The Firm Yield of Rainwater Harvesting in Texas

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Abstract

Since the inception of humanity, rainwater has been crucial to the survival of humankind. In Texas, rainwater harvesting has historically been an alternative source of water for centuries. Despite the promise of rainwater harvesting as an alternative supply in Texas, rainwater harvesting does not provide a large amount of supply in the state. Part of the issue is that planners and others generally don't consider rainwater harvesting a reliable source of water. The purpose of this study was to evaluate the firm yield of rainwater harvesting across the state to provide information the planning groups need to include rainwater harvesting in their plans. I developed a spreadsheet obtaining rainfall data from various cities across the state and created various graphs showing firm yields. Not surprisingly, smaller storage volumes are needed in the wetter, eastern parts of the state than the dry, more western parts. The drier the climate, the less likely the rainwater harvesting system is going to reliably provide uses of higher volumes. To achieve larger firm yields, catchment areas in drier climates have to be much larger than in wetter climates, sometimes substantially larger. One interesting aspect of my analysis is that the drought that controlled the firm yield changed depending on demand for firm water. Results showed that finding firm yields across the entire state depends mostly on water use. In addition, most of the state could benefit from reliable rainwater harvesting than currently understood.

Keywords: firm yields, rainwater harvesting, catchment area, storage size

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Introduction

For thousands of years, rainwater has been a reliable source of water for many civilizations. As far back as 9000 years ago, the people of the Negev desert of Israel began collecting rainwater for agriculture (Yannopoulos et al., 2019). Between 4000 and 6000 years ago, many early civilizations began to collect water for many purposes such as irrigation and livestock (Battenberg, 2020). Civilizations such as early China captured rainwater during the monsoon season (Battenberg, 2020). The people of Mesopotamia also captured rainwater in addition to using the Euphrates and Tigris rivers for irrigation (Rost, 2017). For example, the people of the city of Ur started collecting rainwater about 4500 years ago like many other Middle Eastern societies in the desert climate (Yannopoulos et al., 2019). Other early civilizations such as those in the Indus Valley also collected rainwater in what is modern-day Pakistan (Singh et al., 2020).

Early European societies also collected rainwater. The Romans may have perfected rainwater harvesting by including rooftop gutters that directed water to underground cisterns (Yannopoulos et al., 2019). Romans constructed aqueducts that received some of their flow from captured rainfall (Yegul, 2023).

During the Roman Empire, the rise in popularity of public cisterns became more desired than building reservoirs (Yegul, 2023). Cisterns served as storage for rainwater that was later distributed for different purposes. The early urban design of many cities also became a factor in advancing rainwater harvesting (Mays et al., 2021). Dense pre-modern cities meant that experimentation to solve the lack of water would occur during times of change (Mays et al., 2021).

Early European and Asian societies were not the only people collecting rainwater for various purposes. Before the arrival of Anglo Europeans, many Native American societies had a sustainable relationship with the environment (Battenberg, 2020). In the Southwest, natives like the Pueblo Indians captured rainwater through various techniques like trenches that intercepted runoff from storms (Cordell, 2008). The Mayans were heavily reliant on rainwater harvesting systems to store water and manage flooding (Espindola et al., 2020). During their short empire, the Aztecs were able to perfect more advanced rainwater harvesting systems until their downfall during Spanish colonization (Espindola et al., 2020). The influence of indigenous communities in Latin American countries like Mexico is still visible through modern architecture and engineering that deals with limited or excessive rainfall (Espindola et al., 2020).

For thousands of years before Texas existed, Native Americans used natural cisterns that naturally captured rainwater (Texas Parks & Wildlife Department, 2023). These natural cisterns, known as tinajas in Spanish, were points of depression in the surface that caused them to retain water (Texas Parks & Wildlife Department, 2023).

Following statehood, rainwater harvesting also made Texas habitable during its settlement. People relied on underground cisterns for water storage. Such was the case 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). Although rainfall is more abundant in East Texas, capturing rainwater was rare (City of Brenham, 2023). Overall, storing rainwater has served as a strategy for survival in early Texas.

Due to limited access to conventional water supplies, such as water wells or community water systems, landowners in parts of the Hill Country rely on rainwater to meet all their potable and non-potable needs (Krishna, 2005). This has allowed Texas to be a leader in modern-day rainwater harvesting in the United States, including creating the American Rainwater Catchment Systems Association (Krishna, 2020), hosting the first national conference on rainwater harvesting, and providing various tanks and technology associated with rainwater harvesting. Many communities, including Austin, San Marcos, and Midland, provide rebates and incentives to homeowners using rainwater harvesting (generally for non-potable use), and the state provides tax incentives for anyone to install rainwater-harvesting systems anywhere in the state (Krishna, 2005).

Despite the promise of rainwater harvesting as an alternative supply in Texas, rainwater harvesting does not provide a large amount of supply in the state, especially outside the Hill Country. Part of the issue is that planners and others generally don't consider rainwater harvesting a reliable source of water. While there has been some work to provide actionable information to regional water planning groups in Texas (Lawrence and Lopes, 2016), the procedures and analysis provided do not meet the state's planning needs which require firm supplies (100 percent reliable) during the 50-year planning period. The purpose of this study is to evaluate the firm yield of rainwater harvesting across the state to provide information the planning groups need to include rainwater harvesting in their plans.

Background

To evaluate using rainwater and include it in the regional and state water plans, we need to consider the law, ethics, how water is handled in water planning, and previous work.

Rainwater and the Law

Other than some states in the United States, rainwater harvesting is widely accepted and not regulated. Rainwater harvesting is highly encouraged in developing countries where infrastructure is unreliable or not fully developed.

The legality of rainwater harvesting throughout the world is strongly supported by countries that want to find alternative water sources for their growing populations. One such country is Australia. In Australia, the overall rainfall amount makes it one of the driest places in the world (Juergensmeyer and Durham, 2018). In response Australia offers rebates and incentives to people who invest in rainwater harvesting systems. Bermuda is another notable place that uses rainwater. In fact, the British Overseas Territory requires rainwater harvesting systems by law (Rowe, 2011). Their remote location and lack of alternative freshwater water sources has transformed this island territory into a rainwater paradise. Singapore is also a role model in rainwater harvesting. The highly urbanized city-state has incorporated rainwater harvesting into its existing buildings as an alternative water source (Juergensmeyer and Durham, 2018). The city hopes to increase the rainwater catchment area throughout the city by 90% by 2060 (Juergensmeyer and Durham, 2018).

In the United States, there are no federal laws dictating the legality of rainwater, so it is left to the states to decide (Triplett, 2018). According to the U.S. Department of Energy, most of the states do not regulate the practice. Most of the states that do regulate rainwater harvesting encourage rainwater harvesting and even provide some incentives.

All states currently allow rainwater harvesting although some states, particularly in the water-poor Southwest, only allowed it recently and allow limited collection of rainwater. In 2016, Colorado still did not allow the collection of rainwater, citing impacts to the flow of the Colorado River. After the passage of House Bill 16-1005 in 2017, Colorado allowed two tanks with a total capacity of 110 gallons per household (Department of Energy, 2023). Similarly, collecting rainwater was illegal in Nevada before the passage of Senate Bill 74 in 2017 that allows the collection of rainwater in rain barrels without a permit (Juergensmeyer and Durham, 2018). Today, Nevadans can collect water runoff from their roofs for non-potable uses (Department of Energy, 2023). Utah allows 2,500 gallons of water to be collected per land parcel (Department of Energy, 2023). If a landowner wants to collect more water, they must register with the Utah Division of Water Rights (Juergensmeyer and Durham, 2018). Arizona allows almost three times the amount of Utah with a tank size up to 6,500 gallons (Department of Energy, 2023). Arizonans may receive a rebate or property tax reduction depending on the city or county they live in. Rainwater harvesting is completely legal in New Mexico and highly encouraged for all its residents (Department of Energy, 2023).

In Texas, rainwater is a property right (Crow, 2019). This is supported by the Texas Supreme Court declaring that “rainwater which falls on his land is a property right which vested in him when the grant was made" (Crow, 2019). Under Texas Law, rainwater is considered surface water once it falls on the surface and enters a state-recognized watercourse (Scott, 2014). Rainwater that enters a watercourse becomes state water, or the state's property (Scott, 2014). Rainwater also becomes groundwater once it seeps into the ground and reaches the water table of a groundwater district (Scott, 2014). Therefore, water that is captured through a rain harvesting system is private property.

Rainwater harvesting is also supported by the Texas Water Development Board, a state agency designed to study, plan for, and finance the state's water supply. In 2005, the Board released a rainwater harvesting manual to encourage the practice (Krishna, 2005). The manual includes in-depth information on rainwater harvesting like guidelines, costs, and maintenance. In 2011, House Bill 3391 passed which makes it a requirement for future state buildings to have rainwater harvesting systems incorporated into their designs (Scott, 2014). However, the act also allowed these buildings to avoid the requirement if shown to not be cost effective. The requirement only applies to buildings that exceed 10,000 square feet (Scott, 2014). While rainwater harvesting has not progressed much at the state level, cities and counties regulate and even encourage the use of rainwater harvesting through various methods.

Some of the biggest supporters of rainwater harvesting are cities, counties, and other local regulators. In Austin, the city encourages residents to invest in rainwater harvesting systems through various rebates and city-led programs (Maxwell-Gaines, 2022). To lead the change, the city has various buildings that use rainwater for non-potable uses. The Austin Public Library collects rainwater, filters it through a collection system, then uses it for irrigation and restrooms (New Austin Public Library, 2023). Some counties also provide incentives like fee reimbursements and property tax reductions. Other entities such as groundwater conservation districts have programs to encourage residents to invest in rainwater harvesting. For example, the Panhandle Groundwater Conservation District has a rebate program for its residents and offers workshops to inform the public about rainwater harvesting (PGCD, 2023). Overall, there is growing support for rainwater harvesting at local levels.

One of the biggest concerns of rainwater harvesting is the possible backflow of rainwater into the local water supply. Because rainwater is considered a water of unknown quality and hasn't undergone treatment, such as the application of a chlorine residual, the backflow of rainwater into the public water supply could contaminate the public water supply, causing damage to the water infrastructure and possibly public health (TWDB, 2005). One requirement to prevent the backflow is the installment of a reduced pressure zone backflow preventer. In the city of Austin, a permit and a reduced pressure zone backflow preventer is needed to comply with city regulations if storage is more than 500 gallons and the rainwater system is pressurized (Maxwell-Gaines, 2022). Maintenance is required to ensure the backflow preventer is up to standard (Maxwell-Gaines, 2022). Rainwater harvesting is expensive compared to the municipal supply, and the cost of maintenance can deter prospective adopters.

Another interesting issue is the protection of rainwater harvesting by the Texas legislature. Under Texas Property Code §202.007, homeowners associations are not able to prevent the installment of a rainwater harvesting system on private property (Crow, 2019). This protects residents in homeowner associations and bypasses the local bylaws of the associations. This can become an issue of aesthetically pleasing architecture, with some homeowners willing to show or hide their rainwater harvesting systems. Regardless, the state protects homeowners who want to use rainwater as an alternative water source.

The Ethics of Rainwater Harvesting

One of the biggest ethical concerns with rainwater harvesting is capturing water that would normally flow to people downstream. This concern is prevalent in communities that have water insecurity like those along the Colorado River of the West (Bretsen, 2018). Water going downstream provides freshwater for millions across state lines. In Colorado, collecting rainwater for personal use is governed by the prior appropriation doctrine (Bretsen, 2018). There is a fear it could impact communities downstream who have allocated water rights and violate their property rights (Bretsen, 2018). If enough water is captured by upstream users, there is an ethical concern that it could be presented as a legal taking by a court and a subsequent injury resulting in damages (Bretsen, 2018). Although a scenario like the Tragedy of the Commons—where communal resources are depleted by landowners through excessive taking—is unlikely, landowners could escalate litigation in state and federal courts. In this case, state regulation prevents excessive takings, but an ethical dilemma is always a concern when resources are scarce.

Another issue to consider is the taking of water from the environment. In Texas, environmental flows are the amount of water needed for an ecosystem to survive and propagate. Environmental flows are recognized as an important component to environmental health by the passage of Senate Bill 3 during the 80th legislative session (TWDB, 2022). The bill established a stakeholder process to develop environmental flow standards (TWDB, 2022). Capturing rainfall could harm this natural process, which can sometimes be under stress due to droughts and other factors. Rare and endangered species could also be affected if streamflow decreases, possibly gearing up legal challenges through the Endangered Species Act. This raises an ethical concern of the intrinsic value of the environment. Wildlife, even if they have little use for people, should deserve a chance to prosper and propagate without alteration. The state acknowledges that environmental flows are important, however, does not indicate when human needs outweigh environmental needs.

A major existential debate regarding the environment is our dualism with our environment. Humans, the apex predators of the world, are diminishing water resources around the world. What is there to do when the water becomes scarce? One debate is considering nature as "other" (Hailwood, 2020). According to this debate, humans and nature are not meant to mix, meaning that humanity is not of natural occurrence. On the other hand, deep ecology, an environmental ethical perspective, would suggest humans and nature are symptoms of each other. This includes the organic and non-organic components of an ecosystem (Golley, 1987, p. 49). Consequently, humans are part of an ecosystem web that is naturally occurring. Human actions are justifiable through the natural order because they have the right to meet their vital needs (Golley, 1987, p. 49). Humanity is nature and our actions are that of nature.

Water conservation is more than just using less water. In the realm of rainwater, conservation efforts can influence future generations. Conservation methods like rainwater harvesting improve the lives of millions by providing a potable or non-potable source of freshwater while saving water from conventional sources such as rivers, lakes, and aquifers. Rising popularity of rainwater harvesting can also have cultural significance. Texas has always been progressive in water regulation and conservation. Currently, there is a growing demand for rainwater harvesting, along with other water conservation strategies, in Texas (WCAC, 2022). An environmentally conscious generation will be more aware of water conservation if it confronts a water crisis early. In doing so, they will cause a cascade of social, economic, and political effects. A legislative body aware of their constituent needs will be more productive to protect the natural resources of the state.

