Meadows Report 25-003

Reliable Rainwater Is Only a Roof Away: The Firm Yield of Rainwater Harvesting in Texas


Storm over a Texas field along Route 66 © David Smith

Prepared by

Ricardo O. Briones and Robert E. Mace, Ph.D., P.G.

September 2025

The Meadows Center for Water and the Environment
Texas State University

MEMBER THE TEXAS STATE UNIVERSITY SYSTEM

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Prepared by

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Rainwater harvesting at the Lady Bird Johnson Wildflower Center ©Robert E. Mace

Executive Summary

Rainwater harvesting has long been part of Texas's water story—from ancient tinajas used by Indigenous peoples to cisterns that made early settlements viable. Today, however, rainwater harvesting remains underutilized in modern water planning, primarily due to the perception that it is unreliable—particularly during droughts. This report addresses that perception by introducing a firm-yield framework to quantify the reliability of rainwater harvesting systems across Texas.

Using long-term daily precipitation records from 19 locations representing all regional water planning areas in the state, we developed and applied the Rainwater Assessment and Interactive eNumator for Firm-yield Analysis Limits (RAINFAL) tool—a spreadsheet-based modeling tool that allows users to evaluate the performance, reliability, and firm yield of rainwater harvesting systems. The tool uses a daily water balance equation incorporating rainfall, catchment area, runoff efficiency, first-flush volumes, storage capacity, and daily use.

Our analysis shows that rainwater harvesting systems can be designed to provide a 100-percent reliable supply under drought of record conditions—known as firm yield—even in Texas' most arid regions. Systems with 3,000 square feet of catchment and 30,000 gallons of storage can reliably support different levels of indoor household use in every part of the state, even in El Paso. For drier regions, larger firm yields can be achieved with larger catchments, additional storage, or lower daily use. We also found that the drought that defines a system's reliability depends on catchment, storage, and level of use, suggesting that the drought of record for the local reservoir or aquifer may not apply to rainwater harvesting.

These findings have significant implications for water planners, regulators, builders, and homeowners. They demonstrate that rainwater harvesting is not merely a conservation strategy— it is a legitimate, quantifiable water-supply option. Incorporating firm-yield rainwater systems into regional and state water planning can reduce dependence on strained conventional supplies, especially during drought.

We provide the RAINFAL tool and its accompanying user guide freely through The Meadows Center for Water and the Environment to empower practitioners, planners, and the public with the ability to design reliable, resilient rainwater systems and evaluate the reliability of their current systems. With thoughtful planning and robust design, rainwater harvesting can play a meaningful role in Texas's water future.

Introduction

For thousands of years before Texas existed, Native Americans used natural cisterns to capture rainwater (TPWD 2023). These natural cisterns, known as tinajas in Spanish, were small depressions in the surface for retaining rainwater (TPWD 2023). Following statehood, rainwater harvesting also made Texas habitable during its settlement. People relied on underground cisterns for water storage (Mace 1994) such as in the Texas Panhandle, where families needed cisterns to store water during the scorching summers or snowy winters (Trew 2002). In East Texas, cities like Brenham used cisterns to store water for firefighting or personal use (City of Brenham 2023). The Texas capitol building captured rainwater for drinking water, fire protection, and operating elevators (TSPB undated).

With the advent of centralized water systems, deeper wells, and affordable pumps, rainwater harvesting became less popular as a water supply. However, over the past several decades, rainwater harvesting has re-emerged as an alternative supply, especially when local supplies are scarce or of poor quality and as a water conservation strategy to minimize the use of more conventional water supplies such as surface water and groundwater (Krishna 2005). Rainwater has several advantages over conventional supplies, including water quality, minimization of infrastructure, stormwater benefits, and cost (Krishna 2005). Rainwater can also serve as a back-up supply when city supplies are interrupted, such as during Winter Storm Uri or other power outages.

Despite the many benefits of rainwater harvesting, there has been a reluctance by communities to adopt it beyond the rain barrels used to engage ratepayers with water conservation. In part, this is due to the perception that rainwater harvesting is not reliable. For example, the 2012 State Water Plan states that, "While it is often a component of municipal water conservation programs, rainwater harvesting was not recommended as a water management strategy to meet needs since, like brush control, the volume of water may not be available during drought conditions" (TWDB 2012). Banks will sometimes not finance a home with rainwater harvesting (GEM 2016) due to perceived unreliability issues, something we heard still occurs in the Hill Country where conventional groundwater resources are often, ironically, unreliable (and becoming more so).

The lack of a rigorous method to assess the reliability of rainwater harvesting may be an impediment to the wider adoption in Texas. A rule of thumb we have heard for single-family homes wholly dependent on rainwater in the Texas Hill Country near Dripping Springs over the years is 10,000 gallons of storage per person. Installers have told us that 30,000 gallons of storage for a typical home in the Hill Country is a good unwritten rule. One system installer told us that "40,000 is the new 30,000" to address the droughts that Central Texas has suffered over the past couple of decades.

The Texas Water Development Board provides a spreadsheet to size rainwater systems for 19 locations around the state (TWDB 2010). However, the spreadsheet uses average monthly precipitation for 1970 to 2000 to size tanks. Given the variability of rainfall in Texas, designing a system for an average is unlikely to be reliable during droughts. In addition, 1970 through 2000 was a wetter-than-normal period for Texas, further decreasing reliability when using the tool. Similarly, a spreadsheet-based rainwater calculator available to the public by Texas Agrilife Extension uses average monthly rainfall values (Agrilife Extension, undated). The Rainwater Harvesting Manual published by the American Rainwater Catchment Systems Association (Audry 2015) also recommends using monthly averages in addition to high and low monthly averages if available (although it does not show how to use the high and low monthly averages in an analysis).

One of us (Mace) modified the Texas Water Development Board's calculator to use daily data when designing a rainwater harvesting system to meet outdoor needs at his house in Austin. He found that a system designed as "reliable" using the Texas Water Development Board's calculator would, in fact, fail in four out of every ten summers (Mace 2013).

David Venhuizen, P.E., who works as a consultant on alternative water supplies, developed a spreadsheet model that uses monthly precipitation totals for one to two decades to design systems (Venhuizen 2008). This tool is an improvement over the TWDB (2010) tool, but the limited record may miss the local drought of record and thus overestimate reliability while the monthly averaging decreases accuracy and may overestimate reliability.

Like us, Lawrence and Lopes (2016) noted the lack of rainwater harvesting in the state water plan and set out to provide actionable information to regional water planners. They used an approach by Imteaz and others (2012) that identifies the 10th, 50th, and 90th percentile years for annual precipitation and then uses the daily precipitation record from those years to calculate reliability and optimize storage volume. Lawrence and Lopes (2016) calculated systems for Dallas, Houston, and San Antonio. Unfortunately, the method grossly underestimates reliability (it does not use the full record) and substantially underestimates (by an order of magnitude) storage volumes needed to achieve a certain level of reliability (Briones 2023). Furthermore, in all the scenarios that Lawrence and Lopes (2016) investigated, the reliability was less than 100 percent and therefore not firm.

Water planning in Texas is based on how much water existing and planned supplies can provide during a repeat of the drought of record (TWDB 2022). While the statewide drought of record remains the drought of the 1950s, and the worst one-year statewide drought occurred in 2011, local or regional climatic conditions define the drought of record for each water source across the state. For surface-water resources in Texas, including rivers, streams, and reservoirs, firm yield is the term of art for how much water can be consistently produced through the full period of record[1]. The period of record includes, by definition, the worst drought of that record[2].

Rainwater harvesting systems and surface-water reservoirs both collect and store rainwater for use. Precipitation falls from the sky, water runs off a surface, water collects in storage, and water is available for use. Given the similarities between the two water systems, it follows that engineering concepts and techniques to quantify the reliability of surface-water reservoirs can—and perhaps should—be used for rainwater

1 *There can, of course, be droughts worse than the drought of record. Tree rings suggest that there have been droughts worse than the drought of record (Cleaveland and others 2011), and climate modeling suggests Texas may face more frequent and worse droughts in the future (Nielsen-Gammon and others 2020).*

2 *Firm yield is defined differently in different parts of the country and the world and is oftentimes referred to as the safe yield (Mace 2022). In Texas, safe yield refers to extending the drought of record to include a safety factor in supply estimates.*

harvesting systems as well. Since regional and state water planning in Texas seeks firm, 100-percent reliable supplies, assessing firm yields may advance rainwater harvesting in the state.

To our knowledge, no one has developed a tool to calculate the firm yield of rainwater harvesting. Therefore, our goal was to develop this tool using daily precipitation data from representative locations in regional water planning areas across the state. Our goal was to also make this tool user-friendly and freely available to water planners, rainwater harvesting designers, and the public to help them design rainwater harvesting systems and determine the reliability and firm yield of existing or planned projects. Although the focus of this work is on Texas, the approach and tool can be used at any location with long-term daily precipitation data.

Methods

To achieve our goals, we first developed a governing equation to model the harvesting of rainwater and its use. We then identified reasonable values for the different variables in the governing equation for Texas. After that, we generated a series of graphs for various locations across the state that optimized storage volume and catchment area to achieve a range of firm yields. We then analyzed those graphs for patterns and general observations and used the tool to more closely investigate reliability and rainwater harvesting.

Although our graphs and results are focused on household-scaled rainwater harvesting, our methods and tools can be applied to any sized roof. However, our tool is directed toward optimizing systems that provide consistent daily use and does not, at this time, include a seasonal component.

Governing Equation

In a rainwater harvesting system, rainwater is collected after it falls onto a roof, moves across the roof, enters the gutters, overfills a first flush system, and empties into storage. Not all the rain that falls on a roof makes it to storage. A dry roof and gutter will retain some of the rain before water runs into storage. In watersheds, this retention is estimated through a runoff coefficient that describes the efficiency of rainfall turning into runoff. For a roof, this runoff coefficient is generally a function of roof material and slope (Farreny and others 2011).

The water that runs off a roof enters and flows down a gutter, and then interacts with a first flush system. Recommended for potable systems, the first flush diverts a certain amount of the initial runoff before rainwater enters the tank. The purpose of the first flush is to prevent the initial wash-down of the roof, which includes dust, dry deposition of air pollution, and other contaminants, from affecting water quality in the tank.

Once there is enough flow to overcome the first flush, rainwater enters the tank. Because most storage for rainwater harvesting is closed, there is little to no evaporative loss. If the storage fills past capacity, an overflow allows excess water to exit storage, and that water is lost. Collected rainwater remains in storage until used. In the case of storage being almost exhausted, a dead pool of water (another term borrowed from surface-water reservoir management) remains in the bottom as a sediment reservoir and is therefore not available for use (but could be available in an emergency, just as in surface reservoirs).

Non-potable systems do not generally have dead pools and pull from the bottom of the tanks while potable systems generally have floating intakes which disallow draining the entire tank.

Depending on the purpose of the use, the stored rainwater may undergo filtration and exposure to ultraviolet light for indoor use or no treatment for outdoor use. Filtration and ultraviolet light do not result in any treatment losses. If a user decides to use reverse osmosis for additional treatment, there may be a loss of water. To generalize the terminology, we refer to roofs as catchment and tanks as storage from this point forward.

In mathematical form, the governing equation for a daily water budget is:

$$V_t = V_{t-1} + R \times A \times C - V_{ff} - V_u \quad (1)$$

unless

$$V_{ff} > R \times A \times C \text{ in which case } V_{ff} = R \times A \times C \quad (2)$$

$$V_t > V_{tot} \text{ in which case } V_t = V_{tot} \quad (3)$$

$$V_t < 0 \text{ in which case } V_t = 0 \quad (4)$$

where:

A = area of the catchment [L^2]

C = runoff coefficient for the catchment [-]

R = precipitation on day t [L]

V_{ff}= volume of the first flush [L^3]

V_t = volume of water in storage at the end of day t [L^3]

V_{t-1} = volume of water in storage at the end of the previous day [L^3]

V_{tot} = total storage volume [L^3]

V_u = volume of daily use [L^3]

The first term in Equation 1 (V_{t-1}) is the volume of water in storage yesterday, the second term is the volume of water running off the roof (R × A × C), the third term is loss of volume from the first flush (V_{ff}), and the fourth term is the loss of storage from use (V_u). Equation 2 is for the case when the volume of the first flush is less than the rainfall collected from the roof, setting the volume of the first flush equal to the volume of the rainfall collected from the roof. This results in no water being added to storage when the flow from the roof cannot overcome the first flush. Equation 3 is for when the tank is full, setting the maximum volume in storage to the maximum volume of storage. Equation 4 is for when the storage is exhausted (including the dead pool) setting the volume of storage to zero when use of water is greater than the remaining storage.

RAINFAL

We programmed our governing equation into an Excel workbook we named the Rainwater Assessment and Interactive eNumator for Firm-yield Analysis Limits (aka RAINFAL). The workbook includes two sheets, the first focused on input parameters and output, and the second focused on calculations. Sheet 1 includes user-adjustable parameters and presents the results in a graph (Figure 1). Users can optimize catchment area, storage volume, or daily use through trial-and-error on the parameter of interest or, for more sophisticated users, can use Excel's iteration tools to semi-automatically optimize a parameter of interest.

