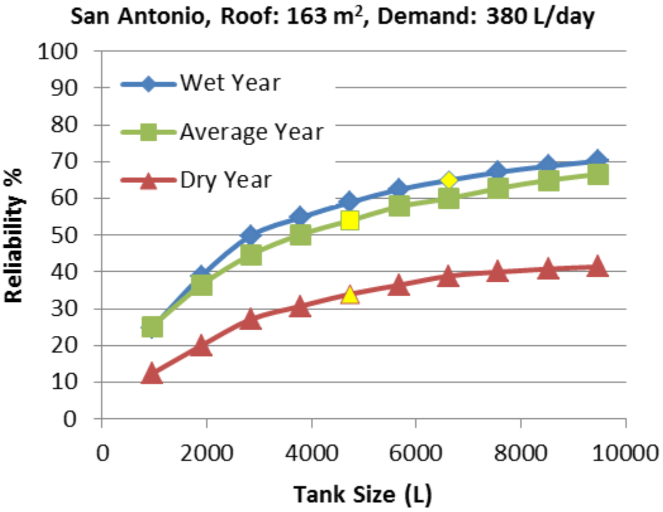

Fig. 2 Reliability curves for San Antonio under three rainfall conditions for a roof size of 163 m^2 and a rainwater demand of 380 L per day. Operational threshold tank sizes marked in yellow.

Figure 2 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. For a dry year, reliability increases with tank size until the operational threshold is reached at 4732 L with a reliability of 34%. For an average year, reliability increases also to 54% when the operational threshold is reached with a 4732 L tank. The operational threshold tank size is identical in dry and average rainfall conditions with only a difference in reliability. For 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 tank and 65% reliability.

Dallas

Figure 3 shows the reliability curves for the city of Dallas and different tank sizes for a roof catchment of 163 m^2 and rainwater demand of 210 L per day. For a dry year, reliability increases with tank size until the operational threshold is reached at 6624 L with a reliability of 76%. The maximum threshold is reached on the very next tank size of 7571 L with a reliability of 77%.

For an average year, reliability improves minimally after the first few tank sizes until the operational threshold is finally reached at 7571 L with 91% reliability. For a wet year, reliability increases greatly over the first three tank sizes until the operational threshold is reached at 3785 L with 98% reliability. The maximum threshold is then reached on the next tank size of 4732 L with a reliability of 100%.

Figure 4 shows the reliability curves for Dallas under a similar scenario but with a rainwater demand of 380 L. For a dry year, reliability increases with tank size until the operational threshold is reached at 6624 L with

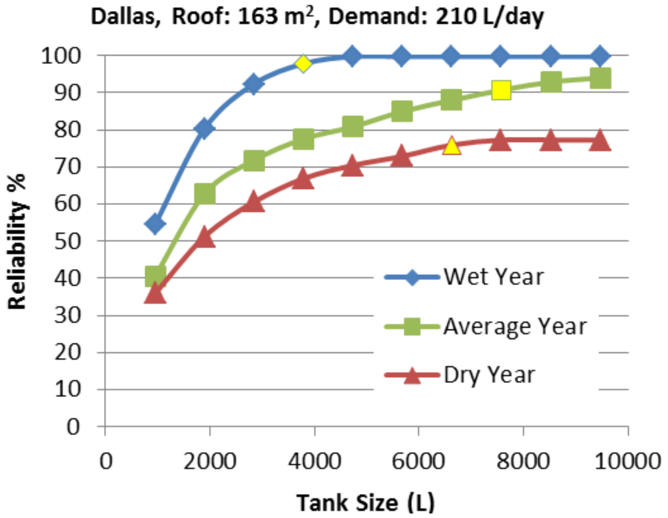

Fig. 3 Reliability curves for Dallas under three rainfall conditions for a roof size of 163 m^2 and a rainwater demand of 210 L per day. Operational threshold tank sizes marked in yellow.

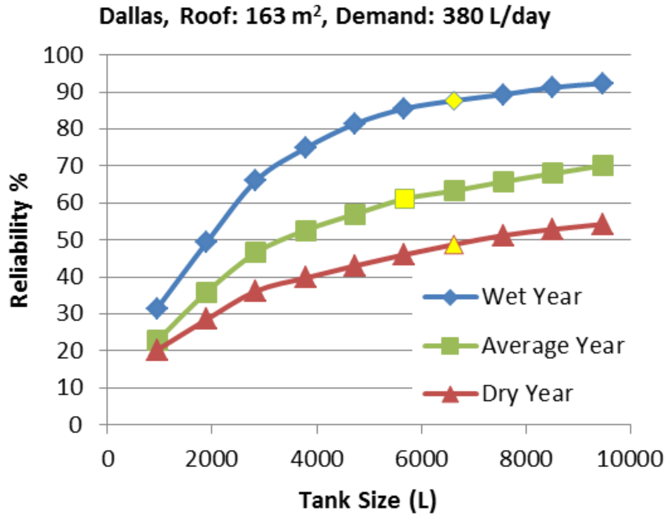

Fig. 4 Reliability curves for Dallas under three rainfall conditions with a roof size of 163 m^2 and a rainwater demand of 380 L per day. Operational threshold tank sizes marked in yellow.