Texas Water Planning

During the 1950s, Texas experienced its longest and driest drought on record. This event became known as the Drought of the 1950s and remains the worst statewide of record (TWDB, 2022). In response, the Texas Legislature created the Texas Water Development Board in 1957. The TWDB was tasked with creating the 1961 State Water Plan to address water supply, demand, and using the local drought of record as the benchmark for the water planning process (TWDB, 2022).

Before 1997, the Texas Water Development Board had the sole responsibility of developing the state water plan, a “top-down” approach. After the passage of Senate Bill 1 in 1997, the Texas Legislature established regional water planning as a “bottom-up” approach to the water planning process (TWDB, 2022). This different approach was more inclusive of the unique goals and interests of every region of the state and allowed stakeholders across the state to participate in water planning.

The Texas Water Development Board created 16 regional water planning areas, each governed by its own regional water planning group. These regional water planning groups consist of about 20 different members that represent different sectors in the water, including municipal, agricultural, and environmental interests (TWDB, 2022). The planning groups' most important task is the completion of a regional water plan every five years (TWDB, 2022). Broadly speaking, the planning process consists of evaluating future population and demands for water, existing water supplies, identifying needs (where existing supplies won't meet future demands), and evaluating and choosing water management strategies (actions to be taken to meet identified needs) (TWDB, 2022). The resulting regional water plan is then submitted to the Texas Water Development Board for review and approval. Following the submission and approval of regional water plans, the Texas Water Development Board created a state water plan based on the 16 regional water plans.

Because the water plans are intended to respond to the local drought of record, water availability, current water supplies, and supplies from water management strategies are based on what is available during a repeat of the local drought of record. For surface-water resources in Texas, the amount of water available during a repeat of the local drought of record is referred to as the firm yield. A firm yield results in a water supply that is 100 percent reliable, at least based on the drought of record.

Rainwater Harvesting in the State Water Plans

Before the 2000s, rainwater harvesting was rarely mentioned in the water plans. The practice would often be clumped with other conservation methods such as landscaping conservation and stormwater runoff. In the 1997 State Water Plan, the last “top-down” plan, rainwater harvesting was mentioned as an alternative water supply twice (TWDB, 1997). Starting with the 2002 State Water Plan, the first “bottom-up” plan, rainwater was mentioned as a conservation strategy (TWDB, 2002). In subsequent plans, several planning groups included rainwater harvesting as a water management strategy and included a supply amount. Most recently, rainwater harvesting was mentioned in the 2022 State Water Plan with an estimated supply amount of 5,000 acre-feet by 2070.

In their regional water plans developed for the 2022 State Water Plan, regions E, J, and K (the areas of Far West Texas, western Hill Country, and Lower Colorado River, respectively) mention rainwater harvesting as a recommended water strategy in some form. Rainwater harvesting is mostly recommended for small communities, mostly in response to droughts and water shortages. Region J has constantly recommended rainwater harvesting as an alternative water source since 2001 (TWDB, 2001). Based on the most recent regional plan, Region J estimates that it will obtain 1 acre-foot per year from rainwater from 2030 through 2070. The total capital cost for rainwater harvesting is expected to be $56,000 for the region (TWDB, 2021). Their focus is to promote, design, and install rainwater harvesting systems in public buildings throughout the City of Bandera (TWDB, 2021). The regional plan also encourages residents of both the City of Bandera and Bandera County to use rainwater harvesting for non-potable and potable uses. The regional plan also recommends that a rainwater harvesting program should be supported by the State.

Region K, where Austin is located, mentions rainwater harvesting in the most recent regional plan. In addition, the region plans to invest millions of dollars in small-scale projects to expand onsite rainwater and stormwater harvesting since being mentioned in the 2016 regional plan (TWDB, 2021). To specify, onsite rainwater harvesting involves using the captured rainwater to meet demands at the building/lot scale throughout various cities. The expansion of rainwater harvesting in the region also includes entities and cities such as Dripping Springs Water Supply Corporation, Hays County, and Sunset Valley (TWDB, 2021). Together, Region K plans to achieve a supply of rainwater of 5,278 acre-feet per year by the year 2070 and have the strategy online by 2030 (TWDB, 2021). Overall, the region is a leader in rainwater harvesting throughout the state and country.

Unlike the other two regions, Region E mentions rainwater harvesting and stormwater harvesting as a combined strategy in the most recent regional water plan (TWDB, 2021). The region focuses on capturing rainwater runoff for irrigation in the city of Alpine. The captured rainwater is being used for the restoration of Alpine Creek to improve wildlife habitat and recreation in the area (TWDB, 2021). The total capital cost of rainwater harvesting in this region is expected to be $1.296 million. In addition, the strategy supply is expected to be 70 acre-feet per year starting in 2030 until 2070. Although listed as rainwater harvesting, this strategy is really stormwater harvesting.

Although these regions have shown interest in rainwater harvesting, their plans do not show how they obtained their yield numbers. The calculations are not shared and appear to be an estimate based on rainwater harvesting potential. Specifications of any rainwater harvesting systems are also withheld. There is no storage or catchment specified to estimate their goal of obtaining a firm yield.

Previous Work

In this section, I first focus on previous work related to rainwater harvesting and then focus on a paper by Lawrence and Lopes (2016) that conducts research in my same area of interest.

One of the determining success factors for rainwater harvesting is roof area. The larger the area of the roof, the more water that can be collected during rain events. Ghisi et al. (2009) found that roof area matters when considering potable water savings in gas stations in Brasilia, Brazil. Roof catchments of 350, 550, and 750 square meters (3770, 5920, and 8070 square feet, respectively) resulted in more potential for potable water savings (Ghisi et al., 2009). Overall, a bigger roof area can collect more rainwater runoff during rain events.

In addition to catchment area, catchment shape can also influence water quality and quantity. Farreny et al. (2018) studied catchment area and shape in Spain as a determining factor in rainwater capture. Sloping smooth roofs were found to have up to 50 percent better rainwater capture than flat rough roofs (Farreny et al., 2018). Water quality was also affected. Results showed low levels of pollutants like NO^2 and NH^4 on sloping roofs and high levels on flat roofs (Farreny et al., 2018). The first few millimeters of runoff, also called the first flush, were diverted from the tank as they were deemed dirty and could contaminate the tank (Farreny et al., 2018). The pH levels of the collected water were also affected. Levels of pH were acidic during the water capture but then turned neutral after reaching the storage tank (Farreny et al., 2018). Overall, sloping smooth roofs were found to contribute to better water quantity and quality. Ghisi et al. (2009) found that increasing roof area increased the available volume of water to be harvested.

The first flush is considered a safeguard for maintaining the stored water from becoming heavily contaminated. Kus et al. (2010) studied the effects of the first flush in Australia, where most systems have a first flush mechanism to their rainwater harvesting systems. Current practice diverts up to 2 millimeters of runoff from the roof to bypass the rainwater harvesting system. By doing so, it greatly improves the quality of the stored water.

Another determining success factor for rainwater harvesting is the storage volume. Lawrence and Lopes (2016) found higher reliability with increasing storage. Increased storage was able to increase reliability with the same water demand. The highest dry year curve was significantly higher than the lowest average and wet year in relation to storage volume. Storage volume is connected to the reliability of rainwater harvesting and is affected by the water demand in an area. Ghisi et al. (2009) found that, with the same water demand and same catchment area, storage volume reached a point where no more rainwater could be captured.

In Central Texas, rainwater harvesting systems can be expensive and affordable to only a small portion of the population, especially for people already connected to a central water-supply system. However, rainwater harvesting can compete financially with water wells depending on the depth of the well. And if there is no city water or groundwater, rainwater harvesting may be the only source of water. Kim et al. (2016) conducted a study to test the reliability of rainwater harvesting and its economic feasibility in Austin. A hypothetical single-family home was used in the study with a roof area of 223 square meters (2400 square feet), reflecting the average American home. The estimated cost of a storage tank with a capacity of 13,249 liters (3500 gallons) and its parts such as filters, disinfectants, and others were estimated to cost around 3,800 to 4,900 dollars.

Kim et al. (2016) found that rainwater could also serve as an alternative for the estimated 2,271 to 3,028 million liters per day (60,000 to 80,000 gallons per day) that the city will need in the next 100 years. As of this study, the city has estimated an increase to about 1,136 million liters per day (30,000 gallons per day) through the expansion of its water treatment plans in various phases (Kim et al., 2016). For rainwater harvesting to be successful, the city would have to subsidize the cost of the rainwater harvesting equipment (Kim et al., 2016). If the city can subsidize rainwater harvesting equipment, it would be able to save millions from the many water-expansion projects it has proposed. However, the cost of rainwater harvesting equipment is still a challenge for those unable to afford it, even with the help of the incentives the city has put forward (Kim et al., 2016). Thus, there is a fine line between those who can afford it and the willingness to invest in the practice by the public. Kim et al. (2016) used Texas Water Development Board's calculator (TWBD, 2005) which is based on average monthly rainfall.

Rural homeowners tend to benefit the most from rainwater harvesting. A study conducted by Capehart and Eden (2021) of the University of Arizona Cooperative Extension showed the benefits of choosing large-scale harvesting for potable supply. Arizona, for the most part, has a low amount of rainfall and relies heavily on the Colorado River and groundwater. A huge challenge is finding year-round water for many communities that rely on trucked-in water and groundwater wells. Rainwater presents a solution for many of these rural communities that have low gallons per person per day of use. Capehart and Eden (2021) also showed that a goal of 35 gallons per person per day, down from 85 gallons per person per day, is obtainable through restrictive water use. Their study relied on multiplying the square feet of catchment, average annual inches of rainfall, and a conversion factor of 0.6 that estimated rainwater collection potential in gallons. The collected rainwater would then be treated by a filtration system and stored in tanks of various sizes. Maintenance, storage volume, and location also greatly impacted the cost-benefit relationship of owning a rainwater harvesting system.

An arid climate can test the reliability of rainwater systems. Adham et al. (2021) tested the reliability of rainwater harvesting in southeastern Tunisia, which has a desert climate. The study area consisted of rainwater catchment systems in multiple locations in an isolated area. The results looked promising for a small country that heavily relies on desalination. Results showed that wet years provided 30 to 70 percent reliability. On the other hand, dry years provided only 10 to 24 percent reliability (Adham et al., 2021). A similar study conducted by Judeh et al. (2022) in Jenin, Palestine, showed reliability peaking around 41 percent using rainwater for potable use. One major variable was also the different tank sizes that ranged up to 200 cubic meters (58,000 gallons). Results from both studies may shed light on the effectiveness of rainwater harvesting in the desert of West Texas.

Rainwater harvesting on affordable housing in the face of climate change may be beneficial when teamed with other conservation strategies. Marinoski et al. (2017) studied about 20 low-income, single-family households with rainwater harvesting systems in the Florianopolis metro area of Brazil. The houses had 62 square meters (670 square feet) of built area and 80 square meters (860 square feet) of roof catchment. A combination of water-efficient appliances, greywater reuse, and rainwater harvesting was used to find potable water savings. Results showed up to 42.9 percent of potable water savings possible when combining all three methods (Marinoski et al., 2017). An environmental benefit analysis was also conducted showing a reduction in sewage and energy of the households. Thus, implementing a combination of all three alternative water resources showed positive environmental benefits and potable water savings.

Rainwater harvesting remains a solution for developing countries that face water shortages because of climate change. Monjardin et al. (2019) studied rainwater harvesting systems in the Philippines, which was experiencing dry spells despite its tropical location. Barangay San Jose, Antipolo City, Rizal, and a weather station in Science Garden, Quezon, was used to find historical rainfall records of the past 30 years. Results showed a high reliability in average and wet years where rainwater could maintain users for an extended amount of time based on catchment area and storage area (Monjardin et al., 2019). Monjardin et al. (2019) concluded that 68 cubic meters (18,000 gallons) of rainfall could be harvested in a 40 square meter (430 square feet) catchment area with a barrel or drum of about 55 gallons. A bigger catchment area of about 100 square meters (1080 square feet) could yield about 234 cubic meters (61,800 gallons) of water with a 12,000 liters (3170 gallons) tank. Overall, the study recommended rainwater harvesting as a countermeasure to the effects of climate change.

In Australia, almost 100 percent of rural homes have a rainwater harvesting system. Imteaz and Moniruzzaman (2022) found rainwater harvesting as an alternative water source in the Sydney metro area. Similar to Central Texas, the Sydney metro area has a humid subtropical climate that makes rainwater harvesting similar in nature. Their area of study consisted of five different buildings across the area with a consistent catchment area of 200 square meters (2150 square feet) (Imteaz and Moniruzzaman, 2022). The tank size was 5,000 liters (1320 gallons) with a water demand of 400 liters per day (106 gallons per day) (Imteaz and Moniruzzaman, 2022). Results showed a water-saving potential of about 40 percent on average. Due to inconsistent rainfall patterns, reliability is expected to decrease in the upcoming decades by almost 20 percent. Although weather patterns show potential for water savings by using rainwater, weather patterns can change reliability throughout an average year with rainfall becoming sporadic (Imteaz and Moniruzzaman, 2022).

The concept of rainwater harvesting at a national level raises some promising results. Urban sprawl is a challenge for many cities that do not have alternative water sources. Steffen et al. (2013) conducted a study measuring rainwater potential for cities across the United States. Cisterns were the main rainwater harvesting systems used in the study. In addition, year-round weather heavily impacted the data collection and rainwater harvesting systems (Steffen et al., 2013). Results showed cisterns were able to collect more stormwater runoff depending on their size, rooftop area, and annual rainfall. Cities in the Southwest and Midwest were able to obtain a higher rooftop water yield capture of about 70 percent, as opposed to cities in the Southeast or West Coast. The cisterns were not able to impact stormwater management, but enough water was collected to benefit homeowners in residential water use like toilets in addition to other indoor water usage.