The spreadsheet provides a graph of results for users to visualize storage in the tank over the period of record and identify when water storage in the tank is at its lowest.

Although the focus of our research was on defining firm yields, we also provide the ability for users to assess system reliability (100 times the total number of days storage is zero divided by the total number of days in the record) and the total number of days storage is zero.

Because assessment of the system begins at the start of the record, we allow the user to define the initial condition of how full the tank is at the beginning of the simulation. By varying this initial condition, a user can test whether initial conditions influence results.

Also included on Sheet 1 is the daily precipitation data for the identified location. We also provide the ability to proportionally adjust the precipitation record. This allows a user not in the identified locale but near it to modify the precipitation record to more reflect local conditions. For example, if someone in Llano, Texas, wants to design a rainwater harvesting system for their drier conditions, they can proportionally adjust Austin's rainfall by dividing Llano's average precipitation (27.6 inches) by Austin's average precipitation (35.5 inches) and inserting that number (0.777) into the "Proportional adjustment" cell. The spreadsheet will then multiply all daily precipitation values for Austin by the proportional adjustment value. Local daily data is preferred, but, lacking that data or a long record of that data, this is a better approach. Proportional adjustment can also be used to design resilience for a drier climate. For example, if you want to design a system where rainfall is 10 percent less than the record, you can put 0.90 into the proportional adjustment cell.

Sheet 2 is where we coded the governing equation and different logic tests to calculate storage over time.

We developed RAINFALs for each of the cities we investigated for this report and provide them at the Meadows Center's website (www.meadowscenter.txst.edu). We also provided a blank version for use at any locale with long-term, daily rainfall data. Anyone who changes or updates the precipitation data on Sheet 1 needs to make sure that the equations in columns A through K on Sheet 2 cover the same number of rows of precipitation data on Sheet 1.

We provide a standalone User's Guide (Mace 2025) separate from this report so we can continue to extend the record and add functionality without having to update this report.

Quantifying the Terms

Each of the user-adjusted parameters need reasonable estimates or ranges for use. We did this specifically in our focus on Texas, but many of the estimates and much of the logic conveys to other locales.

For precipitation, *R*, we downloaded daily data from Climate Data Online (NCEI, 2023). We chose data from Climate Data Online because it is the only online database that has continuously collected precipitation data throughout the state. Throughout every regional water planning area, there are multiple weather stations that have recorded rainfall data since the early 1900s. We assumed that any frozen precipitation will melt and end up flowing through the rainwater harvesting system. This assumption probably overestimates water volumes since snow may blow off of a roof, accumulated frozen precipitation may slide off of roof without snow guards, or the system may freeze if it is not designed for cold weather. Given that Texas does not receive much frozen precipitation, this assumption is workable.

Our goal was to calculate the firm yield of rainwater harvesting throughout the state with at least one station in each regional water planning area (Figure 2). We chose two locations in some planning areas to reflect the range of precipitation across regions that are long and cross different climatic zones (Figure 2). We chose stations that had long records with good data coverage (in other words, a high percentage of precipitation data collected every day). Given the wide range of climatic conditions across the state, average annual precipitation for the locales we investigated ranged from 14 inches in El Paso to 52 inches in Texarkana (Table 1).

We based our "typical" catchment area on the median square footage of new contractor- built single-family homes of 2,609 square-feet as reported for 2021, the most recent available number (U.S. Census Bureau, 2023a). We used new construction because new construction is more likely (and easier) to include a whole-house rainwater harvesting system than retrofitting an existing house. We assumed a single-story structure. To account for eaves, we assumed a square structure with two-foot eaves which resulted in an additional 212 square feet of catchment. We also assumed a two-car garage, which generated an additional 360 square-feet of catchment. Adding these areas up resulted in 3,181 square-feet of total catchment. We assumed rainwater would be collected from the entire catchment but rounded down to 3,000 square-feet.

Note that catchment may be (and often is) different than roof area. Roof area represents the area of the roof's surface. Catchment is the area that captures rainfall. A roof at an angle will have a roof area greater than the catchment area. For the same roof area, the greater the slope, the lower the catchment area (think of the difference between roof area and catchment on an A-frame). In other words, geometry may be required to calculate the catchment of your roof.

Given our assumptions, we may have overestimated catchment given the size of the home (although homes continue to get larger) and the assumption of a single-story structure (although buyers do prefer single-story homes); however, we have also underestimated catchment by not including covered porches and entry ways. Regardless, RAINWATR can be used with any catchment area the user prefers, including superstore or larger roofs.

We used 0.92 for the runoff coefficient, C, for metal catchments (Farreny and others 2011). This means that when there is a precipitation event, 92 percent of that event makes it off the catchment, into the gutter, and to the first flush. We apply the runoff coefficient on a daily basis in RAINFAL, which may underestimate flow off the catchment for multi-day rainfall events. Average runoff coefficients for other catchment type are 0.84 for clay tiles, 0.91 for polycarbonate plastic, and 0.62 for flat gravel (Farreny and others 2011); 0.9 for asphalt shingles and concrete and 0.8 to 0.85 for tar and gravel (Downey and others 2009); and 0.23 for green roofs (TWDB 2010). If you have a rain gage, know your catchment area, and know how much rain makes it into your take (accounting for a first flush), you can calculate your own runoff coefficient.

For the first flush, V_{ff}, we used 10 gallons per 1,000 square feet of catchment (TWDB 2010). Accordingly, the first flush is calculated based on the catchment area in RAINFAL (Briones [2023] used a fixed first flush of 50 gallons regardless of catchment size). Several factors can (or should) be considered when choosing a first flush volume, including local precipitation, storm intensity, and canopy (Charlebois and others 2023).

Kus and others (2010) suggested flushing the first 1 to 5 millimeters of rainwater depending on treatment to improve water quality which amounts to 25 to 123 gallons per 1,000 square feet.

The 10-gallons-per-1,000-square-feet value appears to be the industry standard, at least in Texas, and is referred to by the American Rainwater Catchment Systems Association (Audrey 2015) and is why we chose this value for our analysis. However, as shown above, recent research suggests that perhaps larger amounts of water should be diverted from the tank to protect water quality.

Storage for rainwater harvesting ranges from a 55-gallon rain barrel (and smaller) to hundreds of thousands of gallons (and larger). Accordingly, the total storage volume, V_{tot}, required varies according to catchment area, precipitation, and use. Areas with more rainfall usually require a smaller amount of storage, while areas in more arid climates require larger storage volumes. The volume of the water in storage, V_t, can also vary depending on recent rainfall and daily use. We used 30,000 gallons of storage as the "base" volume for our analyses because this is the commonly installed volume in the Texas Hill Country for whole-house systems and is cost-competitive to drilling a well.

For daily, firm use, V_u, we investigated a range of 10 to 160 gallons per day. We based the lower value, in part, on Petrie (2020), who lives off the grid near Bastrop, Texas, with 3,000 gallons of storage and an average daily use of 10 gallons per person per day. WCAC (2022) reported annual medians for residential daily water use in Texas of 65 to 72 gallons per person per day for 2017 through 2021 with 66 for 2021, but this includes outdoor use. People who rely on rainwater to meet their indoor water needs do not tend to use their supply for outdoor irrigation. Hermitte and Mace (2012) reported that 31 percent of total residential use in the state was for outdoor use. Assuming this percentage applies to the more recent WCAC (2022) numbers, average indoor water use in Texas is perhaps 45 to 50 gallons per person per day.

Some may question these low numbers as compared to typical urban use of water. People who rely on rainwater to meet their water needs tend to be efficient users of their water (Capehart and Eden, 2021). High-efficiency homes in general use 36.7 gallons per person per day (DeOreo and others 2011). California state agencies recommend indoor water use standards of 55 gallons per person per day by 2023, 47 by 2025, and 42 by 2030 (CA- DWR, 2021). Californians currently use 48 gallons per person per day, with a quarter of homes using less than 42 (CA-DWR, 2021). Denver Water would like its customers to use 40 gallons per person per day indoors (they are currently using about 50) (Denver Water 2025). One of us (Mace) lives in Austin with a partner, eight cats, WaterSense-rated fixtures, EnergyStar-rated appliances, dual-flush toilets, and no outdoor use, resulting in about 35 gallons per person per day. A two-year pilot project by the 50 Liter Home Coalition and the U.S. Green Building Council California, with 31 homes using existing water-efficiency products such as plumbing fixtures, faucets, appliances, and consumables, reduced indoor water use to 23 gallons per person per day (Du Brow 2025).

Although we used indoor household use to define the range of water demands we investigated, it ultimately does not matter what the water is used for—what matters is the amount. For example, a building seeking to use rainwater for indoor non-potable uses could also use our approach to design a firm rainwater system.

Just as surface-water reservoirs collect sediment, so do rainwater-harvesting systems. In surface-water reservoirs, the part of storage dedicated to sediment collection is called the dead pool. Potable rainwater harvesting systems should also have dead pools to protect the integrity of water quality and filters in the system. Audry (2015 p 2-7) recommends placing the outflow pipe greater than or equal to 4 inches from the bottom of the storage or using a floating outflow device.

Ultimately, the size of the dead pool depends on the quality of water entering the tank (sediment load), quality requirements for the end use of the water, and the design of the intake (how water is removed from the tank), among other factors. We assumed that the dead pool was 5 percent of the total storage. For a 30,000-gallon tank with a diameter of 26.33 feet, 5 percent of storage is 1,500 gallons and represents 4.4 inches of water in the tank.

Analyzed Locations

We chose our analysis sites based on having at least one site in each of the regional water planning areas. For water planning areas that extended across a range of precipitation amounts, we chose two sites. We also based site selection on the availability of daily precipitation records that included the drought of the 1950s. In all, we selected 19 locations across the state: Abilene, Amarillo, Austin, Brownsville, Dallas, Del Rio, El Paso, Fort Davis, Hallettsville, Houston, Laredo, Lubbock, Lufkin, Midland, San Angelo, San Antonio, Texarkana, Waco, and Wichita Falls (Figure 1). Average annual precipitation for these gages ranged from 14 inches in El Paso to 52 inches in Texarkana (Table 1).

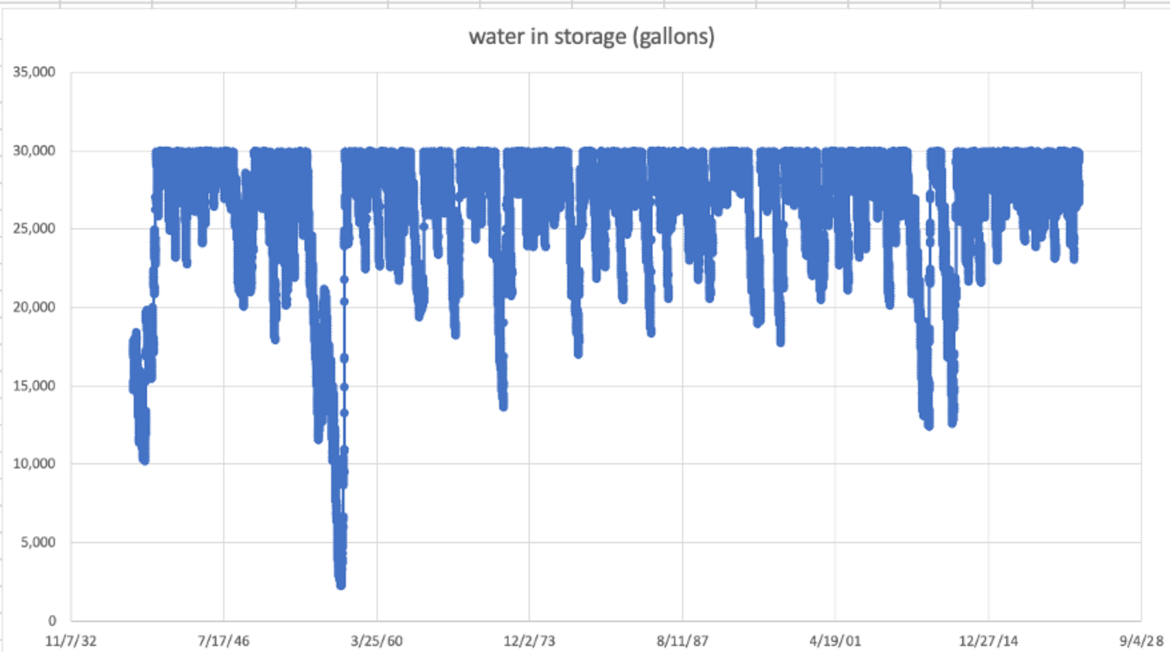
We downloaded precipitation data from NOAA (2023) where the shortest record was 76.4 years long for Laredo and Corpus Christi and the longest record was 131.1 years long for Texarkana (Table 2) with an average record of 93.3 years. Early data collection was often incomplete, so we truncated incomplete early data resulting in a shortest record of 58.8 years long for Laredo and a longest record of 131.1 years for Texarkana (Table 2) with an average record of 89.3 years. This truncation still resulted in incomplete records for 10 of the locations. In these cases, we assigned days without measurements a value of zero. This means that our analysis may slightly underestimate firm yields since the record is probably missing some days that rained. However, most days in Texas do not see precipitation. For example, 87 percent of the days in El Paso, 82 percent of the days in San Angelo, 77 percent of the days in Austin, and 69 percent of the days in Houston recorded no precipitation (these numbers are based on the data we downloaded from NOAA [2023]).