a reliability of 49%. For an average year, reliability increases to 61% when the operational threshold is reached with a 5678 L tank. For a wet year, reliability increases greatly over the first few tank sizes until the operational threshold is reached at 6624 L with a reliability of 88%. It should be noted that the maximum threshold was not reached for any of the three rainfall conditions in this scenario within the range of tank sizes under consideration.

Houston

Figure 5 shows the reliability curves for the city of Houston and different tank sizes for a roof catchment of 163 m^2 and rainwater demand of 210 L per day. For a dry year, reliability increases with tank size until the operational threshold is reached at 5678 L with a reliability of 86%. For an average year, reliability increases to 95% when the operational threshold is reached with a 3785 L tank. Reliability goes up a little for the next three tank sizes before the maximum threshold is reached with a 6624 L tank and reliability of 100%. For a wet year, the reliability increases greatly with tank size until an operational threshold is reached with a capacity of 2839 L and 93% reliability. Reliability goes up slightly for the next tank size when a maximum reliability of 95% is met at 4732 L demonstrating that a larger tank would provide no additional benefit beyond that size. An interesting situation occurs in this scenario where more reliability can be attained in an average year than in a wet year.

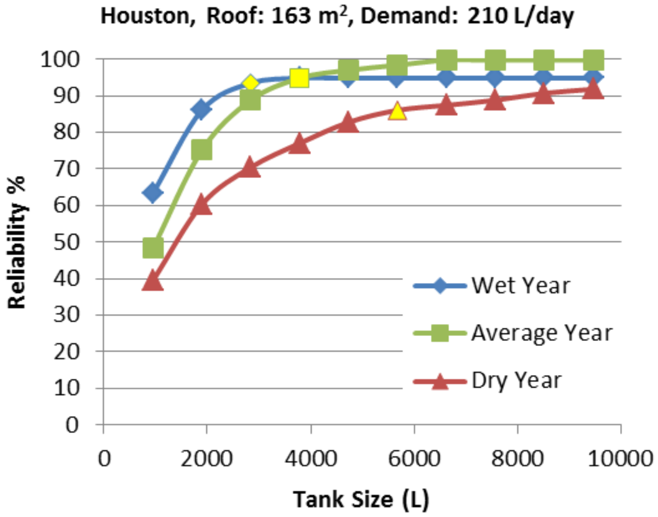

Fig. 5 Reliability curves for Houston under three rainfall conditions for a roof size of 163 m^2 and a rainwater demand of 210 L per day. Operational threshold tank sizes marked in yellow.

The next Houston scenario is similar to the former but with a 380 L rainwater demand. Its reliability curves can be seen in **Fig. 6**. For a dry year, reliability

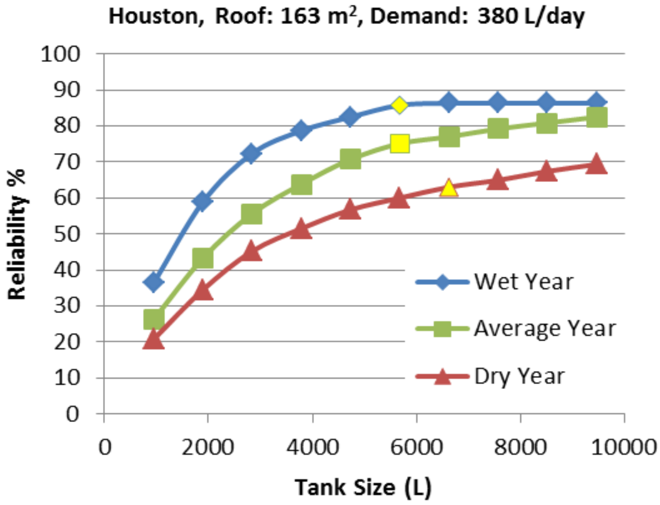

Fig. 6 Reliability curves for Houston under three rainfall conditions for a roof size of 163 m^2 and a rainwater demand of 380 L per day. Operational threshold tank sizes marked in yellow.

increases with tank size until the operational threshold is reached at 6624 L with a reliability of 63%. For an average year, reliability increases to 75% when the operational threshold is reached with a 5678 L tank. For a wet year, reliability increases with tank size until the operational threshold is also reached at 5678 L with a reliability of 86%. This tank size also happens to be the maximum threshold, so a larger tank would provide no additional benefit.