One of the many solutions to combat the lack of alternative water sources is to increase rainwater harvesting throughout the world. Yannopulos et al. (2019) explain the rise of rainwater collection systems on a global scale. Most of the adoption is happening in Sub-Saharan countries such as Kenya, Malawi, and Namibia. Catchment area stands out as an important factor to collect the seasonal rainfall, which is followed by periods of minimal rainfall. European countries have more established rainwater laws, policies, and regulations. Germany, one of the world leaders in rainwater harvesting, encourages its citizens to have a rainwater harvesting system at their households. New buildings are encouraged to have rainwater harvesting systems, and the general population installs about 50,000 to 80,000 systems every year (Yannopoulos et al., 2019). Other countries like the United Kingdom, France, Malta, and Portugal also encourage the use of rainwater harvesting. Popularity is also increasing on other continents like South America. Brazil has no regulation at a federal level, but multiple cities and municipalities have enacted guidelines to regulate rainwater harvesting (Yannopoulos et al., 2019). Forgotten for more than a hundred years, rainwater harvesting is making a return as an alternative water source for millions.

Lawrence and Lopes (2016)

Lawrence and Lopes (2016) evaluated the resilience of rainwater harvesting for three Texas cities (Dallas, Houston, and San Antonio) to support the inclusion of rainwater harvesting in the regional and state water plans in Texas. The purpose of our study is to also provide information to support the quantify the inclusion of rainwater harvesting in the regional and state water plans in Texas. Ostensibly, Lawrence and Lopes (2016) already answered this question with their work. However, their work and the approach it's based on greatly limits its applicability to water planning in Texas.

Water planning in Texas is based on a repeat of the drought of record: what is the reliable water supply (not the reliability of that supply) that users can count on during a repeat of the worst drought that the supply experienced. In Texas water-planning parlance, this is referred to as the firm yield (a term that has different meanings elsewhere in the country). The analysis presented by Lawrence and Lopes (2016) results in a firm yield of zero for all the cases of use, catchment area, and rainfall variation they investigated (a supply with a reliability less than 100 percent has, by definition, a firm yield of zero). Therefore, Lawrence and Lopes (2016) do not provide the information needed by water planning groups and others in designing a reliable rainwater harvesting system.

Another issue with Lawrence and Lopes (2016) is the methodology based on Imteaz et al. (2012). One critical issue with this methodology is only evaluating a year of precipitation for a certain climatic condition. Droughts are often multiple years in duration and straddle the beginnings and ends of years, at least in Texas. Limiting an analysis to one year of precipitation distorts the reliability. Single-year analysis also grossly underestimates the required storage volume since it can take more than a year to fill, resulting in many scenarios not being reliable. The largest tank size Lawrence and Lopes (2016) considered was 2,500 gallons for 55 gallons of daily use, remarkedly small for the parts of the state considered.

A couple other issues concern geographic scope and use. Lawrence and Lopes (2016) only used three examples covering three regional water planning areas in the central to southeast part of the state and only considered two use scenarios, 55 gallons per day and 100 gallons per day.

Methods

Working with my advisor, I developed an Excel spreadsheet model to calculate a daily water balance of a rainwater harvesting system. This model accounts for catchment area, rainfall, runoff losses, first flush, storage volume, and daily use when calculating daily storage for the system. We named this spreadsheet RAINFAL (Rainwater Assessment and Interactive eNumerator for Firm-yield Analysis Limits). RAINFAL allows a user to enter in their rainfall record, input their catchment and storage parameters, and then adjust storage size or catchment area (or any of the parameters) to achieve a firm yield. To provide information for all 16 regional water planning areas, I gathered data on multiple weather stations throughout the state. Using various assumptions of catchment area, storage volume, and daily use, I calculated firm yields for each location.

Governing Equation

In a rainwater harvesting system, rainwater is collected when it falls to the 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 rain falling onto catchment and turning into runoff. This runoff coefficient is a function of roof material and slope. We also assumed that any frozen precipitation will melt and end up flowing through the rainwater harvesting system.

Depending on the complexity and use of the system, a first flush system might be installed. A first flush diverts the first few millimeters of rainfall (about 50 gallons) to decrease the risk of contaminants and pollutants from reaching storage.

Once in storage, the water is available for use. Because most storage intended for human use are closed, we assumed that there are no evaporative losses. Depending on the use, the stored rainwater may undergo filtration and exposure to ultraviolet light for indoor use and no treatment for outdoor use. Filtration and ultraviolet light does not result in any treatment losses. If a user decides to use reverse osmosis for additional treatment, there may be a loss of water due to this treatment. However, we assume no treatment loss since the potable systems we are aware of do not use reverse osmosis (after all, rainwater already has low total dissolved solids).

If the storage fills past capacity, then an overflow allows the excess water to leave storage. Collected rainwater remains in storage until used. In the case of storage being almost exhausted, a dead pool of water remains in the bottom as a sediment reservoir and is therefore not available for use.

The governing equation I used to develop a daily water balance model for rainwater harvesting in Excel is:

$$V_t = V_{t-1} + R * A * C - V_{ff} - V_u \tag{1}$$

unless

$$V_{ff} < R * A * C \text{ in which case } V_{ff} = R * A * C \tag{2}$$

$$V_t > V_{tot} \text{ in which case } V_t = V_{tot} \tag{3}$$

$$V_t < 0 \text{ in which case } V_t = 0 \tag{4}$$

where:

A = area of the roof [L^2]

C = runoff coefficient for the roof [-]

R = rainfall 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]

Equation 2 is for the case for 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. Equation 3 is for when storage overflows, setting the maximum volume in storage to the maximum volume of storage. Equation 4 is for when the storage is exhausted setting the volume of storage to zero when use of water is greater than the remaining storage.

Quantifying the Terms

For rainfall, R, I downloaded data from the Climate Data Online (NOAA, 2023). I chose data from the National Oceanic and Atmospheric Administration for my rainfall data because it is the only online database that has continuously collected rainfall data throughout the state. Throughout every regional water planning area, there are multiple weather stations that have recorded rainfall data since the early mid-20th century. My purpose was to calculate the firm yield of rainwater harvesting throughout the state with at least one station in each regional water planning area (Figure 1). I chose two locations in some regional water planning areas to reflect the change in precipitation across some areas, especially in regions that were long and transitioned into different climates (Figure 1). While locating ideal weather stations, I chose stations that had good data coverage. Ideally, almost a complete record. However, for some regions data had to be excluded because records were inconsistent or substantially missing. Texarkana was the only city where data was collected from outside the state. This was due to the weather station on the Arkansas of the city side having a longer rainfall record. In addition, several scenarios for Houston and Corpus Christi were sensitive to the initial conditions affecting their firm yields for storage and catchment area meaning the first or second droughts had to be tossed out due to their proximity to each other at the start of their records. Average annual precipitation for these cities ranged from 14 inches in El Paso to 52 inches in Texarkana (Table 1).

For catchment area, A, I used 296 square meters (3181 square feet). This number is based on U.S. Census square-footage data, an assumption on eaves, an assumption of each home having a two-car garage, and an assumption that a rainwater harvesting system would be designed to capture all run-off from the roof, The median square feet in new contractor-built single-family homes was 2,609 square-feet in 2021 (U.S. Census Bureau, 2023) To calculate catchment from eaves, we assumed a single-story house with a square footprint (51 by 51 feet) and eaves two feet long, resulting in an additional 212 square feet of catchment. A standard two-car garage is 360 square-feet. These three areas add up to 3,181 square feet.

For runoff coefficient, C, I used a factor of 0.92. The runoff coefficient represents the fraction of water that makes it into the gutters with 8 percent being lost due to retention and bouncing off the roof. This is the same value that Lawrence and Lopes (2016) used in their study. Farreny et al. (2011) also used a runoff coefficient of 0.92 to represent retention of rainfall in relation to roof texture. This runoff coefficient is applied daily regardless of whether or not it rained the day before. As a result, our analysis may slightly underestimate yield from a system.

For volume of the first flush, V_{ff}, I used 50 gallons. This is done to divert the first few millimeters of rainwater to improve water quality (Kus et al., 2010).

The total storage volume, V_{tot}, varies according to size. Areas with more rainfall usually require a smaller amount of storage, while areas with 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.

For volume of daily use, V_u, I used 10 to 60 gallons per person per day. I based the lower value 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. This is down from the 86 gallons per person per day reported by Hermitte and Mace (2012).

People who rely on rainwater to meet their indoor water needs do not tend to use their supply for outdoor irrigation (Robert Mace, personal communication, 2023). 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.

People who rely on rainwater to meet their water needs also tend to be efficient users of their water (Capehart and Eden, 2021). High-efficiency homes use 36.7 gallons per person per day (DeOreo et al., 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). A conservation-minded user in Austin with WaterSense-rated fixtures, EnergyStar rated appliances, and dual-flush toilets uses about 30 to 35 gallons per person per day (Robert Mace, personal communication, 2023). Given the range of indoor water use, I used 60 gallons per person per day to define the top of the range.

Total water use for a household is also defined by the number of people living in the house. According to the most recent Census in July 2021, the average number of people living in an average Texas household is 2.76 (U.S. Census Bureau, 2023). The gallons per person per day multiplied by the average number of people in a home equals the total water use for the home.

Although I used indoor household use to define the range of water demands I investigated, it ultimately doesn't 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 my approach to design a firm rainwater system.

We assumed that the dead pool was 5 percent of the total storage.

Table 1: Average annual precipitation for the cities included in my study.

City	Precipitation (inches)
Abilene	25
Amarillo	20
Austin	36
Brownsville	27
Corpus Christi	32
Dallas	36
Del Rio	21
Fort Davis	17
El Paso	14
Hallettsville	40
Houston	50
Laredo	20
Lubbock	19
Lufkin	50
Midland	15
San Angelo	21
Texarkana	52
Waco	36
Wichita Falls	29

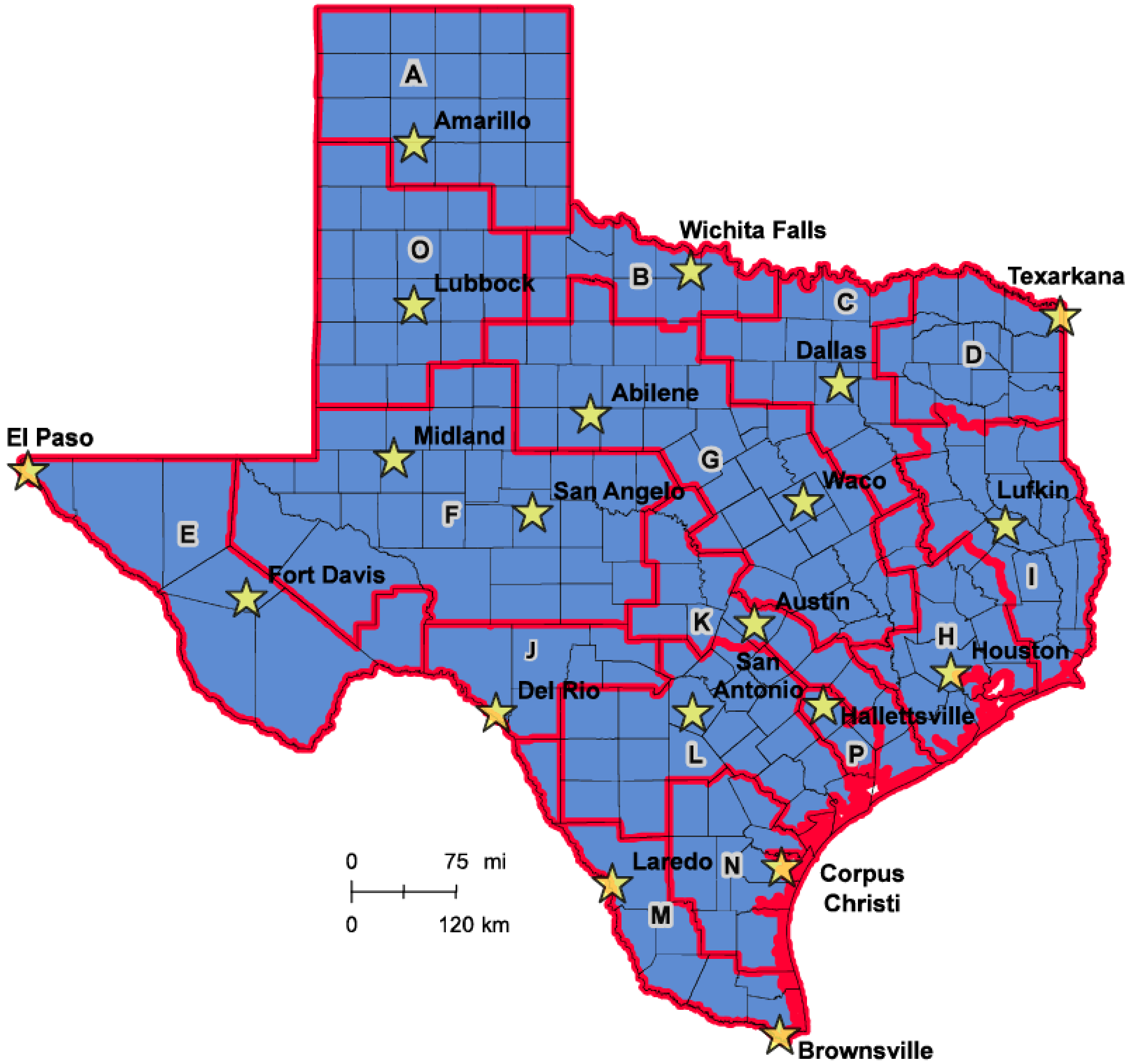

Figure 1: Location of weather stations (stars) in the sixteen regional water planning areas (outlined in red and named with letters) analyzed in this study.