Assessing Firm Yield

We used the RAINFAL spreadsheet to estimate firm yields, which we defined as when reliability equals 100 percent over the period of record without storage in the tank falling below the dead pool.

There are three primary variables when calculating the firm yield of a rainwater harvesting systems: (1) rainfall, (2) catchment area, and (3) storage. To facilitate interpretation, we conducted three separate analyses: (1) the minimum amount of storage required to achieve a firm yield for a range of daily water use with a fixed catchment area of 3,000 square feet, (2) the minimum amount of catchment required to achieve a firm yield for a range of daily water use with a fixed storage volume of 30,000 gallons, and (3) the maximum daily water use to achieve a firm yield for a fixed roof area of 3,000 square-feet and a fixed storage volume of 30,000 gallons.

	A	B	C	D
1				
2	RAINFAL (Rainwater Assessment and Interactive eNumator for Firm-yield Analysis Limits)			
3	*items in* **red** *are user-assigned; items in* **black** *are calculated*			*version: 2025-0528*
4	**Austin**			
5	*Weather station:*	**Camp Mabry**		
6				
7	**user-adjusted parameters:**			
8	**Ar**	**3,000**	ft*ft	*catchment area*
9	**Vt**	**30,000**	gallons	*volume of storage*
10	**daily demand**	**94**	gallons per day	
11	**runoff coefficient**	**0.92**	unitless	*what fraction of rain runs off catchment*
12	**precip adjuster**	**1**	unitless	*fractional adjustment to precipitation record*
13				
14	**conversions & calculations:**			
15				
16	**Vt**	**4010.4**	ft*ft*ft	*volume of storage*
17	**Vff**	**4.01**	ft*ft*ft	*volume of first flush (assumes 10 gallons per 1,000 square feet)*
18	**daily demand**	**12.57**	ft*ft*ft per day	
19	**starting tank storage**	**50**	percent full	*should be greater than dead pool percentage to determine firm yield*
20	**starting tank storage**	**2005.2**	ft*ft*ft	
21	**dead pool**	**5**	percent full	
22				



dead pool storage:	**1500**	gallons
lowest storage:	**2224**	gallons
reliability:	**100.00**	percent
days with no water:	**0**	days
overflow:	**1,602,338**	gallons

Figure 1. Input and output of the Rainwater Assessment and Interactive eNumator for Firm-yield Analysis Limits (RAINFAL, version 2025-05).

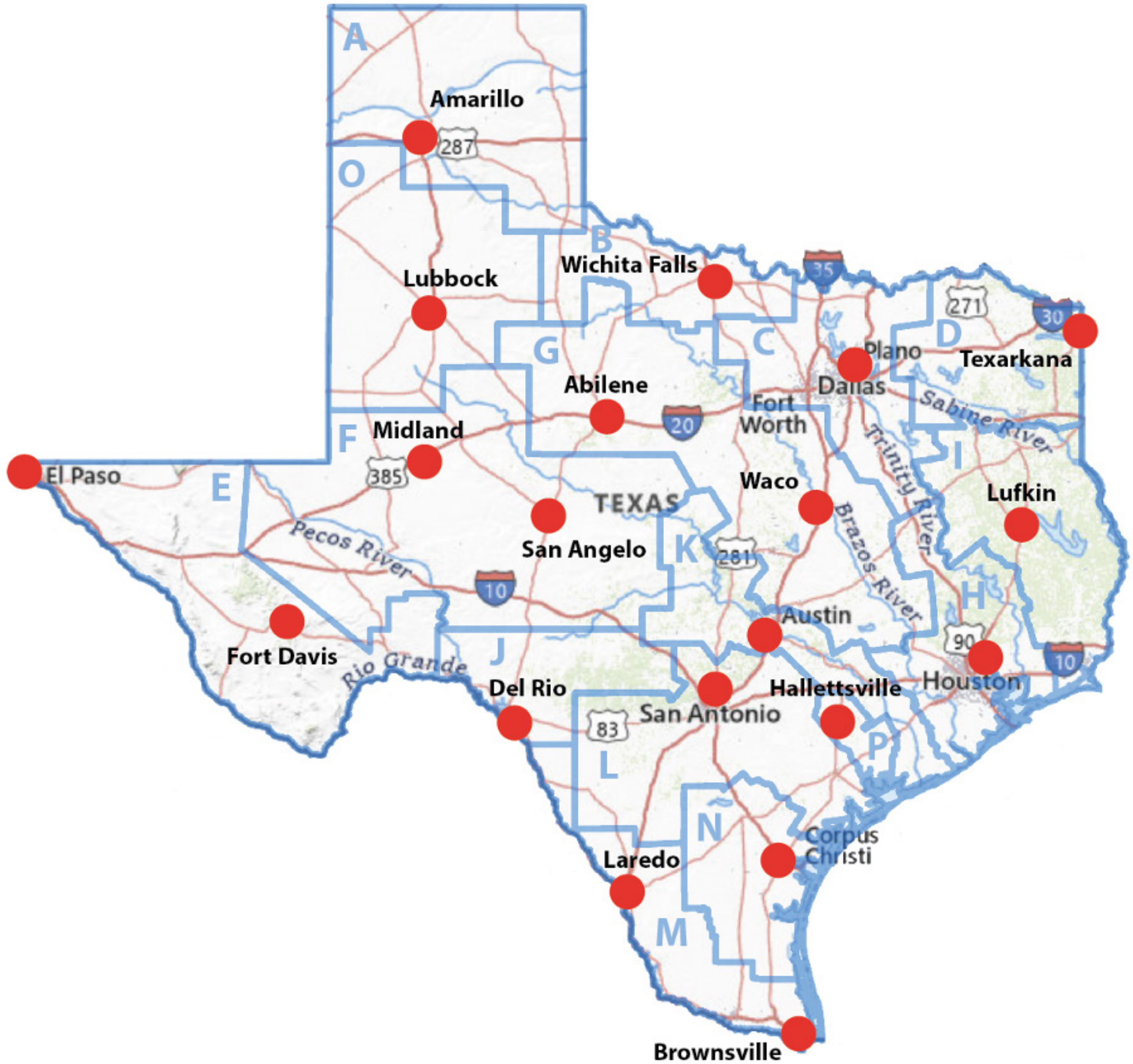


Figure 2. Location of weather stations (red dots) in the sixteen regional water planning areas (outlined in blue and named with letters) analyzed in this study.

Table 1. Average annual precipitation (1991 through 2020) for the cities included in the study (based on data from NCEI 2025a).

CITY	AVERAGE ANNUAL PRECIPITATION (inches)
Abilene	25.2
Amarillo	19.7
Austin	36.2
Brownsville	26.8
Corpus Christi	31.7
Dallas	38.3
Del Rio	19.8
Fort Davis	14.0
El Paso	8.8
Hallettsville	40.4
Houston	51.8
Laredo	21.4
Lubbock	19.4
Lufkin	50.3
Midland	15.0
San Angelo	20.9
Texarkana	52.4
Waco	36.4
Wichita Falls	27.9

Table 2. Range and coverage of available precipitation data for the different cities in our analysis before and after truncating time with missing data (data from NOAA 2023).

REGION	CITY	COVERAGE (dates of coverage [years])	DATA COVERAGE	FINAL COVERAGE (dates of coverage [years])	DATA COVERAGE (days missing)
A	Amarillo	3/1/1943–2/25/2023 (80.0)	95%	1/1/1947–2/25/2023 (76.0)	100% (0)
B	Wichita Falls	1/1/1897–2/25/2023 (126.2)	94%	1/1/1900–2/24/2023 (123.2)	100% (2)
C	Dallas	8/1/1939–3/20/2023 (83.6)	100%	8/1/1939–3/20/2023 (83.6)	100% (0)
D	Texarkana	2/1/1892–2/24/2023 (131.1)	95%	3/1/1892–2/24/2023 (131.1)	97% (1,836)
E	Fort Davis	1/1/1902–2/22/2023 (121.3)	87%	12/1/1911–2/22/2023 (112.3)	90% (4,031)
E	El Paso	4/1/1938–2/25/2023 (84.8)	100%	4/1/1938–2/25/2023 (84.8)	100% (0)
F	San Angelo	8/1/1907–3/16/2023 (115.6)	97%	10/1/1944–3/16/2023 (78.5)	99% (61)
F	Midland	6/1/1930–2/27/2023 (93.3)	100%	6/1/1930–2/27/2023 (93.3)	100% (0)
G	Abilene	8/1/1946–4/20/2023 (76.7)	98%	1/1/1948–4/20/2023 (75.3)	100% (1)
G	Waco	1/1/1941–3/2/2023 (82.2)	100%	1/1/1941–3/2/2023 (82.2)	100% (0)
H	Houston	6/1/1930–3/3/2023 (92.8)	96%	6/1/1930–3/3/2023 (92.8)	96% (1,412)
I	Lufkin	10/1/1906–2/23/2023 (116.4)	96%	11/1/1906–2/23/2023 (116.3)	97% (1,458)
J	Del Rio	8/9/1946–2/23/2023 (76.5)	87%	3/1/1963–2/23/2023 (60.0)	100% (1)
K	Austin	6/1/1938–2/9/2023 (84.8)	100%	6/1/1938–2/9/2023 (84.8)	100% (0)
L	San Antonio	8/14/1946–2/25/2023 (76.5)	100%	8/14/1946–2/25/2023 (76.5)	100% (0)
M	Brownsville	12/1/1898–2/24/2023 (124.3)	80%	1/1/1948–2/24/2023 (75.2)	100% (0)
M	Laredo	9/1/1946–2/25/2023 (76.4)	77%	4/20/1965–2/25/2023 (58.8)	99% (278)
N	Corpus Christi	9/1/1946–2/25/2023 (76.4)	98%	1/1/1948–2/25/2023 (75.2)	100% (0)
O	Lubbock	8/10/1945–2/25/2023 (77.5)	98%	1/1/1947–2/25/2023 (76.2)	100% (0)
P	Hallettsville	1/1/1893–2/21/2023 (130.2)	98%	1/1/1893–2/21/2023 (130.2)	99% (510)

Results and Discussion

Our results include firm yields for different storage volumes, firm yields for different catchment areas, and the defining droughts for the different firm yields.

Firm Yields for Different Storage Volumes

To investigate the storage volumes required to achieve firm supplies for homes in various parts of the state, we estimated firm yields for different amounts of use for a catchment area of 3,000 square feet.

Not surprisingly, the wetter, eastern parts of the state required smaller storage volumes to achieve firm yields as compared to the drier, western parts (Figure 3). For example, storage of about 30,000 gallons can reliably meet about 160 gallons per day of use in Houston (Figure 3t) while almost 130,000 gallons are needed in Dallas (Figure 3q) to reliably meet the same level of use (note that when we use "reliable" in this context, we mean 100-percent reliability through a repeat of the drought of record).

The firm yield curves for storage all bend upwards to a certain degree with less upward bending in higher-rainfall cities than lower rainfall cities (Figure 3). This is due to less additional catchable rainfall with incrementally larger volumes of storage. At some point, the system captures all the precipitation that falls on the catchment during the period of record such that additional storage has no additional benefit. In these cases, total rainfall volume for the specified catchment area limits the firm yield (you can only get what you can get). You could collect more rainfall—and support higher use levels—with additional catchment area.

The drier the climate, the less likely the rainwater harvesting system is going to reliably support higher volumes of use. A dramatic case of this is El Paso where the most water use that can be supported with a 3,000 square-foot roof is about 30 gallons per day (Figure 3a), enough to support one water-conserving person. In all cases across the state, the rainwater harvesting systems we investigated could achieve a firm yield, albeit at lower use levels. If there is rain, there is a firm yield.

It is unlikely that a home would have storage of 140,000 gallons, so we next focused on storage up to 50,000 gallons for the investigated cities to give a closer look at the curves relative to each other (Figure 4). Storage for rainwater-fed homes in the Hill Country is typically 30,000 to 40,000 gallons, so 50,000 gallons did not seem unreasonable for drier climates. Again, in all cases, firm yields for the entire state can be attained for all the cities investigated for the specified catchment and with storage less than 50,000 gallons. Drier climates require lower levels of daily use, but, given that 25 gallons per person per day is achievable in a water-conserving home, all but El Paso, Midland, and Fort Davis meet that standard with a system with 3,000 square feet of catchment.

In the north and central parts of the state, there is a mixture of high and moderate firm yields based on storage with a catchment of 3,000 square feet. Due to decreasing precipitation to the west, the lines began to curve upwards and pull back from the higher yields (Figure 4). Dallas, Hallettsville, and Waco can support higher firm yields than Austin, Wichita Falls, and drier cities for storage less than 50,000 gallons (Figure 4).