Table 2 contains a summary of the operational threshold tank sizes for each scenario in all three cities under different rainfall conditions. Included are tank sizes from the simulations that considered a smaller roof catchment area of 109 m^2. The rainfall scenarios show how the variability of rainfall from year to year might affect a tank's performance.

Effect of Rainfall Variability

It seems to be logical to assume that a wet year would provide more reliability than an average year because more rainfall would maintain a full tank. This was true for the majority of the scenarios under consideration including those for Dallas. However, San Antonio and Houston showed some unusual reliability curves in a couple of scenarios.

In San Antonio for a roof catchment of 163 m^2 and rainwater demand of 210 L per day, the reliability curves for an average and wet year almost overlapped, never being more than 4% apart for any tank size. Reliability in an average year overtook that for a wet year with a 2839 L tank and remained higher for all subsequent tank sizes. This phenomenon can be explained from the water balance calculations.

The accumulated annual overflow was high for a wet year in this scenario when compared to an average year. This was due to rainwater demand being low at 210 L per day and not depleting the water reserves enough to free up storage space to catch the infrequent but heavy rains. The situation also occurred in San Antonio for a roof size of 109 m^2 and rainwater demand of 210 L per day. It is important to remember that being classified as wet year has nothing to do with the distribution of rain throughout the year. If the majority of rainfall comes in few events, the reliability of a rainwater tank can be severely affected.

In Houston, for a roof catchment of 163 m^2 and rainwater demand of 210 L per day, the maximum achievable reliability for a wet year was 95% and was reached with a small tank size of 3785 L. Reliability for an average year was also 95% with a 3785 L tank but continued to increase slightly over the next three tank sizes until 100% reliability was met with a 6624 L 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 was a span of 26 days during the wet year (1976) without rain. This means that the rainwater tank was empty for an extended period which puts an upward limit on the reliability that can be attained.

Payback Period

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 and was combined with the daily outdoor use of 382 L, which resulted in 35057 L total use for the month. The water meter size installed most commonly in single family residences was assumed. No rainwater catchment rebates are offered by the public water systems of the three cities, otherwise they would have

Table 2. Operational threshold tank sizes for each scenario under different climate conditions. Operational tank sizes are displayed in liters with reliability in percent. 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%)

been factored into the payback period. The scenario used to estimate monthly water savings for all cities was the one with a roof catchment size of 163 m^2 and rainwater demand of 380 L per day. 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 is 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 the installation of rainwater harvesting systems such as

As mentioned previously, the demand scenario of 380 L 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 anyway.

The average monthly water bill for San Antonio is $37.29 USD (San Antonio Water System, 2014) when usage is 35057 L. If the optimal tank size of 4732 L is installed, 6156 L of rainwater is provided each month for toilet flushing and laundry. With 54% reliability for this demand met, the adjusted monthly use would be 28901 L at a cost of $31.60 USD. The monthly savings would therefore be $5.69 USD, and it would take 9.3 years for a homeowner to pay off a tank at a cost of $659 USD.

The average monthly water bill for Dallas is $35.51 USD (City of Dallas, 2014) when usage is 35057 L. If the optimal tank size of 5678 L is installed, 6954 L of rainwater is provided each month for toilet flushing and laundry. With 61% reliability for this demand met, the adjusted monthly use would be 28103 L at a cost of $27.69 USD. The monthly savings would therefore be $7.82 USD, and it would take 7.4 years for a homeowner to pay off a tank at a cost of $695 USD.

The average monthly water bill for Houston is $49.50 USD (City of Houston, 2014) when usage is 35057 L. If the optimal tank size of 5678 L is installed, 8550 L of rainwater is provided each month for toilet flushing and laundry. With 75% reliability for this demand met, the adjusted monthly use would be 26 507 L at a cost of $35.34 USD. The monthly savings would be $14.16 USD, and it would take 4.1 years for a homeowner to pay off a tank at a cost of $695 USD.

The payback periods for San Antonio and Dallas are both over seven 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 over 4 years but could also be a deterrent for an otherwise interested homeowner. It needs to be emphasized, however, that none of these three cities offer rebates to

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 those with slab foundations in this respect due to easier access to pipes. The cost of including additional plumbing for a rainwater harvesting 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. make rainwater harvesting more affordable like some other municipalities in Texas do. For example, the City of Austin (2014) provides a rebate of $0.13 USD per liter (non-pressurized) and $0.26 USD per liter (pressurized) to its customers towards the installation cost of new rainwater harvesting 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 promote the installation of residential rainwater harvesting systems, as it will relieve some of the pressure of developing new sources of water supply for a booming population. 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. Furthermore, financial support for rainwater harvesting will encourage the installation of tanks throughout the state, which could help in alleviating water concerns and safeguarding projections of future growth.