Assessing Firm Yield

A firm yield is obtained when reliability equals 100 percent over the period of record. A storage volume that has more water available than total daily use for every day during the period of record will give a firm yield. The biggest challenge is storing enough rainwater during rainfall events to have a reliable supply of rainwater during severe droughts. In addition to rain, having a reliable supply depends on factors such as storage volume, catchment area, and daily use.

I used the RAINFAL spreadsheet to estimate firm yields, which I defined as a situation where the storage never fell below the dead pool volume (5% of total storage).

I conducted two separate analyses: (1) the amount of storage required for a range of daily use amounts with a fixed catchment area of 3,181 square feet and (2) the amount of catchment required for a range of daily use amounts with a fixed storage volume of 30,000 gallons. A fixed storage volume of 30,000 gallons is a typical size for a whole-house rainwater harvesting system for the Hill Country near Dripping Springs, Texas.

Comparing Our Methods to Lawrence and Lopes (2016)

I wanted to compare my methodology to the methodology used by Lawrence and Lopes (2016). Between my research and Lawrence and Lopes (2016), the biggest difference wase my use of the full record in our analysis instead of three individual years. Lawrence and Lopes (2016) used the 10^{th} (dry year), 50^{th} (average year), and 90^{th} (wet year) percentile years of their rainfall records for Dallas (1940–2013), Houston (1941–2013), and San Antonio (1948–2013). Lawrence and Lopes (2016) called the 50^{th}

percentile an "average" year, but it is technically the median year for the historical record of annual rainfall amounts. Dallas had 1972 as a dry year, 2002 as an average year, and 1973 as a wet year. Houston had 1950 as a dry year, 1985 as an average year, and 1976 as a wet year. Lastly, San Antonio used 2011 as a dry year, 1968 as an average year, and 1991 as a wet year.

To test their reliability and parameters I recreated their reliability chart with the full record used for the range of years they used in their analysis. In other words, if Lawrence and Lopes (2016) used precipitation data from 1940–2013 for Dallas, I used the same range of data. I also used the same roof areas of 109 square meters (1170 square feet) and 163 square meters (1755 square feet) and their daily use of 210 liters (55 gallons) and 380 liters (100 gallons). Lastly, I used the tank sizes they used: 2839 liters (750 gallons), 3785 liters (1000 gallons), 4732 liters (1250 gallons), 5678 liters (1500 gallons), 6624 liters (1750 gallons), and 7571 liters (2,000 gallons). Lawrence and Lopes (2016) did not include a first flush in their hypothetical system or a dead pool in their storage; I adjusted RAINFAL to reflect this. Using these parameters, I calculated reliability percentages using my method to compare to the reliability numbers presented by Lawrence and Lopes (2016). Using my methodology (and the range of their climatic data), I also calculated the storage required to achieve a firm yield.

Results and Discussion

My results include an assessment of data coverage, calculations of firm yields for different storage volumes, calculations of firm yields for different catchment areas, droughts defining firm yields, and a comparison of my methodology with that of Lawrence and Lopes (2016).

Data Coverage

The precipitation data I downloaded from NOAA (2023) had a range of dates for data availability (Table 2). The time coverage ranges from 58.8 years for Laredo to 131.1 years for Texarkana (Table 2). However, the data coverage also ranged among the stations from 90 percent in Fort Davis to 100 percent in Austin. I noticed data coverage was often incomplete before the 1940s. Therefore, I inspected each file and identified the date after which data coverage was substantially complete. I then deleted the data before this date to improve overall data coverage and, therefore, the quality of my analysis. For example, I reduced the time coverage range from 124.3 years for Brownsville to 75.2 years but increased the data coverage from 80 percent in Brownsville to 100 percent (Table 2). Most of the cities did not have 100 percent data coverage (Table 2), but I felt that the coverage was adequate for my analysis.

I assumed that any day that did not have a precipitation measurement had zero precipitation. This means that my 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 the 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.

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

Precipitation Data Based on Regional Water Planning Areas					
Region	City	Range of Data (Years)	Data Coverage	Range of Data Used (Years)	Data Coverage (missing days)
A	Amarillo	3/1/1943-2/25/2023 (80)	95%	1/1/1947-2/25/2023 (76)	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% (1836)
E	Fort Davis	1/1/1902-2/22/2023 (121.3)	87%	12/1/1911-2/22/2023 (112.3)	90%(4031)
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% (1412)
I	Lufkin	10/1/1906-2/23/2023 (116.4)	96%	11/1/1906-2/23/2023 (116.3)	97% (1458)
J	Del Rio	8/9/1946-2/23/2023 (76.5)	87%	3/1/1963-2/23/2023 (60)	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)

Firm Yields for Different Storage Volumes

To investigate the storage volumes required to achieve firm supplies for different parts of the state, I estimated firm yields for different amounts of use for a standard catchment area of 3181 square feet. Not surprisingly, smaller storage volumes are needed in the wetter, eastern parts of the state than the dry, more western parts (Figure 2). For example, storage of about 30,000 gallons can reliably meet about 170 gallons per day of use in Houston (Figure 2t) while almost 140,000 gallons of storage are needed in Dallas

(Figure 2q) to reliably meet the same level of use (note that when I use “reliable” in this context, I mean 100 percent reliability).

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 2). This is due to less additional rainfall available to catch with larger amounts of storage. At some point, there’s enough storage to capture all the rainfall that falls during the record and into storage. In these cases, the firm yield is limited by rainfall for the specified catchment area. More rainfall could be collected with additional catchment area.

The drier the climate, the less likely the rainwater harvesting system is going to reliably provide uses of higher volumes. A dramatic case of this is El Paso, where the only firm use that could be supported for the specified catchment area (and the use levels we investigated) was 27.6 gallons per day (10 gallons per person per day multiplied by 2.76 people; Figure 2a). The curve extends toward higher use levels (and firm yields) as cities occupy wetter and wetter areas. In all cases, the rainwater harvesting system I investigated could achieve a firm yield, albeit at lower use levels.

It's unlikely that a home would have a storage of 160,000 gallons, so I next focused on storage up to 50,000 gallons for the investigated cities (Figure 3). Storage for rainwater-fed homes in the Hill Country is typically 30,000 to 40,000 gallons, so 50,000 gallons didn’t 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. 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 but El Paso, Midland, and Fort Davis meet that standard.

In the north and central parts of the state, there was a mixture of high and moderate firm yields based on storage with a catchment area of 3181 square feet. As a result of a decrease in precipitation and the transition to the west, the curves began to pull back with a gap between Texarkana and Hallettsville (Figure 3). Dallas, Hallettsville, and Waco can support higher firm yields than Austin, Wichita Falls, and drier cities for storage less than 50,000 gallons (Figure 3). Most notably, the transition to the wetter, eastern portion of the state is clearly shown through these firm yields.

The southern and western parts of the state could only achieve lower firm yields given the catchment area (Figure 3). El Paso, Midland, and Fort Davis produced the lowest firm yield based on storage size and a firm roof of 3181 square feet (Figure 3). El Paso only gave one firm yield for a storage of 12,600 gallons, making it the driest city in the state (which it is). The biggest storage for firm yields in Midland was 49,900 and for Fort Davis it was 32,800. Despite being more west than Midland, Fort Davis had higher rainfall; however, areas with higher elevations can obtain slightly more rainfall throughout the Big Bend Country. In the western part of the state, rainwater harvesting can be more difficult and yield less water but is possible given the proper amount of use and catchment area.

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 2 and 3). 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 32,100 gallons versus 34,800 for a catchment area of 3181 square feet and daily use of 60 gallons per person and 2.76 people.

One interesting aspect of my analysis is that the drought that controlled the firm yield changed depending on demand for firm water. Seventeen of the 19 cities had different defining droughts depending on the demand (Appendix). In the case of Corpus Christi, a drought at the end of the 2000s was the controlling event for a firm yield of 69 gallons per day while a drought in the 1960s was the controlling event for firm yields of 82.8 and 96.6 gallons per day (Figure 4), although the drought in the 2000s was close to being the controlling event for those firm yields.

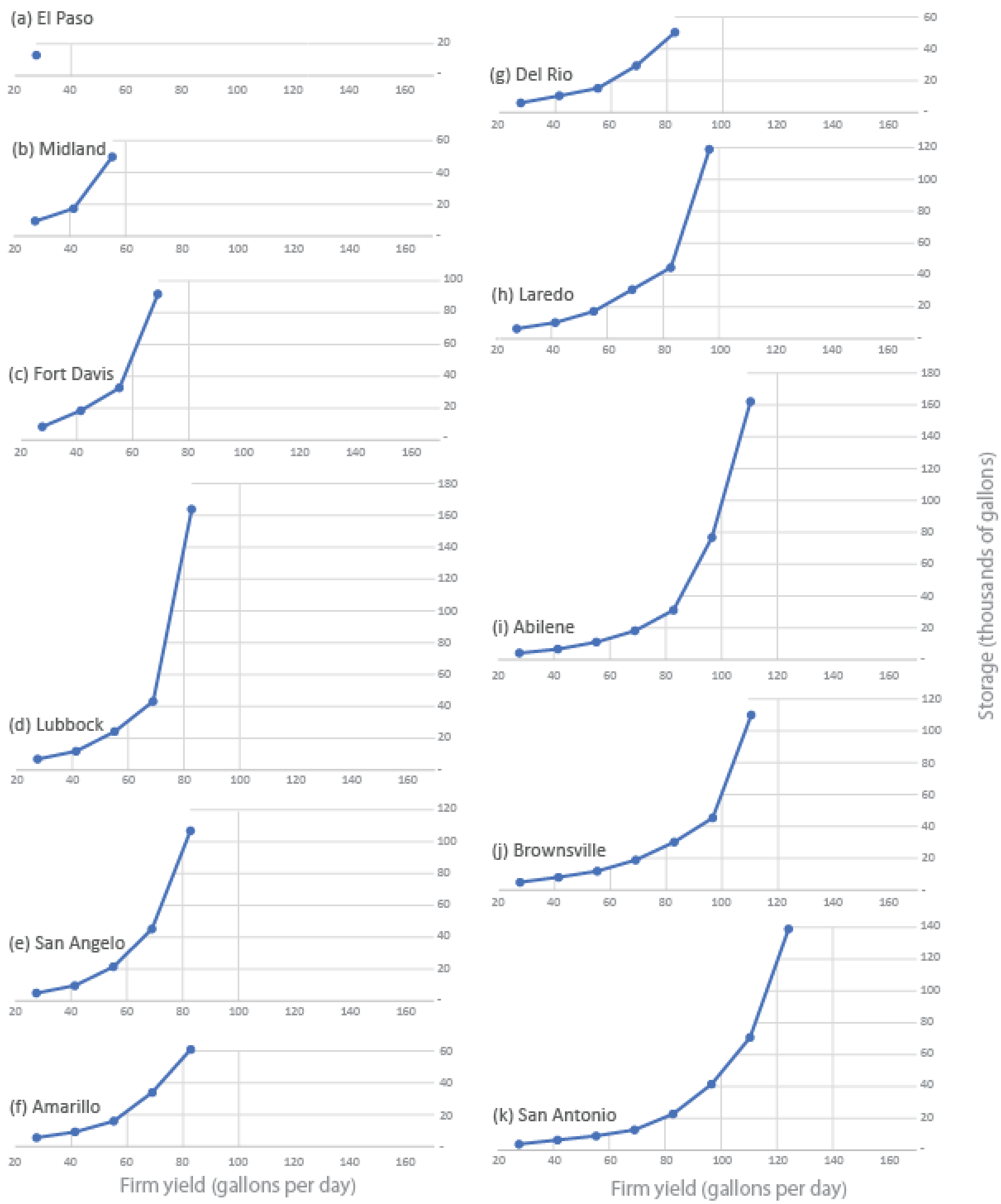

Figure 2: Storage required to achieve a range of firm yields for a catchment of 3181 square feet for a variety of Texas cities. I organized these graphs from least amenable to rainwater harvesting to most amenable. Note that each graph is on the same horizontal and vertical scale to allow direct comparison between plots. Also note that the plots end at the maximum achievable firm yield (for the use levels investigated).