It may be surprising to some (as it was to us) that there are many parts of the state not usually associated with rainwater harvesting that could easily support rainwater harvesting. For example, Wichita Falls is just as good for rainwater harvesting as the Austin-San Antonio area, a region already known for rainwater harvesting. Corpus Christi, Brownsville, and Abilene are also not that different than the Austin-San Antonio area. Storage and catchment may have to be bigger, but rainwater harvesting certainly looks doable in Laredo, Del Rio, and Amarillo as well as other drier locales.

The southern and western parts of the state can achieve lower firm yields given the catchment area (Figure 4). El Paso, Midland, and Fort Davis produced the lowest firm yields based on storage size and a catchment of 3,000 square feet (Figure 4). El Paso achieved the smallest firm yields with the corresponding largest required storage—not unexpected for the driest city in the state (Figure 4). However, it may be surprising that a firm yield could be achieved at all in the city, let alone one that could supply one person or, with a doubling of the system (6,000 square feet of catchment and 60,000 gallons of storage) reliably support two people at 67 gallons of firm yield per day.

The biggest storage for firm yields in Midland was about 70,000 and for Fort Davis it was about 45,000. Despite being more west than Midland, Fort Davis has higher rainfall; however, areas with higher elevations can obtain more rainfall throughout the Big Bend. In the western part of the state, rainwater harvesting can be more difficult and yields less water but is possible given the proper amount of use, catchment area, and storage.

The eastern part of the state could more easily support higher firm yields than the rest of the state due to higher amounts of precipitation (Figures 3 and 4). Houston, Lufkin, and Texarkana had the highest firm yields compared to all the other cities. Houston was able to edge-out Lufkin with a storage of about 30,000 gallons versus about 32,000 for a catchment area of 3,000 square feet and daily use of 160 gallons, enough to support 6.4 people at 25 gallons per person per day.

One unexpected aspect of our analysis is that the drought that defined the firm yield changed depending on the demand for firm water, catchment area, and storage volume. Eighteen of the 19 cities had different defining droughts depending on the demand (Figure 3). In the case of Corpus Christi with a fixed 3,000 square-foot catchment and floating storage, a drought that ended in 1964 was the defining event for a firm yield of 90 gallons per day, 1971 was the defining event for 30 gallons per day, 2009 for 40 gallons per day, and 2010 for 60 gallons per day (Figure 5). This means that the drought of record for a rainwater harvesting system is as much a function of the system (catchment, storage, and use) as the rainfall. This also means that the local drought-of-record, generally defined as the drought-of-record for local surface-water resources, is not likely to be the same drought-of-record for a rainwater harvesting system.

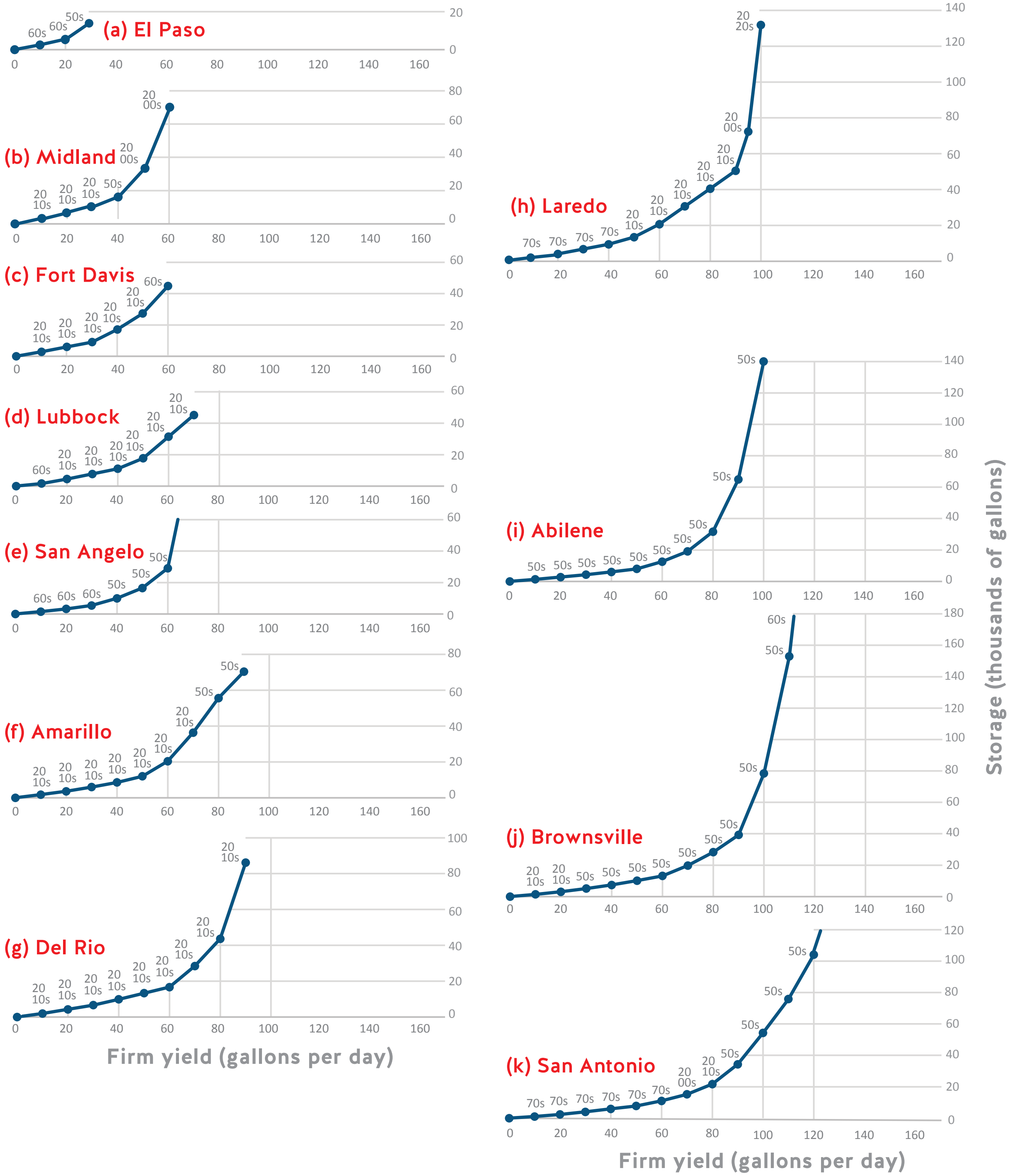


Figure 3. Storage required to achieve a range of firm yields for a catchment of 3,000 square feet for a variety of Texas cities. I organized these graphs from least amenable to rainwater harvesting to most amenable. Note that each graph is on the same horizontal and vertical scale to allow direct comparison between plots. Also note that the plots end at the maximum achievable firm yield (for the use levels investigated). Numbers next to data points represent the decade in which the defining drought ended.

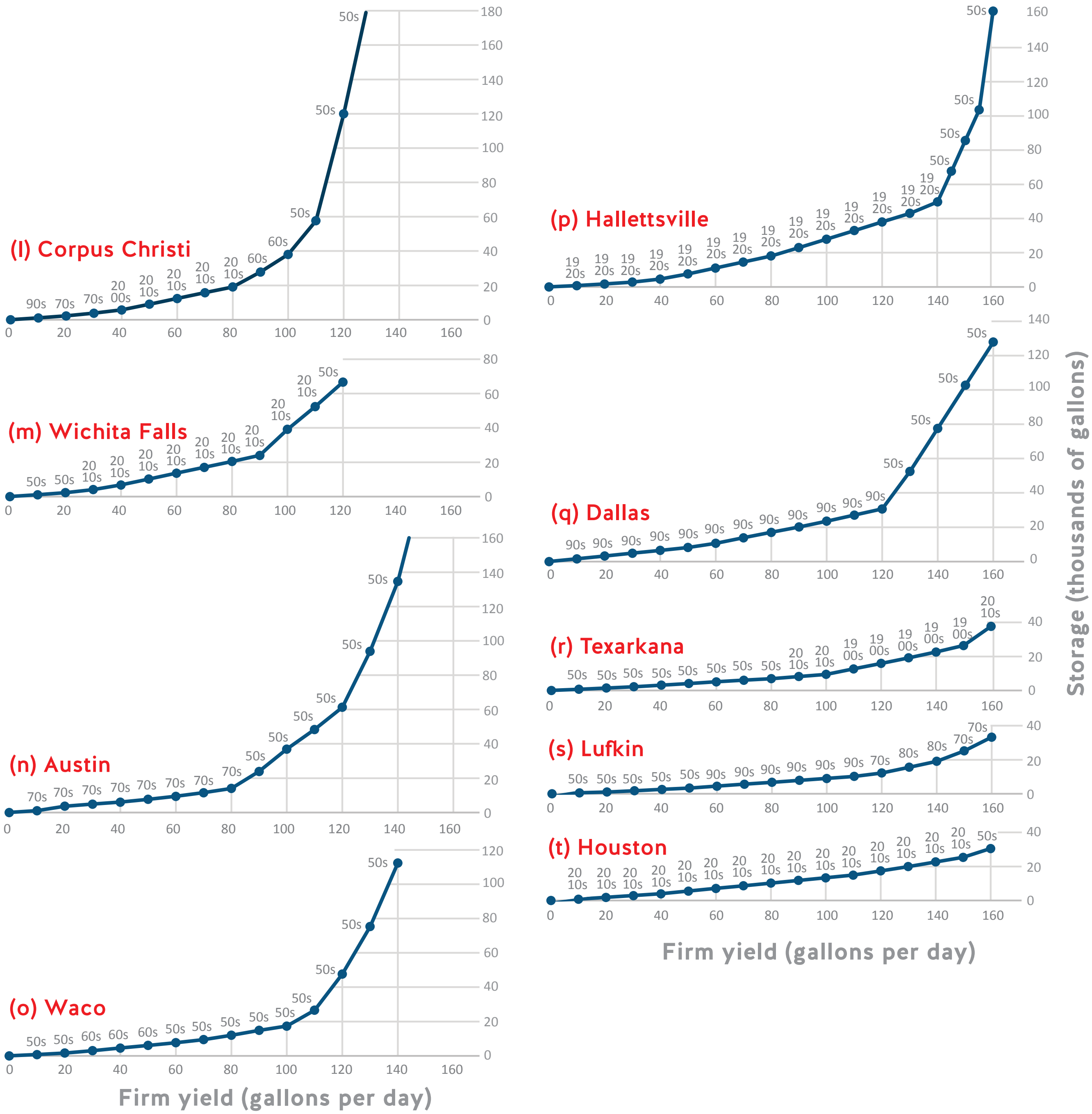


Figure 3. Continued.

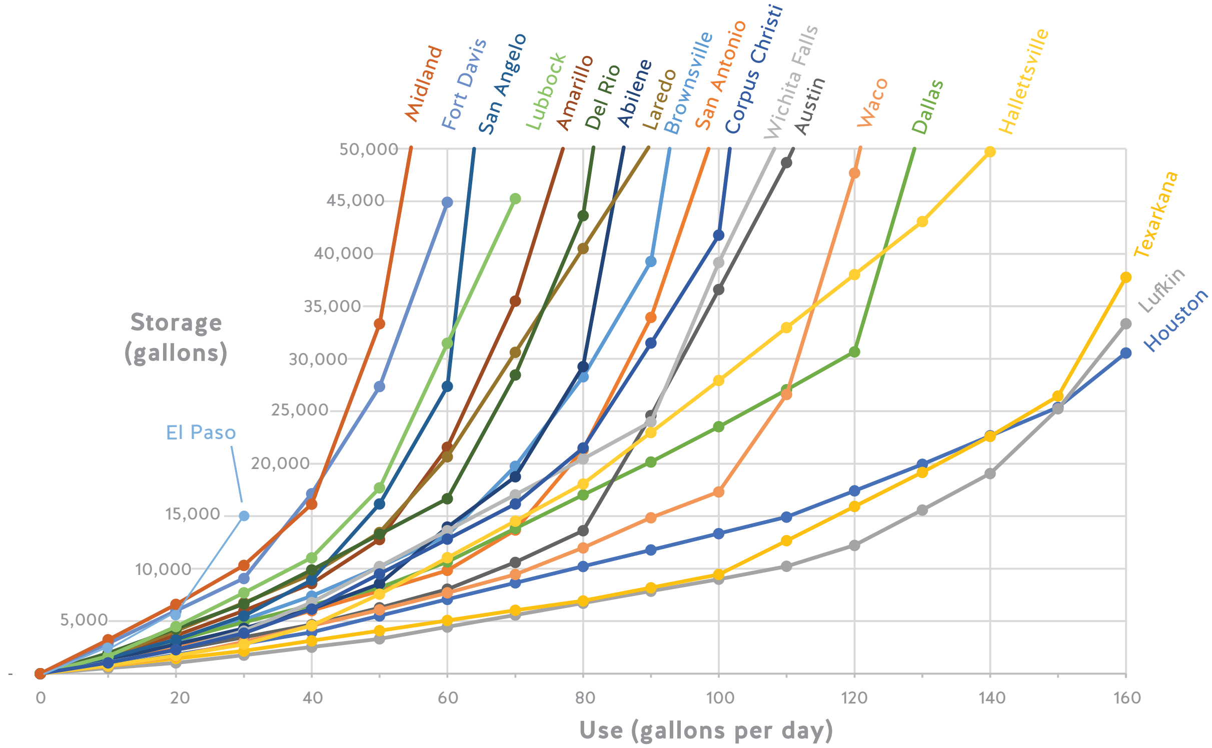


Figure 4. Storage required to achieve a range of firm yields for a catchment of 3,000 square feet for a variety of Texas cities with storage capped at 50,000 gallons.