CONCLUSION

This study explored the feasibility of implementing rainwater harvesting systems in three large Texas cities. Different rainfall conditions and scenarios were investigated and optimal tank sizes were determined with respect to their reliabilities. Understanding reliability is important because it informs decision makers and households of how many days throughout the year a rainwater collection system can satisfy some water demands. The application of the concept of operational thresholds allows 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 did not account for efficient fixtures and strategies to reduce water consumption within the household.

Application of this study's results to other locations in Texas can be accomplished by comparing the average annual rainfall of San Antonio's Bexar County, Dallas County, and Houston's Harris County with other counties. 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), is shown below in **Fig. 7**.

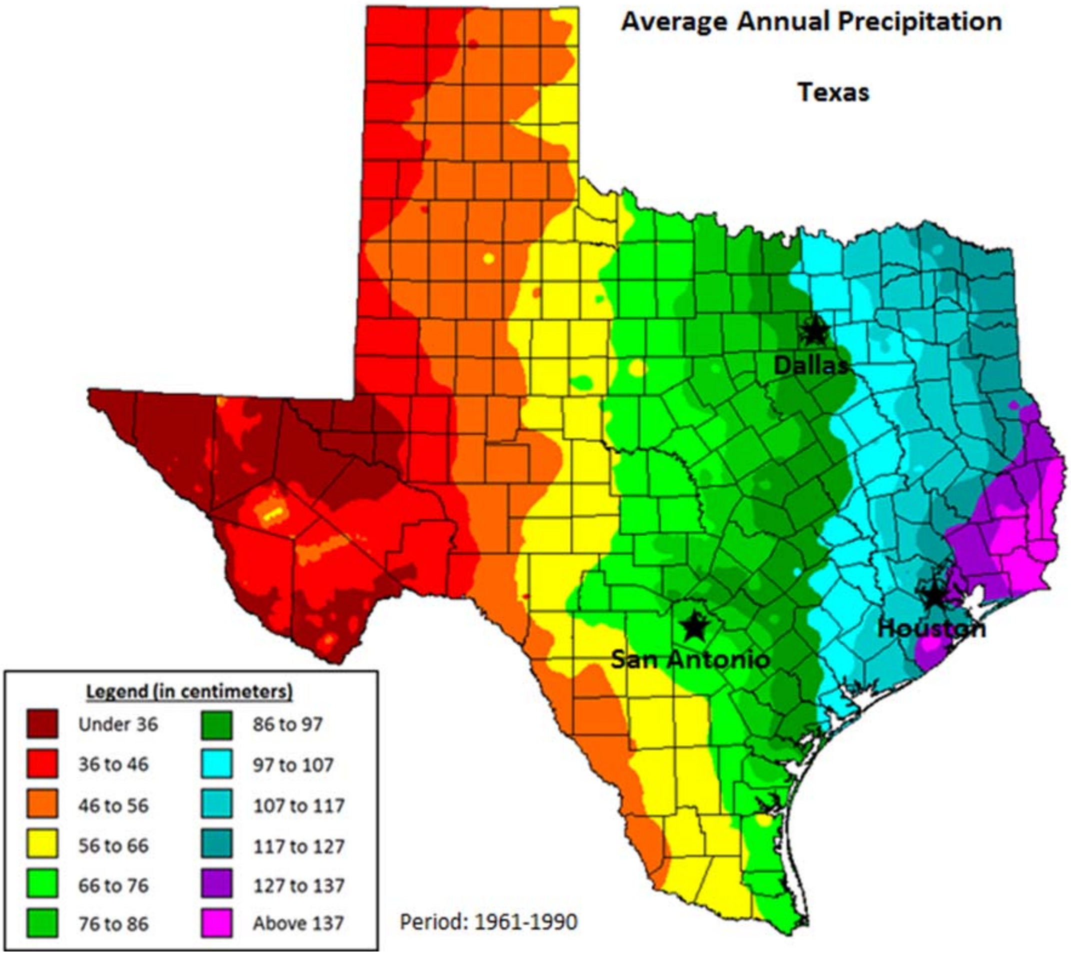

Fig. 7 Average Annual Precipitation for Texas Estimated by PRISM Modeling.

San Antonio lies right in the middle of an isopleth dividing rainfall amounts of 66–76 cm and 76–86 cm which is consistent with the average of 77.1 cm used in this study. Dallas lies within the rainfall category of 86–97 cm (average rainfall of 91.8 cm). Houston also lies along an isopleth dividing rainfall amounts of 117–127 cm and 127–137 cm (average rainfall of 127.9). Therefore, any location within these three zones should expect to have similar rainfall characteristics to the study sites. It should be noted that these associations would assume that the distribution of rainfall during the year is similar within each zone which might not necessarily be the case. Finally, the methods used in this study could be repeated for any municipality or household seeking more accurate results reflecting their unique situation.

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