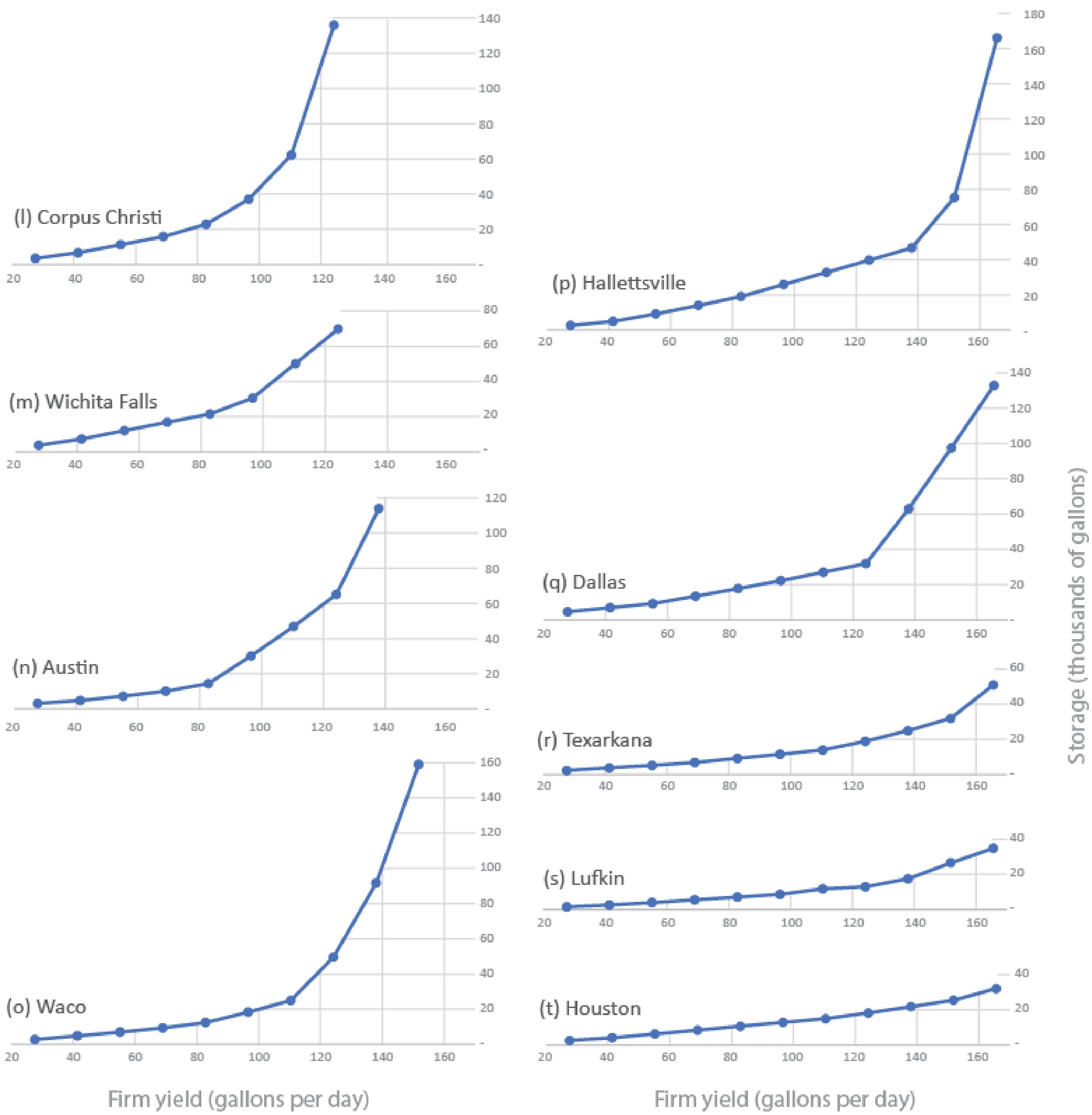

Figure 2: Continued.

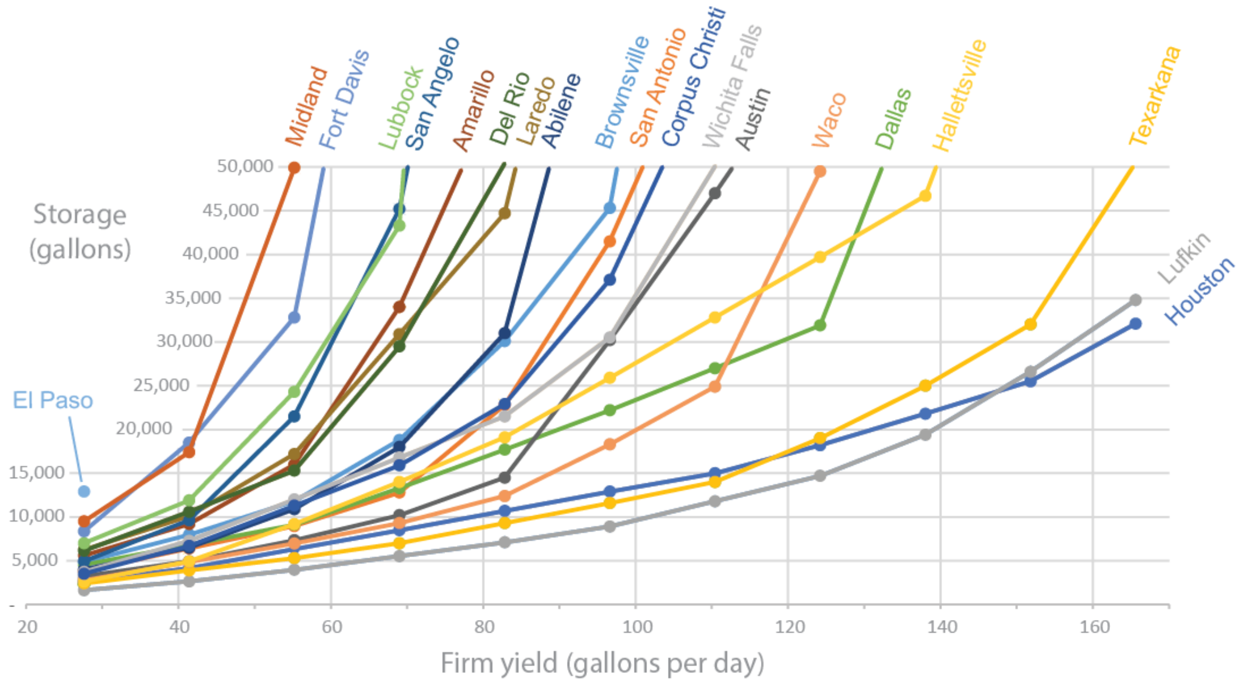

Figure 3: Storage required to achieve a range of firm yields for a catchment of 3181 square feet for a variety of Texas cities with storage capped at 50,000 gallons.

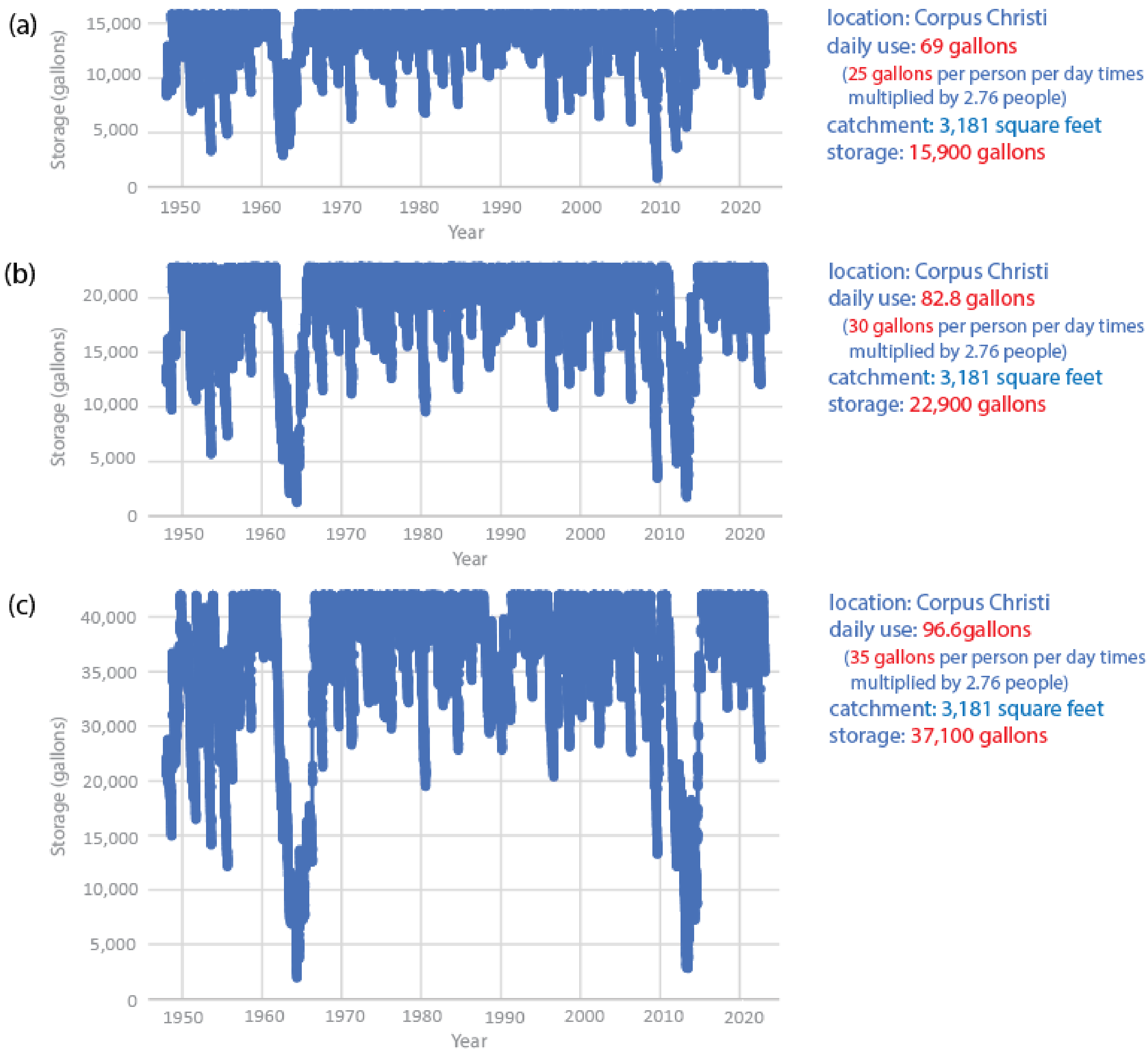

Figure 4: Storage performance for three demand/firm use scenarios with a set catchment area for Corpus Christi.

Firm Yields for Different Catchment Areas

To investigate the catchment areas required to achieve firm supplies for different parts of the state, I 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 5). For example, a catchment of about 3100 square feet can reliably meet about 170 gallons per day of use in Houston (figures 5t and 6) while almost 8000 square feet of catchment is needed in Dallas (figures 5n and 6) to reliably meet the same level of use (note that when I use "reliable" in this context, I 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 is get 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). Whereas with a fixed catchment area there is a maximum amount of rainfall you can collect and a maximum firm yield, you can always increase catchment to achieve a larger firm yield, at least until the catchment area becomes unaffordable or unattainable (such as continental-sizes roofs).

Catchment areas to achieve larger firm yields in drier climates have to be much larger than in wetter climates, sometimes substantially larger. For Midland to achieve a firm yield of 110 gallons per day requires a catchment of about 70,000 square feet while

Houston only requires a catchment of about 2,000 square feet (figures 5 and 6). While 70,000 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 (2.78 cubic meters) 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. My model shows that even with the gigafactory's massive roof, regardless of the amount of storage, it's not possible to meet that water demand. However, with 25 million gallons of storage (municipality-scaled storage tanks), Giga Texas could reliably produce 45,000 gallons a day.

The catchment area is critical to achieving a firm yield throughout the state. Based on catchment area, Houston, Lufkin, and Texarkana again topped the list. Their catchment areas of 3,290, 3,400, and 3,750 square feet, were enough to sustain a firm yield through dry periods. In combination with a moderately-sized storage of 30,000 gallons, it was enough to gather enough water.

The catchment area was also important in between the north and central parts of the state. The catchment area was also closely tied with a firm storage size of 30,000 gallons. Austin, San Antonio, and Dallas had the highest firm yields with catchment areas between 5,400 and 8,000 square feet. Following this trend, Hallettsville, Abilene, and Wichita Falls also showed moderate firm yields with bigger catchment areas.

It's unlikely that a home would have a catchment of 70,000 square feet, so I 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 except for Midland, El Paso, and Fort Davis (Figure 6).

Similar to my analysis on storage, the drought that controlled the firm yield changed depending on demand for firm water. Fourteen of the 19 cities had different defining droughts depending on the demand (Appendix). In the case of Wichita Falls, the controlling drought changed from the 1950s to the 2000s to the 1950s to the 2010s with increasing demand (Figure 7). Another interesting aspect of increasing demand and catchment is that at some level of demand, the defining drought thereafter focused on a single event (Figure 7). Once this defining drought was reached, any increase in demand could be met by a linear increase in catchment (Figure 7), something that can be clearly seen in a number of the drier cities (Figure 5).

For Wichita Falls, lower demands with associated smaller catchments (and a set storage of 30,000 gallons), required more than five decades to move from full storage to dead pool (and another two decades for storage to be completely full again; Figure 8). In this case, smaller demands and catchments require larger storage to overcome long-term climatic variation (During the 50-year period described above, Texas experience the Dust Bowl of the 1930s, the state-wide drought of record in the 1950s, and a severe drought in the 1960s). The end of the defining drought shifted from the 1970s to the 1960s when demand increased to 41.4 gallons per day and then shifted to the 2010s when demand increased to 55.2 gallons per day (Figure 8). Although the drought of the 2010s was shorter than the drought of the 1950s by two to three years, it was more intense.

In Texarkana, the defining drought for most scenarios happened during the 1890s. Texarkana was the only city I investigated that had adequate data coverage to include pre-1900 measurements of precipitation in my analysis. My Texarkana analysis is a reminder that the length of the record controls the firm yield and thus the reliability of a rainwater harvesting system. Just as with mutual funds, past results do not guarantee future rainwater returns.