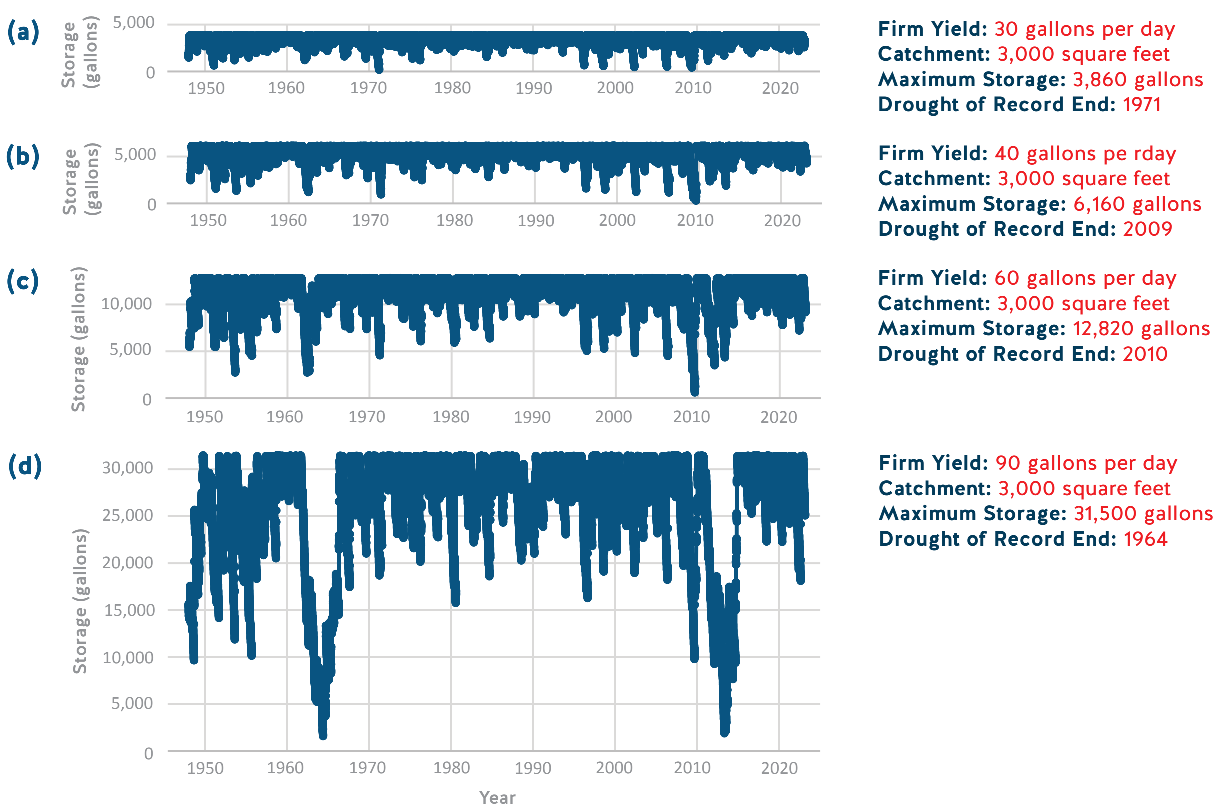


Figure 5. Storage performance for four demand/firm use scenarios with a set catchment area for Corpus Christi. Note that each scenario for the same location results in a different drought of record for the rainwater harvesting system.

Firm Yields for Different Catchment Areas

To investigate the catchment areas required to achieve firm supplies for different parts of the state, we estimated firm yields for a standard storage volume of 30,000 gallons. Not surprisingly, smaller catchment areas are needed in the wetter, eastern parts of the state than the drier, western parts (Figure 6). For example, a catchment of about 3,000 square feet can reliably meet about 160 gallons per day of use in Houston (Figures 6t and 7) while almost 7,400 square feet of catchment is needed in Dallas (Figures 6n and 7) and about 33,600 square feet is needed in Lubbock (Figure 6e) to reliably meet the same level of use (note that when we use "reliable" in this context, we continue to mean 100 percent reliability).

The firm yield curves for catchment all bend upwards to a certain degree with less upward bending in higher-rainfall cities than lower rainfall cities (Figure 5). This is because the ability to meet higher firm yields becomes more and more focused on shorter and more intense drought events until the firm yield (as it gets larger) is focused on the most intense drought event. Once increasing firm yields are defined by the most intense, short-term drought event, the increase in catchment becomes linear with the increase in firm yield (Figure 7). With a fixed catchment, there is a maximum amount of rainfall you can collect and a maximum firm yield; however, you can increase catchment to achieve a larger firm yield, at least until the catchment area becomes unaffordable or unattainable (such as continental-sized roofs!).

Catchment areas to achieve larger firm yields in drier climates with fixed storage must be larger than in wetter climates, sometimes substantially larger. For Midland to achieve a firm yield of 100 gallons per day with 30,000 gallons of storage requires a catchment of about 81,000 square feet while Houston only requires a catchment of about 1,700 square feet (Figures 5 and 6). While 81,000 square feet of catchment on a home may be unattainable for most of us, the square-footage of big box retail and large manufacturing centers would be able to support much larger firm yields. For example, Wal-Mart supercenters range from 99,000 to 250,000 square feet (ILS-R 2006), and the Tesla Gigafactory in Austin has a catchment of 4.2 million square feet (CAPE Analytics 2023).

Giga Texas is expected to use about 734 gallons per car (Fox, 2023) and currently produces 5,000 vehicles a week (Bleakly, 2023) which equals a daily water demand of 524,000 gallons per day (it was unclear if this is consumptive use or not). Our model shows that even with the gigafactory's massive roof, regardless of the amount of storage, it is not possible to meet that water demand. However, with 25 million gallons of storage (municipality-sized storage tanks), Giga Texas could reliably produce 117,000 gallons a day. Because rainwater has low total dissolved solids (and many manufacturing uses require removing solids from source water), its freshness may provide additional cost savings.

It is unlikely that a home would have a catchment of 70,000 square feet, so we next focused on catchments up to 10,000 square feet for the investigated cities (Figure 6). Again, in all cases, firm yields for the entire state can be attained for all the cities investigated for the specified storage and with catchments less than 10,000 square feet. Again, drier climates require lower levels of daily use, but, given that 25 gallons per person per day is achievable in a water-conserving home, all cities could achieve that firm yield with catchment less than 4,000 square-feet (Figure 6).

Similar to our analysis on storage, the drought that controlled the firm yield changed depending on demand for firm water. All 19 cities had different defining droughts depending on the demand.

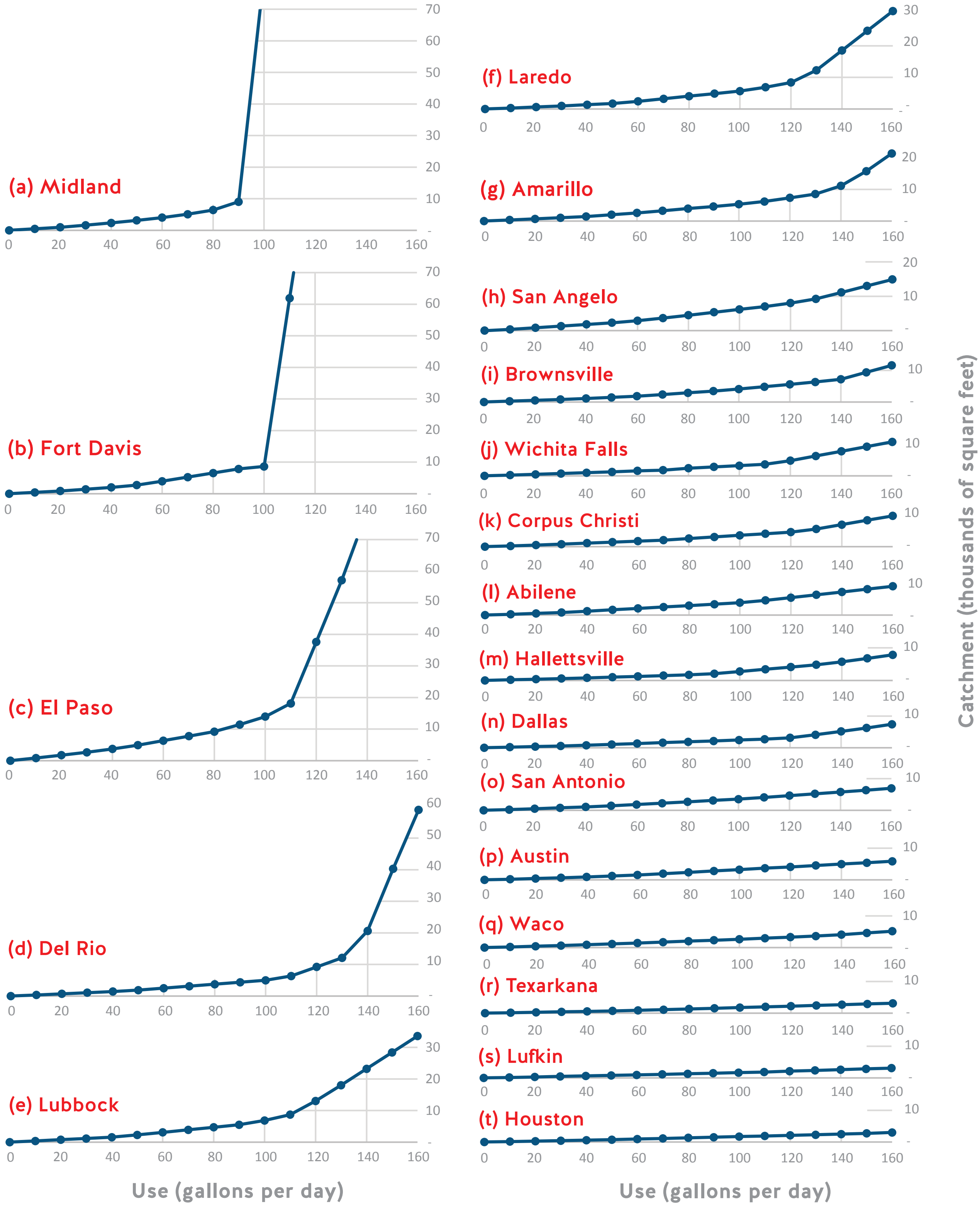


Figure 6. Catchment required to achieve a range of firm yields for storage of 30,000 gallons for a variety of Texas cities. We organized these graphs from least amenable to rainwater harvesting to most amenable. Note that each graph is on the same horizontal and vertical scale to allow direct comparison between plots.

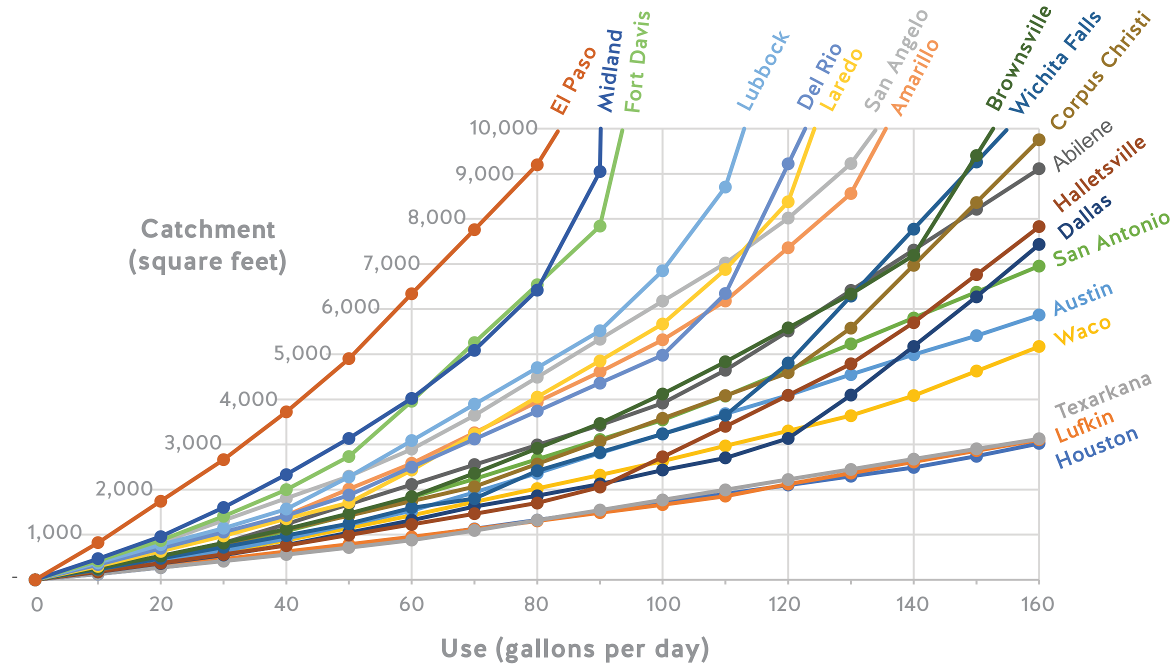


Figure 7. Catchment required to achieve a range of firm yields for storage of 30,000 gallons for a variety of Texas cities with catchment capped at 10,000 square feet.