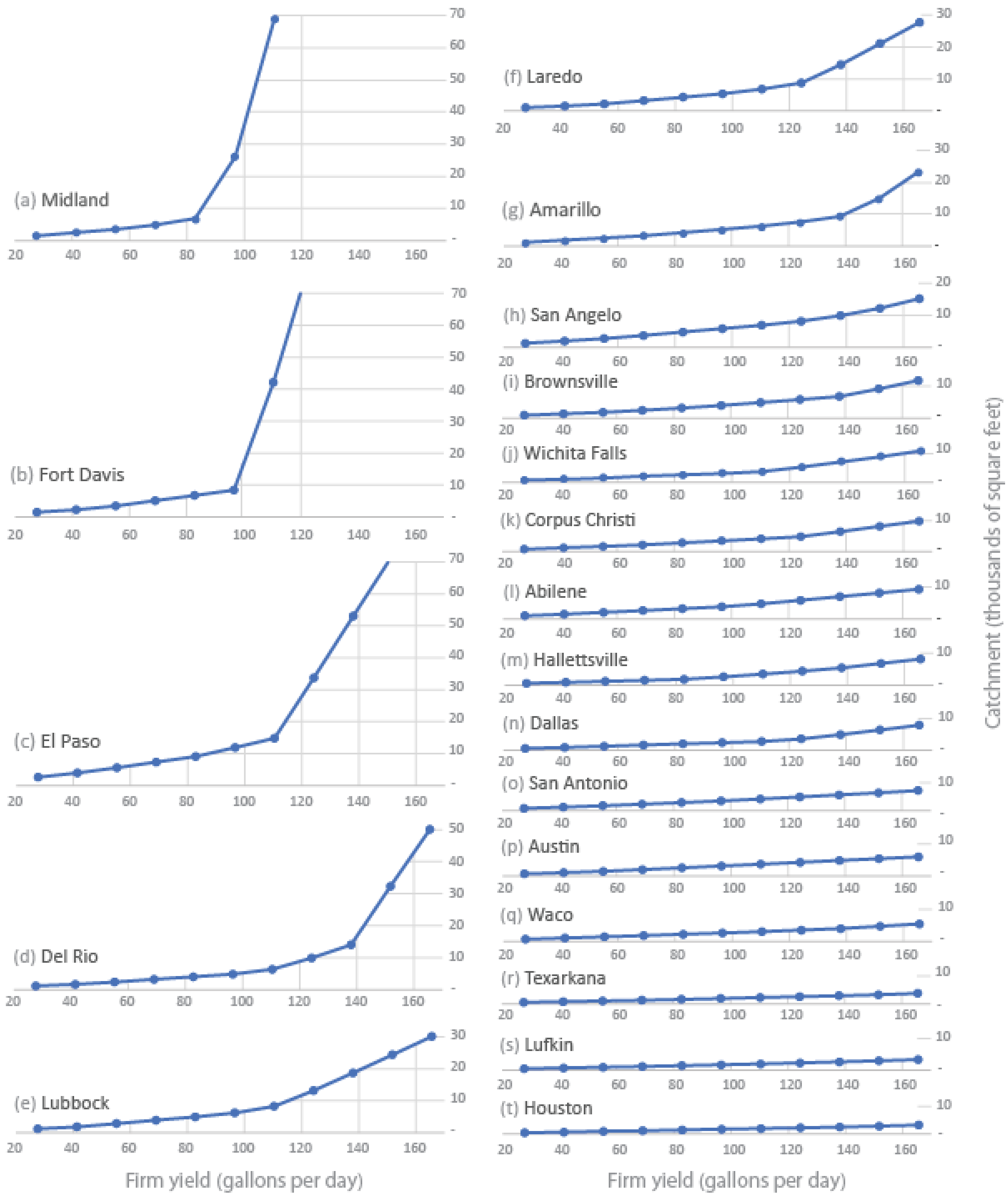

Figure 5: Catchment required to achieve a range of firm yields for a storage of 30,000 gallons for a variety of Texas cities. I organized these graphs from least amenable to rainwater harvesting to most amenable. Note that each graph is on the same horizontal and vertical scale to allow direct comparison between plots.

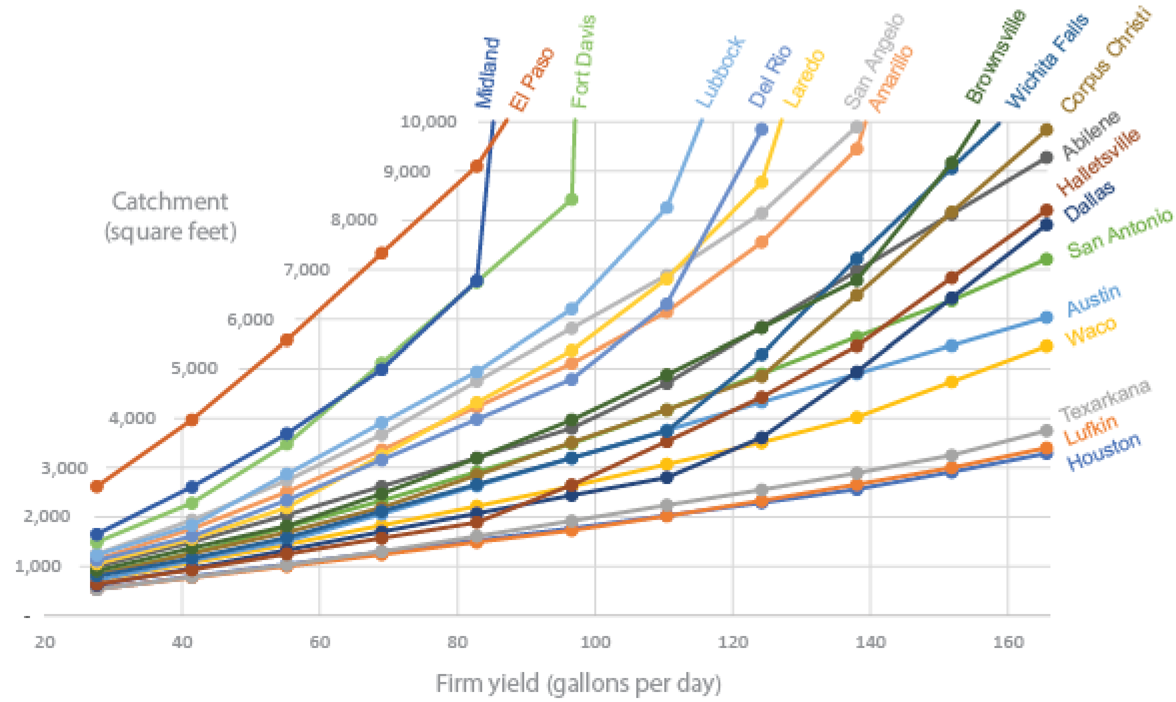

Figure 6: Catchment required to achieve a range of firm yields for storage of 30,000 gallons for a variety of Texas cities with storage capped at 50,000 gallons.

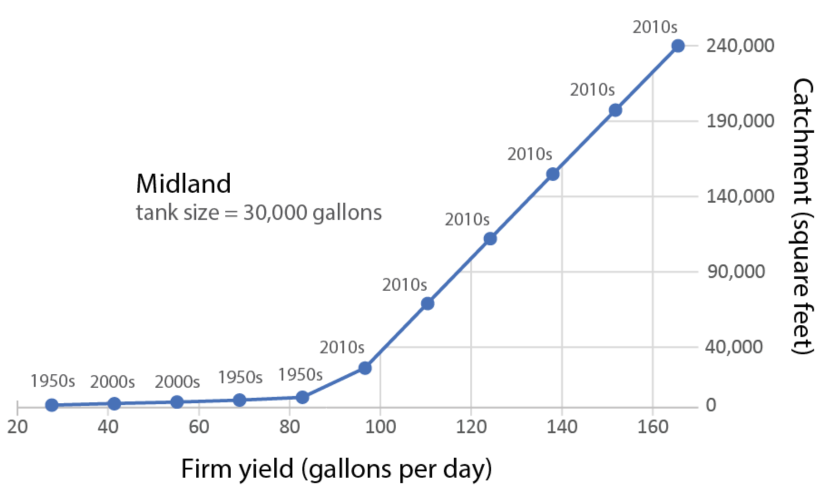

Figure 7: Example of increasing catchment area with increasing firm yield (use) for Midland including the decade the storage reaches a minimum (the decade of the end of the drought defining the firm yield).

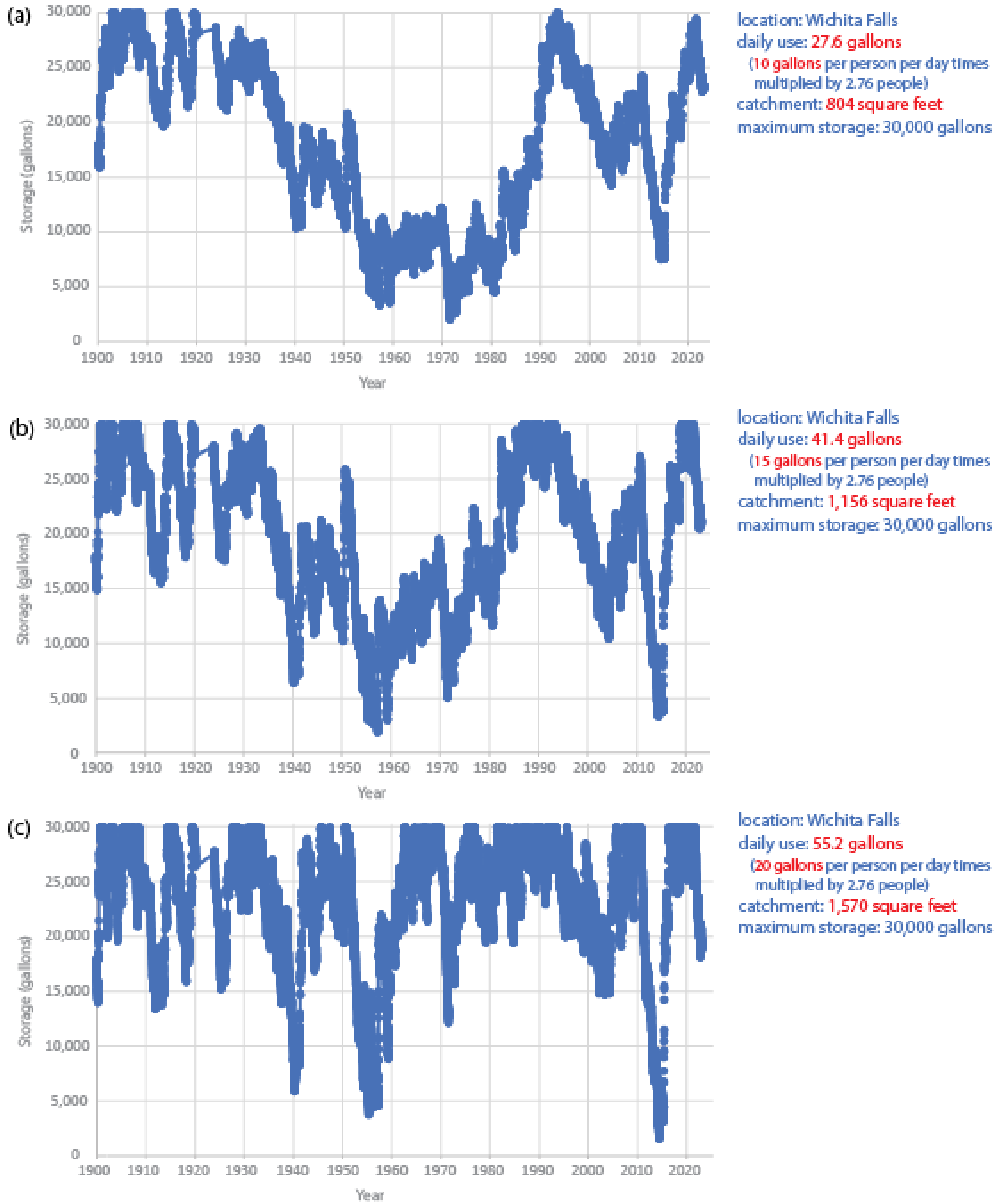

Figure 8: Storage performance for three demand/firm use scenarios with a set storage volume for Wichita Falls.

Comparison with the Lawrence and Lopes (2016)

Lawrence and Lopes (2016) summarized their results in a table that includes the three cities they investigated (Dallas, Houston, and San Antonio) for dry, “average,” and wet years; two demands (210 liters per day [55 gallons per day] and 380 liters per day [100 gallons per day]), two catchment areas (109 square meters [1173 square feet]) and 163 square meters [1755 square feet]), and six tank sizes 2839 liters (750 gal), 3785 liters (1000 gal), 4732 liters (1250 gal), 5678 liters (1500 gal), 6624 liters (1750 gal), and 7571 liters (2,000 gal). They reported the reliability (percent of days the tank held water) for each of their scenarios (Table 2). For comparison, I also reported the reliability using my approach (Table 2). In fact, my reliabilities are the actual reliabilities for these systems for the historic record.

In all cases, using the full precipitation record instead of a year for the 10th, 50th, and 90th percentiles resulted in substantially lower reliabilities (Table 2). For example, the 99 percent reliability Lawrence and Lopes (2016) calculated for a wet year, a demand of 210 liters per day, and a 109 square meter roof in Dallas results in a reliability of 26 percent using the full period of record. On the lower end, the 24 percent reliability Lawrence and Lopes (2016) calculated for a dry year, a demand of 380 liters per day, and a 109 square meter roof in San Antonio results in a reliability of 8 percent using the full period of record.

The major difference between the method used by Lawrence and Lopes (2016) and my method is how the precipitation data is used. I used the full record to simulate the use of rainwater harvesting whereas Lawrence and Lopes (2016) only used a year of the record for dry, average, and wet conditions. This can be ineffective as a drought generally does not last one year, but multiple consecutive years, and can straddle the beginning or end of a year. The 2011 drought is an example of a drought that lasted multiple years in different parts of the state. Using the full record reflects the lasting nature of droughts and true reliability. And if you have the full record, why would you use something less?

Another difference between the two methodologies is that Lawrence and Lopes (2016) did not include the driest conditions on record. This results, by definition, in a firm yield of zero, which is not helpful for water planning.

Another issue with their analysis is the resulting size of the tanks (storage) they recommended to meet certain water demands. In short, they are way too small (as noted above, the resulting tank sizes they recommended were 2839 liters (750 gallons), 3785 liters (1000 gallons), 4732 liters (1250 gallons), 5678 liters (1500 gallons), 6624 liters (1750 gallons), and 7571 liters (2,000 gallons). Achieving firm yields for their demands, catchment area, and locations requires storage that ranges from 28,400 to 208,000 liters, 5 to 31 times greater than what they recommended (Table 3).

Lawrence and Lopes (2016) study consisted of the three biggest cities in Texas: Dallas, Houston, and San Antonio, all in the eastern half of the state. My study consisted of cities located in each regional water planning group. I did this to show the difference in geography, climate, and rainfall. It would also show how rainfall harvesting would fare better across a statewide setting.

Table 2: Comparison of reliability between Lawrence and Lopes (2016) and my method (dpd = demand per day, L = liters, m2 = square meters). My method used the full period of record to assess reliability for their storage, catchment, and use numbers and represent actual reliabilities.

		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 m2 Roof	4732 L (45%)	3785 L (24%)	4732 L (76%)	3785 L (37%)	7571 L (84%)	6624 L (51%)
	My Method	*19%*	*8%*	*19%*	*8%*	*21%*	*10%*
	163 m2 Roof	6624 L (59%)	4732 L (34%)	7571 L (98%)	4732 L (54%)	5678 L (90%)	6624 L (65%)
	My Method	*30%*	*14%*	*31%*	*14%*	*20%*	*15%*
Dallas	109 m2 Roof	5678 L (62%)	4732 L (33%)	7571 L (84%)	4732 L (48%)	5678 L (99%)	5678 L (72%)
	My Method	*26%*	*12%*	*27%*	*12%*	*26%*	*12%*
	163 m2 Roof	6624 L (76%)	6624 L (49%)	7571 L (91%)	5678 L (61%)	3785 L (98 %)	6624 L (88%)
	My Method	*38%*	*20%*	*40%*	*18%*	*30%*	*20%*
Houston	109 m2 Roof	5678 L (76%)	7571 L (57%)	5678 L (91%)	5678 L (65%)	2839 L (88%)	5678 L (76%)
	My Method	*32%*	*18%*	*32%*	*17%*	*26%*	*17%*
	163 m2 Roof	5678 L (86%)	6624 L (63%)	3785 L (95%)	5678 L (75%)	2839 L (93%)	5678 L (86%)
	My Method	*46%*	*26%*	*48%*	*24%*	*33%*	*24%*

Table 3: Comparison of storage between Lawrence and Lopes (2016) and my method (dpd = demand per day, L = liters, m2 = square meters). Results are rounded to three significant figures and converted from gallons. My numbers show the storage needed to achieve 100% reliability. A dash (no number) means that 100% reliability could not be attained with their parameters.

		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 m2 Roof	4732 L (45%)	3785 L (24%)	4732 L (76%)	3785 L (37%)	7571 L (84%)	6624 L (51%)
	My Method	-	-	-	-	-	-
	163 m2 Roof	6624 L (59%)	4732 L (34%)	7571 L (98%)	4732 L (54%)	5678 L (90%)	6624 L (65%)
	My Method	*120,000 L*	-	*120,000 L*	-	*120,000 L*	-
Dallas	109 m2 Roof	5678 L (62%)	4732 L (33%)	7571 L (84%)	4732 L (48%)	5678 L (99%)	5678 L (72%)
	My Method	*170,000 L*	-	*170,000 L*	-	*170,000 L*	-
	163 m2 Roof	6624 L (76%)	6624 L (49%)	7571 L (91%)	5678 L (61%)	3785 L (98 %)	6624 L (88%)
	My Method	*49,200 L*	-	*49,200 L*	-	*49,200 L*	-
Houston	109 m2 Roof	5678 L (76%)	7571 L (57%)	5678 L (91%)	5678 L (65%)	2839 L (88%)	5678 L (76%)
	My Method	*42,000 L*	-	*42,000 L*	-	*42,000 L*	-
	163 m2 Roof	5678 L (86%)	6624 L (63%)	3785 L (95%)	5678 L (75%)	2839 L (93%)	5678 L (86%)
	My Method	*28,400 L*	*208,000 L*	*28,400 L*	*208,000 L*	*28,400 L*	*208,000 L*

Discussion

With the development of this tool, planners, landowners, and installers can accurately assess the reliability of their existing or planned rainwater harvesting system and determine what it would take to have a truly reliable supply, at least based on the historical record for the locale of that system. Although I have created spreadsheets for specific cities across Texas, the tool can be used anywhere in the world as long as there is a record of daily measured precipitation.

Another lesson from this study is that greater resilience comes with larger catchment areas and larger storage volumes. Reliability or firm yield will always increase with increasing catchment area, but after storage captures all the precipitation, larger storage size doesn't matter. Efficient use of water results in lower catchment and storage needs or, with an existing system, increased resilience.

You can't assume that the local drought of record—however it's defined—is the same drought of record you should plan for with your rainwater harvesting system. The unique combination of demand, catchment, and storage (and other system parameters such as runoff coefficient, first flush volume, and dead pool) determine your system's drought of record. It is best to use the full precipitation record when designing rainwater harvesting systems.

High reliability that is less than 100 percent could result in frequent water hauling for system owners. For example, a system in Austin with 98 percent reliability with 581 days out of 30,935 total days with zero storage would result in hauling water in 26 of the 85 years in the record (31 percent of the years, Figure 9a). So, in any given year, there would be nearly a one in three chance of hauling water. For that same system with 99 percent reliability, it would have 274 days out of 30,935 total days with zero storage would result in hauling water in 17 of the 85 years in the record (20 percent of the years, Figure 9b). That may not be acceptable to a property owner.

I found that rainwater harvesting can be a reliable source of water for much of the state. If 30,000 gallons of storage is considered reasonable (as it is in the Hill Country), all the cities I investigated except El Paso, Fort Davis, and Midland can have a firm yield of at least 60 gallons per day. From lowest to highest firm yield, Brownsville, San Antonio, Corpus Christi, Wichita Falls, and Austin achieve firm yields ranging from 83 to 97 gallons per day, suggesting that the viability for reliable rainwater harvesting in Texas is far larger than currently thought. Even El Paso, Midland, and Fort Davis could achieve some level of reliable rainwater supply despite their desert climates.

My findings show that there is high rainwater potential throughout the state. Firm yields throughout the state are clear indicators that rainwater harvesting can be successful if encouraged by the state. Storage size and catchment area are determining factors for firm yield throughout the state. Storage size is also an easier factor to change. Based on daily use and rainfall, increased storage can yield more water for a household. Catchment area on the other hand, can be more challenging to add. Certainly, there will be an economic cost on homeowners who wish to add or modify rainwater harvesting systems to their homes.

Results can be used to formulate a more detailed economic plan for encouraging rainwater harvesting at the state level. Establishing more incentives and rebates at the state level for homeowners can become a sustainable solution to water insecurity or low water quality. Communities that stand to benefit more are those in rural areas of the state. For example, the colonias in South Texas lack sufficient development like drinking water or adequate sewage treatment (Office of the Attorney General, 2023). Making rainwater harvesting more affordable for these communities could increase their standard of living. Currently, the state is investing billions into rebuilding the aging and leaking water infrastructure throughout the state. If combined with rainwater harvesting, homeowners throughout the state could greatly benefit from having more freshwater for potable and non-potable uses.

More work could be done on this topic. For example, my work was focused on determining firm yield for water planning purposes; however, an owner may want to optimize cost between storage volume and reliability with hauled water making up the difference.

My analysis is backward-looking—I used the historical record to estimate firm yields. A warming climate is expected to change spatial and temporal precipitation. Preliminary analysis using this tool suggests, not surprisingly, more storage or catchment is needed for lower amounts of precipitation but also that more storage or catchment is needed if precipitation amounts stay the same but become more focused on rainier events (Robert Mace, personal communication, 2023).

My analysis assumes consistent daily use. For designers seeking to build a reliable system for outdoor irrigation, a more complicated seasonal and rainfall-dependent use profile could be developed.

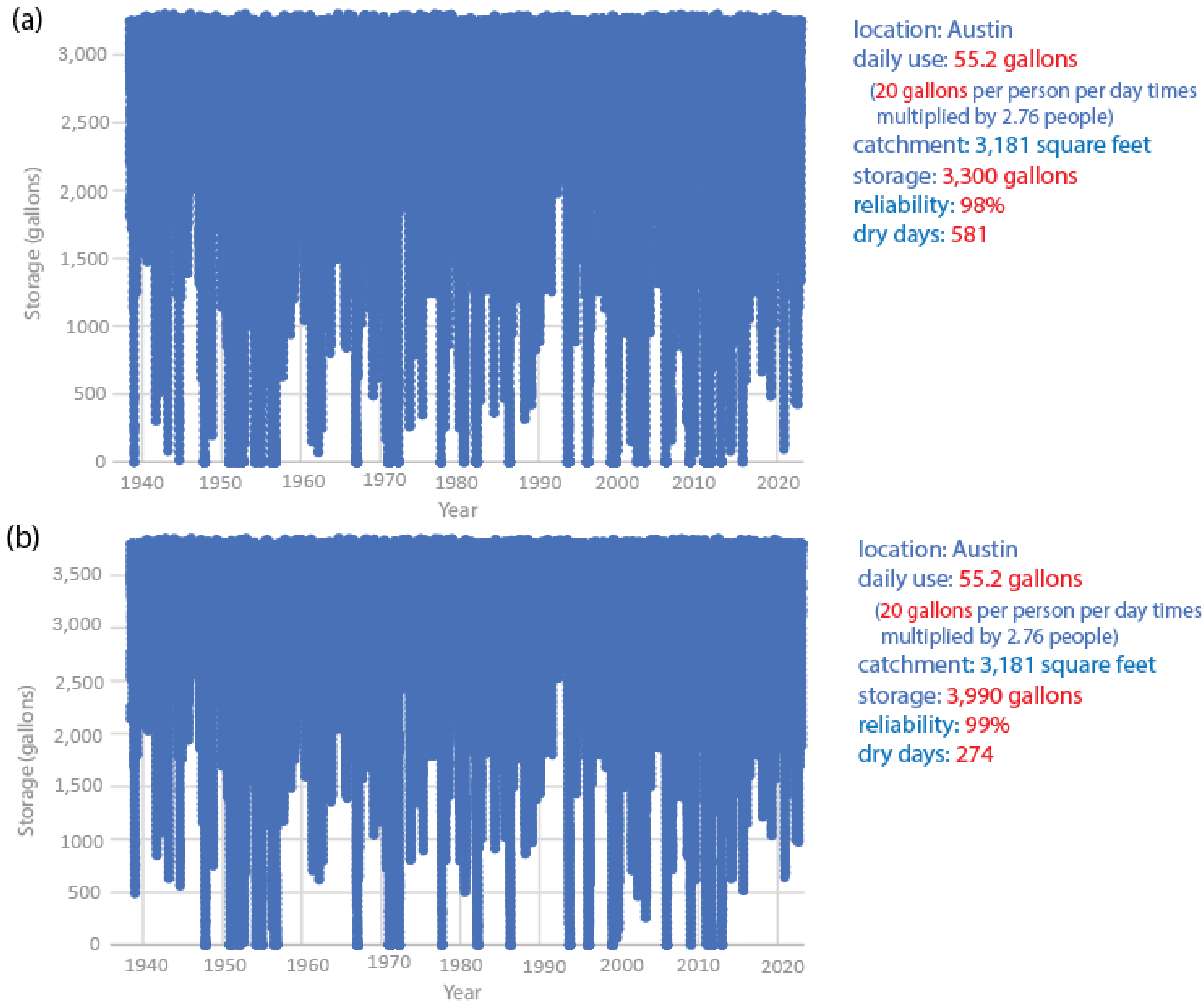

Figure 9: Storage performance and reliability for a couple rainwater systems in Austin.

Conclusion

Since the inception of time, rainwater has been crucial to the survival of humankind. Ancient civilization captured rainwater with simple infrastructure and were able to store it for future use. Rainwater uses included agriculture, irrigation, and even drinking. As the world modernized and went through rapid industrialization, rainwater was forgotten as a reliable source of water. Recently, rainwater harvesting has resurfaced as a sustainable solution to many modern issues like water shortages, poor water quality, and climate change. Encouraging rainwater harvesting proves to be effective for individuals who live an environmental-conscious lifestyle. Its mention and implementation in small-scale plans of the water policymaking process proves its effectiveness.

In Texas, rainwater harvesting has historically been an alternative source of water for centuries. Old cisterns scattered throughout the state prove the state has a background in water harvesting. Early settlers relied on rainwater to survive the untamed Texas geography. Due to limited access to conventional water supplies, such as water wells or community water systems, landowners in parts of the Hill Country rely on rainwater to meet all their potable and non-potable needs, allowing Texas to be a leader in modern-day rainwater harvesting in the United States.

Despite the promise of rainwater harvesting as an alternative supply in Texas, rainwater harvesting does not provide a large amount of supply in the state, especially outside the Hill Country. Part of the issue is that planners and others generally don’t consider rainwater harvesting a reliable source of water. The purpose of this study is to evaluate the firm yield of rainwater harvesting across the state to provide information the planning groups need to include rainwater harvesting in their plans.

To find firm yields in Texas, I chose a city located in every regional water planning area throughout the state. Due to the irregular sizes of the regional water planning areas, I chose two cities in some regional planning areas to better represent the climate. For every city, I downloaded historical precipitation data from the National Oceanic and Atmospheric Administration's Climate Date Online, while trimming data that was irregular or missing. To understand the effectiveness of rainwater harvesting, I developed a governing equation on an Excel spreadsheet that included: catchment area, rainfall, runoff losses, first flush, storage volume, and daily use. The governing equation, combined with historical rainfall data, created graphs that showed the effectiveness of rainwater harvesting throughout the state. These results were then divided into separate analyses detailing storage volume and catchment area.

To investigate the storage volumes required to achieve firm supplies for different parts of the state, I estimated firm yields for different amounts of use for a standard catchment area of 3181 square feet. Not surprisingly, smaller storage volumes are needed in the wetter, eastern parts of the state than the dry, more western parts. The drier the climate, the less likely the rainwater harvesting system is going to reliably provide uses of higher volumes. In all cases, firm yields for the entire state can be obtained for all the cities investigated for the specified catchment and with storage less than 50,000 gallons. In the north and central parts of the state, there was a mixture of high and moderate firm yields based on storage size with a catchment area of 3181 square feet. The southern and western parts of the state could only achieve lower firm yields given the catchment area. One interesting aspect of my analysis is that the drought that controlled the firm yield changed depending on demand for firm water. Seventeen of the 19 cities had different defining droughts depending on the demand.