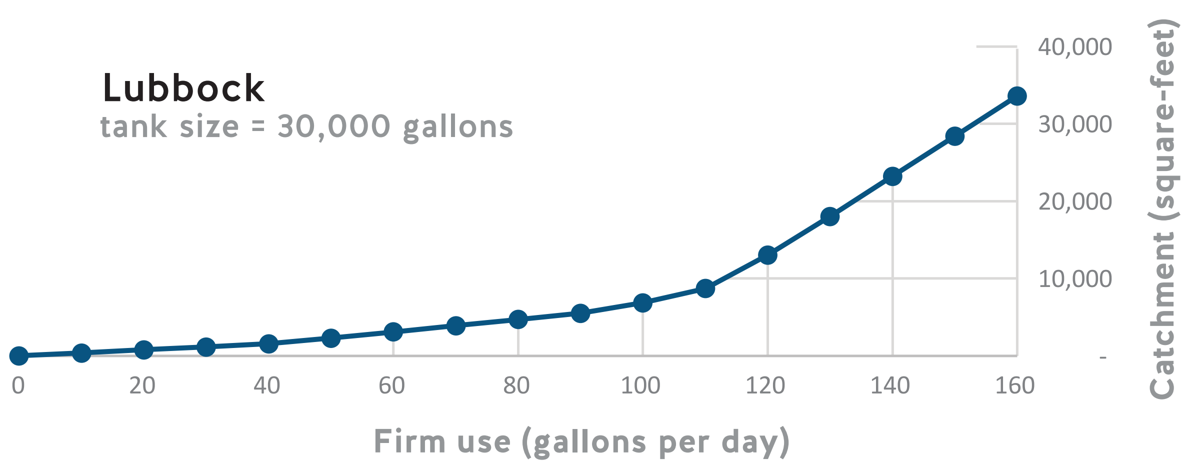


Figure 8. Example of increasing catchment area with increasing firm use for Lubbock.

A Map of Firm Yield for Rainwater Harvesting

We used RAINWATR to develop a state-wide map of firm yields for rainwater harvesting for 3,000 square feet of catchment and 30,000 gallons of storage to demonstrate the potential for rainwater harvesting across the state.

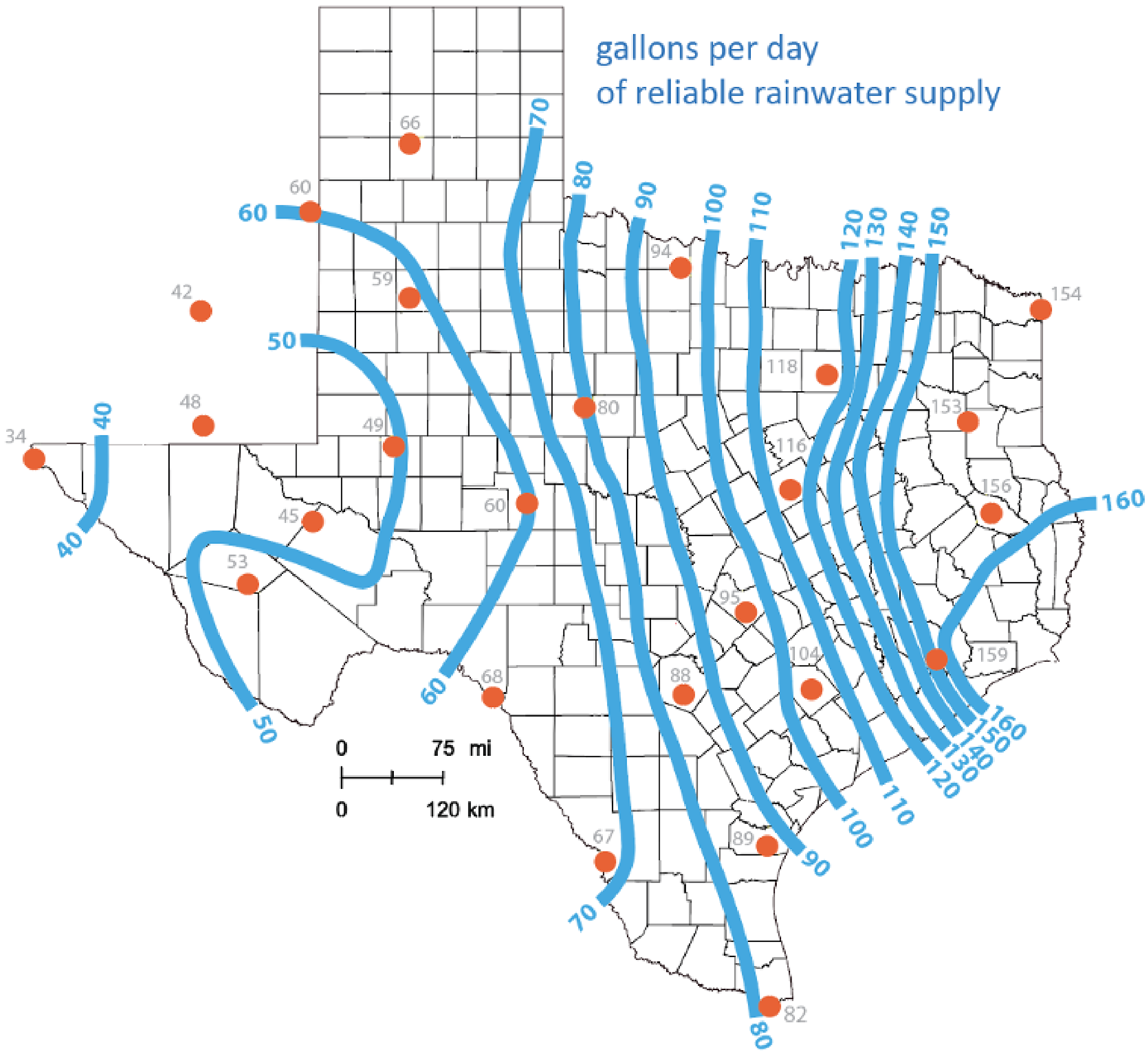


Figure 9. Statewide map of reliable rainwater harvesting in gallons per day of firm yield. This is for a system with 3,000 square feet of catchment and 30,000 gallons of storage—more could be captured with larger catchments and storage volumes. The sudden change in contour-interval spacing in East Texas is due to the storage limiting the catch of higher rainfall amounts.

Reliability

Many rainwater harvesting installers in Central Texas design systems with the expectation that the owner will need to haul water when the tank runs dry. While it is good to have contingency plans for a failed tank (a worse-than-expected drought, a broken pipe, or a drunk brother-in-law backing into the tank), it is also good to present the homeowner with the option of what a drought-proof system looks like.

Furthermore, when balancing the cost of increased storage with the cost of hauling water, an accurate assessment of reliability is needed.

System owners and operators should also be made aware of how often they might need to haul water. RAINFAL provides the number of days the system is not sufficient to meet demands, and the plot allows the user to see how many events might occur over the record. For example, for a 3,000 square-foot roof and a yield of 100 gallons a day, a system in Austin needs 36,500 gallons of storage to be 100 percent reliable (based on past rainfall). For 99.9 percent reliability, the storage requirement drops to 31,800 gallons but with 32 days with no water in one event (Figure 10b). For 99.5 percent reliability, the storage requirement drops to 21,000 gallons but with 154 days with no water in two events (Figure 10d). For 98 percent reliability, the storage requirement drops to 12,000 gallons but with 619 days with no water in at least one event every decade (Figure 10d). In this way, an owner can decide if the extra cost for 100 percent reliability is worth it and, if not, what level of hauling water are they comfortable with.

Robustness for the Future

Drought of record and firm yields are inherently backward-looking. Looking forward, there is always a chance of a new drought of record, and several have been experienced around the state for surface-water reservoirs such as Lake Meredith north of Amarillo and the Highland Lakes upstream of Austin. Some water providers and regional water planning groups use safe yield instead of firm yield to build in additional resilience if they experience a new drought of record.

Global warming is also expected to affect the climate and hence the weather. Unlike river basins, where increased temperatures can increase evapotranspiration, rooftops do not evapotranspire (unless they are green rooftops). Furthermore, due to closed storage, rainwater harvesting systems are not subject to increased evaporation. Climate projections do not agree on whether Texas, or parts of Texas, will experience drier or wetter conditions, although long-term trends show a wetting trend in the eastern part of the state and a drying trend in the west (McPherson and others 2023). General projections suggest more rainfall in fewer rainfall events (McPherson and others 2023).

Preliminary analysis using RAINFAL suggests, not surprisingly, more storage or catchment is needed for lower amounts of precipitation but also that more storage or catchment is needed if annual precipitation amounts stay the same but individual events become more intense (Mace and Briones 2023).

With rainwater harvesting, more—more storage and more catchment—is almost always better (except for use, which is always better when lower). So when designing a system, which under ideal conditions would include designing the catchment, rounding up on tank size is advisable. Using the “Precip adjustor” option in RAINFAL allows a user to proportionally adjust the precipitation up or down according to preference. Based on a review of climate projections, we suggest decreasing rainfall by 15 percent to build additional robustness in your rainwater harvesting system.

Is Rainwater Harvesting Conservation or Supply?

In an urban setting, rainwater harvesting often exists in a purgatory between water conservation and water supply. The Texas Water Development Board describes water

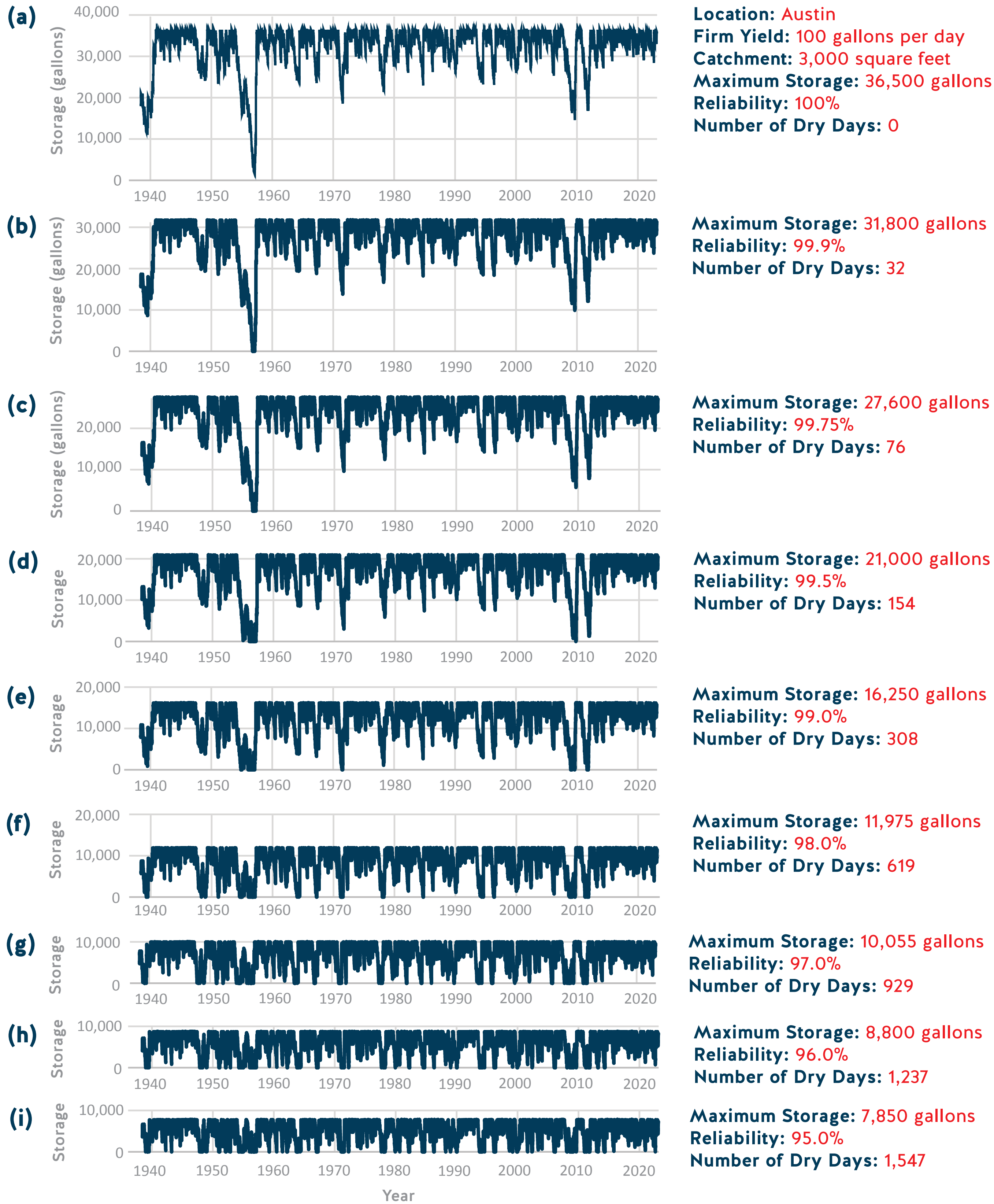


Figure 10. Reliability for a rainwater system in Austin.

conservation as "…practices, techniques, programs, and technologies that will protect water resources; reduce water consumption, loss, or waste; or improve the efficiency of water use" (TWDB 2012 p 119). Rainwater harvesting acts as a water conservation strategy in reducing the consumption of, and thereby conserving, conventional supplies such as rivers and aquifers.

But rainwater is clearly a supply unique from surface water or groundwater. For those who rely on rainwater harvesting to meet all of their needs, rainwater is unquestionably a supply rather than a water conservation strategy. In some areas of the Texas Hill Country where the Trinity Aquifer does not yield adequate fresh water, rainwater is the only supply of water.

The Board further states that water conservation is "a water management strategy that can make a water supply available for future or alternative uses, without restricting desired economic or other activities" (TWDB 2012 p 119). This infers that the benefits of water conservation are permanent and consistent such that those benefits can be assigned elsewhere. For example, if someone conserves water through the installation of water-efficient fixtures, that conserved water is now available to meet growing demands[3].

However, if a rainwater harvesting system is not designed to provide a firm supply during droughts, then any water savings are not assignable to other users. This suggests that rainwater harvesting is not a water conservation strategy. Furthermore, if a rainwater harvesting system does not provide a firm yield, then it is not a water supply either (or, if it is, then it is a water supply with a firm yield of zero). If a rainwater harvesting system is not firm, then it fails at the worst possible time: when conventional sources are in severe drought and water providers, managers, and regulators are trying to reduce use. In this case, water use dependent on a non-firm rainwater harvesting system transfers to the conventional supply. For rainwater harvesting to scale up, it needs to be designed to be firm to increase the resilience of the overall water-supply portfolio.

Rainwater Harvesting and Groundwater Management Plans

The Texas Water Code requires groundwater conservation districts to address rainwater harvesting where appropriate and cost-effective. Most of the 98 districts (77 percent) educate and promote rainwater harvesting, but the rest (23 percent) believe that rainwater harvesting is not appropriate or cost-effective. One district states that "With average annual precipitation in the District about 39 inches, a goal of rainwater harvesting is not applicable at this time," while others with semiarid climates note inapplicability due to a lack of rain. Another claims too much rainfall.

As our study shows, rainwater harvesting can be done reliably anywhere in the state, including El Paso. We would argue that there is no such thing as too much average annual rainfall: conserving source water is conserving source water. Furthermore, it does not take much groundwater production to unsustainably produce an aquifer (Mace

3 *There is also some debate on "conservation" versus "efficiency" where conservation results in water retained in the environment whereas increased efficiency allows an existing resource to meet more demands. In this case, what the Texas Water Development Board defines as conservation is really efficiency.*

2021, 2022), so conserving groundwater by using rainwater has benefits in even the wettest parts of the state.

Rainwater Harvesting and Regional Water Planning

Regional and state water planning in Texas is premised on providing water through a repeat of the drought of record. In other words, how much water can a water supply reliably provide during a repeat of the drought of record? For surface-water resources in Texas, this is referred to as the firm yield. If a water supply is designed such that it cannot provide water through a drought of record, then its firm yield is zero. Therefore, by definition, rainwater harvesting systems that are not designed to provide supplies through the worst drought appropriately have firm yields of zero.

We quoted the 2012 State Water Plan in our introduction as stating, “While it is often a component of municipal water conservation programs, rainwater harvesting was not recommended as a water management strategy to meet needs since, like brush control, the volume of water may not be available during drought conditions” (TWDB 2012). However, since that plan, state water plans have included rainwater harvesting (TWDB 2017, TWDB 2022). The 2017 State Water Plan had about 17,000 acre-feet per year for rainwater harvesting in 2070 (TWDB 2017 p 97), and the 2022 State Water Plan had about 5,000 acre-feet per year (TWDB 2022 p 109) (Table 3). However, our review of these strategies suggests that they are not drought-proof supplies.

The initially prepared plans for the upcoming 2027 State Water Plan include some ambitious plans for rainwater harvesting, with consideration of reliability. The South Central Texas Regional Water Planning Group includes 470,127 potable household rainwater harvesting systems and 6,789 non-potable household systems (SCTWWPG 2025 p 5.2.11-3–5.2.11-4).

Table 3. Water management strategies in the 2017 and 2022 state water plans concerning rainwater harvesting and the expected 2070 yields.

ENTITY	WATER MANAGEMENT STRATEGIES
2017 STATE WATER PLAN	
City of Austin	19.7
City of Bandera	36.2
La Feria	26.8
2022 STATE WATER PLAN	
City of Austin	4,900 acre-feet per year
City of Bandera	1 acre-foot per year
Dripping Springs Water Supply Corporation	81 acre-feet per year
Hays	7 acre-feet per year
Hays County-other	50 acre-feet per year
Sunset Valley	4 acre-feet per year

The Value of Firm Rainwater Harvesting to Conventional Supplies

The value of reliable rainwater harvesting is that the systems will not require make-up water during severe droughts, including a repeat of the drought of record. This means that these rainwater harvesting systems will not be seeking water from alternative supplies at the worst possible time—during a severe drought. For example, the Texas Hill Country has been in a severe drought since 2020. With unreliable rainwater harvesting systems failing, the owners of those systems have had to purchase water from other sources and haul that water to their homes to refill their tanks. One of those other sources is the Dripping Springs Water Supply Corporation. However, the drought has affected the Corporation as well resulting in a 40 percent reduction of the authorized use of the aquifer by the local regulatory authority. In response to their own water supply limitation, the Corporation proposed eliminating all bulk water sales to preserve water for their non-bulk customers, including bulk sales for failed rainwater harvesting systems (Anderson 2025). If these rainwater harvesting systems had been designed for a repeat of the drought of record, they would not be taxing an already taxed alternative supply.

The Dripping Springs example concerns a water provider supplying water to outside customers and having the ability to refuse to provide that water. However, if those customers are internal, it is not as easy to deny them service. For example, as previously described, one of us (Mace) has a rainwater harvesting system in Austin with the goal of not using city water outdoors. If that system fails, then that outdoor use will be met with city water instead of rainwater at the worst possible time, amidst a severe drought.

Is There Value in Unreliable Rainwater Harvesting?

Depending on the character of an associated conventional supply, there may be value in unreliable rainwater harvesting. For example, if the conventional supply is an aquifer that is being depleted (pumped at a rate greater than the maximum sustainable yield), then any water not pumped from the aquifer helps to extend the life of that aquifer. In that case, groundwater is being conserved. One gallon of rainwater used instead of groundwater results in saving one gallon of groundwater (minus a proportionate amount of natural discharge, if occurring).

For a surface-water resource or a sustainably managed aquifer such as the Edwards Aquifer, firm or unfirm rainwater harvesting acting alone does not increase the firm or sustainable yield of those water resources just as the management of those resources has no effect on the firm yield of rainwater harvesting. These resources act independent of each other (see the next section on whether or not rainwater harvesting steals water from surface-water or groundwater systems). However, rainwater harvesting could theoretically be conjunctively coordinated with sustainably-managed conventional resources.

Conjunctive use is the management of surface- and ground-water resources in a coordinated way such that the total yield exceeds the sum of the separate yields without coordination (Coe 1990). For example, El Paso and the Canadian River Water Authority each coordinate the use of surface-water resources (Elephant Butte Reservoir for El Paso and Lake Meredith for the Authority) with unsustainable groundwater resources (the Hueco Mesilla Bolson Aquifer for El Paso and the Ogallala Aquifer for the Authority). They achieve this by prioritizing the use of surface water over groundwater when surface water is plentiful and then using groundwater when surface water is not plentiful (the Authority also uses groundwater to address salinity issues in Lake Meredith). In this way, they are extending the usable life of their groundwater resources. This is analogous to using rainwater harvesting to extend the usable life of a depleting aquifer described in the first paragraph of this section.

Unfirm rainwater harvesting could theoretically increase the firm yield of sustainable conventional supplies by leaving more water in the lake or the aquifer thus delaying the time by which the resource has gone dry, either literally (in the case of lakes) or regulatorily (in the [general] case of aquifers). Note that storage of the conventional supply is required here—there would be no local water-supply benefit for run-of-river uses (but there would be downstream benefits).

Is Rainwater Harvesting Stealing Surface Water and Groundwater?

Not uncommonly, the question arises as to whether or not rainwater harvesting adversely affects surface water and groundwater. After all, both conventional water sources rely on rainwater for their replenishment. Are we robbing Peter to pay Paul?

Total roof area in Texas is estimated at 22.5 billion square feet circa 2006 (TRHEC 2006). Applying a proportional adjustment accounting for increased population (population in 2023 was 29.1 million [TDC 2024], population in 2006 was 23.4 million [TSLAC 2011]) results in an adjusted total roof area of 30.1 billion square feet in 2024.

Average annual rainfall in Texas is 27.2 inches (NCEI 2025b 1895 through 2024). However, about two-thirds of Texans live in the eastern half of the state, so instead of an average statewide precipitation number, we used the average of the average precipitation of the East Texas (46.2 inches) and North-Central (33.2 inches) climate divisions (resulting in 39.7 inches per year; NCEI 2025b 1895 through 2024).

So, if every roof in Texas captured every drop of rainfall in an average year, it would amount to 100 billion cubic feet of water, equivalent to 745 billion gallons or 2.3 million acre-feet. However, because of evapotranspiration, this is not a volume that directly affects runoff or recharge.

Ward (2011) estimated statewide evapotranspiration as consuming 86 percent of precipitation (which is why, in large part, runoff coefficients for natural basins are so low). Evapotranspiration consumes 86 percent of precipitation in the Central part of the state and 63 percent in the eastern part of the state (Ward 2011). Because of how Ward (2011) defines his regions, his central part of the state captures nearly all of the eastern urban areas of the state, so we will use 86 percent for consumption of precipitation by evapotranspiration. That means that the impact of statewide rainwater harvesting on natural runoff and recharge processes is only 14 percent of what is captured, resulting in 322,000 acre-feet per year. Of that 322,000 acre-feet per year, about 9 percent (30,000 acre-feet per year) would have partitioned to recharge with the remainder (292,000 acre-feet) going to runoff.

Rainbow after a storm in Mansfield, Texas © Rod Gardner

Average statewide runoff is about 47.7 million acre-feet per year (Ward 2011), so universal rainwater harvesting would decrease statewide runoff by 0.6 percent. While we do not consider that a lot of impact, some might disagree. However, note that the built environment tends to increase runoff by as much as 16 times natural conditions (Schueler 1995) and that impervious cover from rooftops is generally less than impervious cover from transport systems (Schueler 1995). In other words, the overall built environment increases runoff far more than what rooftops can capture.

Average statewide recharge is about 5.5 million acre-feet per year (Ward 2011), so universal rainwater harvesting would decrease statewide recharge by 0.5 percent. However, even with all the impervious cover, the built environment commonly has higher recharge rates than the natural environment due to landscape irrigation, leaking water (and wastewater) distribution systems, and urban karst (inadvertent preferential flowpaths created through infrastructure construction) (Sharp and others 2003).

In short (and on balance), no: rainwater harvesting is not stealing surface water and groundwater. You can collect and use rainwater guilt-free!

Conclusions

This study demonstrates that rainwater harvesting, when properly designed, can provide a reliable, drought-resilient water supply across the diverse climatic regions of Texas. By applying a rigorous, firm-yield-based methodology analogous to the approach used for surface-water reservoirs, we quantified the potential of rainwater harvesting as a supply—not merely a conservation measure—under a repeat of the drought of record.

Using long-term daily precipitation records and our RAINFAL (Rainwater Assessment and Interactive eNumator for Firm-yield Analysis Limits) tool, we calculated firm yields for household-scale systems at 19 locations across the state. We show that, even in the driest parts of Texas, systems can be designed to provide 100 percent reliability, although the required storage and catchment areas vary widely by location and water use expectations. In the most arid environments, firm yields are modest, but they remain achievable with appropriately scaled infrastructure.

Our findings challenge assumptions that rainwater harvesting is unsuitable due to climatic variability or perceived unreliability. On the contrary, our results indicate that firm-yield systems are feasible statewide and that reliable rainwater harvesting is not only possible but scalable, even in regions with limited precipitation. Furthermore, we show that the defining drought of record varies with system configuration, illustrating the importance of site- and system-specific analysis.

From a planning perspective, the incorporation of firm-yield rainwater systems into regional and state water planning would enhance water supply diversification and reduce stress on conventional supplies during drought. As state water plans move toward more holistic and resilient supply portfolios, our methodology provides a means to rigorously evaluate and include rainwater harvesting strategies.

In short, rainwater harvesting is not merely a stopgap or supplementary option—it can be a dependable, modeled, and quantifiable water supply. With appropriate design tools and planning frameworks, the rain that falls on our rooftops can reliably meet a meaningful portion of the state's water needs, one firm gallon at a time.

References

Agrilife Extension, undated, Texas AgriLife Extension Service Rainwater Harvesting Calculator: Texas A&M University, www.arcsa.org/resource/resmgr/Docs/AP_AgriLife_Ext_RWH_Calcula.xlsx

Anderson, L., 2025, Citizens pour into DSWSC board meeting for discussion on halt of bulk water sales: Dripping Springs Century News, posted May 11, 2025, https://www.drippingspringsnews.com/article/2824,citizens-pour-into-dswsc-board-meeting-for-discussion-on-halt-of-bulk-water-sales

Audry, A. (editor), 2015, Rainwater harvesting manual, First Edition: American Rainwater Catchment Systems Association, Tempe, Arizona, 358 p.

Bleakley, D., 2023, Tesla's Giga Texas reaches 5,000 model Y evs per week in production milestone: The Driven, posted May 11, 2023, https://thedriven.io/2023/05/11/teslas-giga-texas-reaches-5000-model-y-evs-per-week-in-production-milestone/

Briones, R.O., 2023, The firm yield of rainwater harvesting in Texas: unpublished professional project, Sustainability Program, Sociology Department, Texas State University, 92 p.

CA-DWR (California Department of Water Resources), 2021, State agencies recommend indoor residential water use standard to legislature: https://water.ca.gov/News/News-Releases/2021/Nov-21/State-Agencies-Recommend-Indoor-Residential-Water-Use-Standard

CAPE Analytics, 2023, Cape Analytics data reveals America's top 10 largest buildings by roof size: posted June 6, 2023, https://capeanalytics.com/blog/top-10-largest-buildings/

Capehart, M.A., and Eden, S., 2021, Choosing large-scale rain harvesting for potable supply guide for rural homeowners in Arizona: The University of Arizona Cooperative Extension, Report az 1864, 1–13. https://wrrc.arizona.edu/sites/wrrc.arizona.edu/files/attachment/large-scale-water-harvesting.pdf

Charlebois, B., Wittbold, P., Reckhow, D., and Kumpel, E., 2023, Effective first flush volumes in experimental household-scale rainwater catchment systems: Aqua, v 72, n 5, p 814–826, https://doi.org/10.2166/aqua.2023.049

City of Brenham, 2023, City of Brenham Toubin Park: accessed January 30, 2023, https://www.cityofbrenham.org/city_government/departments/parks_and_recreation/toubin_park.php

Cleaveland, M.K., Votteler, T.H., Stahle, D.K., Casteel, R.C., and Banner, J.L, 2011, Extended chronology of drought in South central, Southeastern, and West Texas: Texas Water Journal, v 2, n 1, p 54–96, https://doi.org/10.21423/twj.v2i1.2049.

Coe, J.J., 1990, Conjunctive use—Advantages, constraints, and examples: Journal of Irrigation and Drainage Engineering, v116, n 3, p 427–443, https://doi.org/10.1061/(ASCE)0733-9437(1990)116:3(427)

Denver Water, 2025, How efficient are you indoors? posted January 29, 2025, https://www.denverwater.org/residential/efficiency-tip/how-efficient-are-you-indoors

DeOreo, W.B., Mayer, P., Dziegielewski, B., and Kiefer, J., 2011, Residential end uses of water, Version 2—Executive Report: Water Research Foundation, www.waterrf.org/4309

Downey, N., Schultz, R.D., and Wilson, K., 2009, Roof-reliant landscaping: Rainwater harvesting with cistern systems in New Mexico: New Mexico Office of the State Engineer, https://www.ose.state.nm.us/WUC/Roof-Reliant-Landscaping/Roof-Reliant-Landscaping.pdf

Du Brow, J, 2025, 50L Home Coalition and USGBC California reduce indoor water usage by over 20% while improving consumer delight with whole-home approach: U.S. Green Building Council California, posted on March 20, https://usgbc-ca.org/50l-home-coalition-and-usgbc-california-reduce-indoor-water-usage-by-over-20-while-improving-consumer-delight-with-whole-home-approach/

Farreny, R., Morales-Pinzón, T., Guisasola, A., Tayà, C., Rieradevall, J., and Gabarrell, X., 2011, Roof selection for rainwater harvesting—Quantity and quality assessments in Spain: Water Research, v 45, n 10, p 3245–3254, https://doi.org/10.1016/j.watres.2011.03.036

Fox, E., 2023, Tesla uses less water per vehicle than industry average: Tesla Magazine, posted May 23, 2023, https://www.tesla-mag.com/tesla-uses-less-water-per-vehicle-than-industry-average/

GEM (Green Energy Money), 2016, Transcending antiquated rainwater lending policies: posted August 4, 2016, https://www.greenenergy.money/rainwater-lending-policies/

Hermitte, S.M., and Mace, R.E., 2012, ***The Grass Is Always Greener...Outdoor Residential Water Use in Texas***: Texas Water Development Board, Technical Note 12-01, https://www.twdb.texas.gov/publications/reports/technical_notes/doc/SeasonalWaterUseReport-final.pdf

Imteaz, M.A., Rahman, A., and Ahsan, A., 2012, Reliability analysis of rainwater tanks—A comparison between South-East and Central Melbourne: Resources, Conservation and Recycling, v 66, p 1–7, https://doi.org/10.1016/j.resconrec.2012.05.009

ILS (Institute for Local Self-Reliance), 2006, How big is too big? https://ilsr.org/wp-content/uploads/2008/12/bbtk-factsheet-howbig.pdf

Krishna, H., 2005, The Texas manual on rainwater harvesting: Texas Water Development Board, third edition, https://www.twdb.texas.gov/publications/brochures/conservation/doc/RainwaterHarvestingManual_3rdedition.pdf

Kus, B., Kandasamy, J., Vigneswaran, S., and Shon, H.K., 2010, Analysis of first flush to improve the water quality in rainwater tanks: Water Science & Technology, v 61, n 2, p 421–428, https://doi.org/10.2166/wst.2010.823

Lawrence, D., and Lopes, V.L., 2016, Reliability analysis of urban rainwater harvesting for three Texas cities: Journal of Urban and Environmental Engineering, v 10, n 1, p 124–134, Mace, R.E., 1994, Abandonment of hand-dug wells: a case study in Ellis County, Texas: Texas Journal of Science, v 46, n 4, p 345–359.

Mace, R.E., 2013, Is rainwater reliable? presentation given to the American Rainwater Catchment Systems Association, Austin, Texas, November 5.

Mace, R.E., 2021, Five gallons in a ten-gallon hat—Groundwater sustainability in Texas: The Meadows Center for Water and the Environment, Texas State University, Report 2021-08, 50 p, https://gato-docs.its.txstate.edu/jcr:0abd33a2-0fcf-4af7-8b6b-e888b54508af

Mace, R.E., 2022, ***Groundwater Sustainability—Birth, Development, Application***: Palgrave Studies in Environmental Sustainability, Springer International Publishing, ISBN-13: 9783031135156, 262 p.

Mace, R.E., 2025, Users Guide User's Guide for RAINFAL (Rainwater Assessment and Interactive eNumator for Firm-yield Analysis Limits): version: 2025-05, The Meadows Center for Water and the Environment, 6 p.

Mace, R.E., and Briones, R.O., 2023, The firm yield of (and impacts of climate change on) rainwater harvesting in Texas: presented at the ARCSA 2023 Annual Conference, hosted by The American Rainwater Catchment Systems Association, San Antonio, Texas; September 26, 2023.

McPherson, R.A., Fay, P.A., Alvarez, S.G., Bertrand, D., Broadbent, T.L., Bruno, T., Fares, A., McCullough, B., Moore, G.W., Moorhead, B., Patiño, L., Petersen, A., Smith, N.G., Steiner, J.L., Taylor, A., and Warziniack, T., 2023, Southern Great Plains in Crimmins, A.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Stewart, B.C., and Maycock, T.K., editors, Fifth National Climate Assessment, Chapter 26, U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH26

NCEI (National Centers for Environmental Information), 2023, Climate Data Online: National Oceanic and Atmospheric Administration, https://www.ncdc.noaa.gov/cdo-web/

NCEI (National Centers for Environmental Information), 2025a, U.S. climate normals: National Oceanic and Atmospheric Administration , accessed August 7, 2025, https://www.ncei.noaa.gov/access/us-climate-normals/#dataset=normals-annualseasonal&timeframe=15&location=TX&station=USW00013958

NCEI (National Centers for Environmental Information), 2025b, Statewide time series: National Oceanic and Atmospheric Administration, accessed August 6, 2025, https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/statewide/time-series/41/pcp/12/12/1895-2024?base_prd=true&begbaseyear=1895&endbaseyear=2024&trend=true&trend_base=10&begtrendyear=1895&endtrendyear=2024

Nielsen-Gammon, J.W., Banner, J.L., Cook, B.I., Tremaine, D.M., Wong, C.I., Mace, R.E., Gao, H., Yang, Z.-L., Gonzalez, M.F., Hoffpauir, R., Gooch, T., and Kloesel, K., 2020, Unprecedented drought challenges for Texas water resources in a changing climate: what do researchers and stakeholders need to know? Earth's Future, https://doi.org/10.1029/2020EF001552

Petrie, C., 2020, ***Ten Years Off-Grid—Don't Try This at Home***. Self-published, ISBN: 0578679574, 67 p.

Schueler, T., 1995, The importance of imperviousness: Watershed Protection Techniques, v 1, n 3, p 100–111.

SCTWWPG (South Central Texas Regional Water Planning Group), 2025, South Central Texas (Region L) Regional Water Plan—Initially Prepared Plan: prepared by the South Central Texas Regional Water Planning Group with administration by the San Antonio River Authority with assistance by Black & Veatch, B&V Project No. 411170, 1,172 p.

Sharp, Jr., J.M., Krothe, J.N., Mather, J.D., Garcia-Fresca, B., and Stewart, C.A., 2003, Effects of urbanization on groundwater systems in Heiken, G., Fakundiny, R.H., and Sutter, J.F., editors, ***Earth Science in the City***—A Reader: American Geophysical Union, DOI:10.1029/SP056

TDC (Texas Demographic Center), 2024, Estimates of the total populations of counties and places in Texas for July 1, 2023 and January 1, 2024: The Population Estimates and Projections Program at The Texas Demographic Center, The University of Texas at San Antonio, https://demographics.texas.gov/Estimates/2023/

TPWD (Texas Parks & Wildlife Department), 2023, Hueco Tanks State Park: retrieved January 30, 2023, https://tpwd.texas.gov/state-parks/hueco-tanks/park_history

Trew, D., 2002, ***Water Cisterns made farm life possible in Texas panhandle - farm collector***: Farm Collector, posted October 1, 2002, https://www.farmcollector.com/farm-life/its-all-trew-old-time-cisterns/

TRHEC (Texas Rainwater Harvesting Evaluation Committee), 2006, Rainwater harvesting potential and guidelines for Texas: Report to the 80th Legislature by the Texas Water Development Board, the Texas Commission on Environmental Quality, the Texas Department of State Health Services, and the Texas Section of the American Water Works Association, Conservation and Reuse Division; Texas Water Development Board, 41 p, https://www.twdb.texas.gov/innovativewater/rainwater/doc/RainwaterCommitteeFinalReport.pdf

TSLAC (Texas State Library and Archives Commission), 2011, Population Estimates of Texas Counties, 2000-2009—Arranged in Alphabetical Order: accessed August 6, 2025, https://www.tsl.texas.gov/ref/abouttx/popcnty2000-09.html

TSPB (Texas State Preservation Board), undated, Texas capitol grounds—A self-guided tour: accessed on October 31, 2023, https://tspb.texas.gov/plan/brochures/doc/in_print/grounds/grounds_brochure.pdf

TWDB (Texas Water Development Board), 2010, Rainwater harvesting system sizing calculator: Version 2.0, downloaded on November 1, 2023, https://www.twdb.texas.gov/innovativewater/rainwater/docs.asp

TWDB (Texas Water Development Board), 2012, ***Water for Texas 2012 State Water Plan***: 300 p, http://www.twdb.texas.gov/waterplanning/swp/2012/index.asp

TWDB (Texas Water Development Board), 2017, ***Water for Texas—2017 State Water Plan***: updated February 2019, 133 p, https://www.twdb.texas.gov/waterplanning/swp/2017/index.asp

TWDB (Texas Water Development Board). ***State Water Plan: Water For Texas 2022***. (2022). 1-184. https://www.twdb.texas.gov/waterplanning/swp/2022/index.asp

U.S. Census Bureau, 2023, Characteristics of New Housing—Current data: United States Census Bureau, https://www.census.gov/construction/chars/current.html

Venhuizen, D., 2008, Wimberley, Monthly Rainwater Harvesting Model—1987: Venhuizen Water Works, accessed on November 1, 2023, http://www.venhuizen-ww.com/

Ward, G., 2011, Water Resources and Water Supply in Schmandt, J., North, G.R., and Clarkson, J., editors, ***The Impact of Global Warming on Texas***, Chapter 3, University of Texas Press, https://doi.org/10.7560/723306-007

WCAC (Water Conservation Advisory Council), 2022, Progress made in water conservation in Texas: Report and Recommendations to the 88th Texas Legislature, https://savetexaswater.org/resources/doc/2022%20WCAC%20Report_Final.pdf

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