To investigate the catchment areas required to achieve firm supplies for different parts of the state, I estimated firm yields for a standard storage volume of 30,000 gallons. 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. Catchment areas to achieve larger firm yields in drier climates have to be much larger than in wetter climates, sometimes substantially larger. The catchment area is critical to achieving a firm yield throughout the state. 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 except for Midland, El Paso, and Fort Davis. Similar to my analysis on storage, the drought that controlled the firm yield changed depending on demand for firm water. Fourteen of the 19 cities had different defining droughts depending on the demand.

Lawrence and Lopes (2016) also conducted a similar research paper using reliability to test rainwater harvesting throughout the state. In all cases, using the full precipitation record instead of a year for the 10th, 50th, and 90th percentiles resulted in substantially lower reliabilities than they reported. Achieving firm yields for their demands, catchment area, and locations requires storage that ranges from 28,400 to 208,000 liters, 5 to 31 times greater than what they recommended.

With the development of this tool, planners, landowners, and installers can accurately assess the reliability of their existing or planned rainwater harvesting system and determine what it would take to have a truly reliable supply, at least based on the historical record for the locale of that system. Another lesson from this study is that greater resilience comes with larger catchment areas and larger storage volumes. Reliability or firm yield will always increase with increasing catchment area, but after storage captures all the precipitation, larger tank size doesn't matter. Efficient use of water results in lower catchment and storage needs or, with an existing system, increased resilience.

I found that rainwater harvesting can be a reliable source of water for much of the state. Firm yields throughout the state are clear indicators that rainwater harvesting can be successful if encouraged by the state. Results can be used to formulate more detailed plans for encouraging rainwater harvesting at the state level. Results can be used to formulate more detailed plans for encouraging rainwater harvesting at the state level. Establishing more incentives and rebates at the state level for homeowners can become a sustainable solution to water insecurity or low water quality.

References

Adham, A., Abed, R., & Ritsema, C. (2021). A reliability analysis of rainwater catchment system. *Water Resources*, *48*(3), 361–367. https://doi.org/10.1134/s0097807821030027

Battenberg, E. G. (2009). *Flowing issues a brief history of rainwater harvesting*. WCPIM Online. https://wcponline.com/2009/09/14/flowing-issues-brief-history-rainwater-harvesting/

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

Bretsen, S.N. (2018) *Rainwater harvesting in Colorado and the quandary of a taking.* Texas A&M Journal of Property Law, 4, 165.

California Department of Water Resources. (2021, November 30). 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, June 6). *Cape Analytics Data reveals America's top 10 largest buildings by roof size*. CAPE Analytics. https://capeanalytics.com/blog/top-10-largest-buildings/

Capehart, M. A., & Eden, S. (2021). Choosing Large-scale Rain Harvesting for Potable Supply Guide for Rural Homeowners in Arizona. *The University of Arizona Cooperative Extension,* 1–13. https://wrrc.arizona.edu/sites/wrrc.arizona.edu/files/attachment/large-scale-water-harvesting.pdf

City of Brenham. (2023). *City of Brenham Toubin Park*. Retrieved January 30, 2023, from https://www.cityofbrenham.org/city_government/departments/parks_and_recreation/toubin_park.php

Cordell, L. (2008). *Albuquerque's environmental story*. Pueblo Indian Influence - Heritage and Human Environment - Albuquerque's Environmental Story. Retrieved January 19, 2023, from https://albuqhistsoc.org/aes/s3pueblo.html

Crow, R. (2019). *Who owns the rain? Diffused Surface water, state water, and rainwater harvesting in Texas.* Texas Environmental Law Journal, 49, 1.

Department of Energy. (2023). *Rainwater harvesting regulations map*. Retrieved April 26, 2023, from https://www.energy.gov/femp/rainwater-harvesting-regulations-map

Espíndola, J. A., Sánchez, Y. C., & Flores, C. C. (2020). Mexican rainwater harvesting movement in recent years. *International Rainwater Catchment Systems Experiences*, 73–82. https://doi.org/10.2166/9781789060584_0073

Farreny, R., Morales-Pinzón, T., Guisasola, A., Tayà, C., Rieradevall, J., & Gabarrell, X. (2011). Roof selection for rainwater harvesting: Quantity and quality assessments in

Spain. *Water Research, 45(10),* 3245–3254. https://doi.org/10.1016/j.watres.2011.03.036

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

Golley, F. B. (1987). Deep ecology from the perspective of ecological science. Environmental Ethics, 9(1), 45-55.

Hailwood, S. A. (2000). The Value of Nature’s Otherness. *Environmental Values*, *9*(3), 353–372.

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

Institute For Local Self-Reliance. (2006). How Big is Too Big? https://ilsr.org/wp-content/uploads/2008/12/bbtk-factsheet-howbig.pdf

Judeh, T., Shahrour, I., & Comair, F. (2022). Smart rainwater harvesting for sustainable potable water supply in arid and semi-arid areas. Sustainability, 14(15), 9271. https://doi.org/10.3390/su14159271

Juergensmeyer, J.C. & Durham, A.V. (2019) *Rainwater harvesting: legal frameworks in the United States, Singapore, and other countries.* Journal of Comparative Urban Law and Policy, 3, 81.

Kim, H. W., Li, M.-H., Kim, H., & Lee, H. K. (2015). Cost-benefit analysis and equitable cost allocation for a residential rainwater harvesting system in the city of Austin, Texas. *International Journal of Water Resources Development*, *32*(5), 749–764. https://doi.org/10.1080/07900627.2015.1073142

Krishna, H. (2005). *The Texas Manual on Rainwater harvesting*. Texas Water Development Board. https://www.twdb.texas.gov/publications/brochures/conservation/doc/RainwaterHarvestingManual_3rdedition.pdf

Krishna, H. (2020). *Fifty Years in America with Glimpses of Heaven: The true story of an immigrant from India*. (Independently published)

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

Lawrence, D., & Lopes, V. L. (2016). Reliability Analysis of Urban Rainwater Harvesting for Three Texas Cities. Journal of Urban and Environmental Engineering, 10(1), 124–134.

Mays, L., Angelakis, A. N., & Antoniou, G. P. (2021, January 4). *A history of water cistern engineering since the Ancient World*. Brewminate. Retrieved January 26, 2023, from https://brewminate.com/a-history-of-water-cistern-engineering-since-the-ancient-world/

Maxwell-Gaines, C. (2022, February 6). *Austin Rainwater Harvesting & conservation rebates*. Innovative Water Solutions LLC. Retrieved May 2, 2023, from https://www.watercache.com/rebates/austin

Monjardin, C. E., Ente, A. L., & Lorenzo, G. M. (2022). Analysis of rainwater harvesting methods considering the impacts of climate change. *2022 IEEE Conference on Technologies for Sustainability (SusTech)*, 18–24. https://doi.org/10.1109/sustech53338.2022.9794241

New Austin Central Library. (2023). https://www.leedatx.com/projects/featured-projects/new-central-library

National Oceanic and Atmospheric Administration. (2023). Climate Data Online (CDO) - The National Climatic Data Center's (NCDC) Climate Data Online (CDO) provides free access to NCDC's archive of historical weather and climate data in addition to station history information. | National Climatic Data Center (NCDC). https://www.ncdc.noaa.gov/cdo-web/

Office of the Attorney General. (2023). Colonias Prevention. https://www.texasattorneygeneral.gov/divisions/colonias-prevention

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

PGCD (Panhandle Groundwater Conservation District). (2023). *PGCD - rainwater harvesting*. Retrieved May 3, 2023, from https://www.pgcd.us/rainwater-harvesting

Rost, S. (2017). Water management in Mesopotamia from the sixth till the first millennium B.C. *Wiley Interdisciplinary Reviews: Water*, *4*(5). https://doi.org/10.1002/wat2.1230

Rowe, M.P., (2011). Rain Water Harvesting in Bermuda. *Journal of the American Water Resources Association* (JAWRA) 47(6):1219–1227. https://doi.org/10.1111/j.1752-1688.2011.00563.x

Singh, P. K., Dey, P., Jain, S. K., & Mujumdar, P. P. (2020). Hydrology and Water Resources Management in ancient India. *Hydrology and Earth System Sciences*, *24*(10), 4691–4707. https://doi.org/10.5194/hess-24-4691-2020

Scott, C.T. (2014) *Rain catching: an analysis of rainwater harvesting in Texas.* Texas Environmental Law Journal, 44, 375.

Steffen, J., Jensen, M., Pomeroy, C. A., & Burian, S. J. (2013). Water Supply and stormwater management benefits of residential rainwater harvesting in U.S. cities. *JAWRA Journal of the American Water Resources Association*, 49(4), 810–824. https://doi.org/10.1111/jawr.12038

Texas Parks & Wildlife Department. *Hueco Tanks State Park*. (2023, January 28). Retrieved January 30, 2023, from https://tpwd.texas.gov/state-parks/hueco-tanks/park_history

Texas Water Development Board. *Far West Texas Water Plan.* (2021). 1-515. https://www.twdb.texas.gov/waterplanning/rwp/plans/2021/index.asp#region-e

Texas Water Development Board. *Plateau Region Water Plan.* (2021). 1-460. https://www.twdb.texas.gov/waterplanning/rwp/plans/2021/index.asp#region-j

Texas Water Development Board. *2021 Region K Water Plan For the Lower Colorado Regional Water Planning Group.* (2021). 1-887. https://www.twdb.texas.gov/waterplanning/rwp/plans/2021/index.asp#region-k

Texas Water Development Board. *Water for Texas 1997 State Water Plan.* (1997). 1-150. https://www.twdb.texas.gov/waterplanning/swp/1997/index.asp

Texas Water Development Board. *Water for Texas 2002 State Water Plan.* (2002). 1-156. https://www.twdb.texas.gov/waterplanning/swp/2002/index.asp

Texas Water Development Board. *Water for Texas 2012 State Water Plan.* (2012). 1-300. http://www.twdb.texas.gov/waterplanning/swp/2012/index.asp

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

Trew, D. (2002). *Water Cisterns made farm life possible in Texas panhandle - farm collector*. Farm Collector - Dedicated to the Preservation of Vintage Farm Equipment. Retrieved January 30, 2023, from https://www.farmcollector.com/farm-life/its-all-trew-old-time-cisterns/

Triplett, A.R. (2018) *The right to rainwater: an unlikely fairytale.* Walter F. George School of Law, Mercer University, 69, 575.

U.S. Census Bureau. (2023). *Chars - current data*. United States Census Bureau. https://www.census.gov/construction/chars/current.html

U.S. Census Bureau quickfacts: Texas. (2023). Retrieved March 9, 2023, from https://www.census.gov/quickfacts/fact/table/TX/PST045221

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

Yannopoulos, S., Giannopoulou, I., & Kaiafa-Saropoulou, M. (2019). Investigation of the current situation and prospects for the development of rainwater harvesting as a tool to confront water scarcity worldwide. *Water*, *11*(10), 2168. https://doi.org/10.3390/w11102168

Yegul, F. (2023). *Water Supply Systems: Cisterns, Reservoirs, Aqueducts*. Roman Building Technology and Architecture. Retrieved January 23, 2023, from https://archserve.id.ucsb.edu/courses/arthistory/152k/water.html

Appendix

A dash (-) means that I could not achieve a firm yield with the parameters shown.

Abilene

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	3,181	4,010	*1950s*
41.4	3,181	6,480	*1950s*
55.2	3,181	10,900	*1950s*
69	3,181	18,000	*1950s*
82.8	3,181	31,000	*1950s*
96.6	3,181	76,700	*1950s*
110.4	3,181	162,000	*1950s*
124.2	3,181	-	-
138	3,181	-	-
151.8	3,181	-	-
165.6	3,181	-	-

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	990	30,000	*1950s*
41.4	1,490	30,000	*1950s*
55.2	2,040	30,000	*1950s*
69	2,620	30,000	*1950s*
82.8	3,200	30,000	*1950s*
96.6	3,800	30,000	*1950s*
110.4	4,710	30,000	*1950s*
124.2	5,840	30,000	*1950s*
138	6,980	30,000	*1950s*
151.8	8,130	30,000	*1950s*
165.6	9,280	30,000	*1950s*

Amarillo

Firm Yield (gallons per day)	**Catchment (square feet)**	**Storage (gallons)**	**Defining drought**
27.6	3,181	5,600	*2010s*
41.4	3,181	9,200	*2010s*
55.2	3,181	16,000	*2010s*
69	3,181	34,000	*2010s*
82.8	3,181	61,000	*1950s*
96.6	3,181	-	-
110.4	3,181	-	-
124.2	3,181	-	-
138	3,181	-	-
151.8	3,181	-	-
165.6	3,181	-	-

Firm Yield (gallons per day)	**Catchment (square feet)**	**Storage (gallons)**	**Defining drought**
27.6	1,140	30,000	2010s
41.4	1,760	30,000	2010s
55.2	2,510	30,000	2010s
69	3,360	30,000	2010s
82.8	4,230	30,000	2010s
96.6	5,110	30,000	2010s
110.4	6,150	30,000	2010s
124.2	7,560	30,000	2010s
138	9,450	30,000	2010s
151.8	14,900	30,000	2010s
165.6	23,300	30,000	2010s

Austin

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	3,181	3,240	*1970s*
41.4	3,181	4,940	*1970s*
55.2	3,181	7,340	*1970s*
69	3,181	10,200	*1970s*
82.8	3,181	14,500	*1950s*
96.6	3,181	30,200	*1950s*
110.4	3,181	47,000	*1950s*
124.2	3,181	65,200	*1950s*
138	3,181	114,000	*1950s*
151.8	3,181	-	-
165.6	3,181	-	-

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	720	30,000	*1950s*
41.4	1,120	30,000	*1950s*
55.2	1,510	30,000	*1950s*
69	2,060	30,000	*1950s*
82.8	2,630	30,000	*1950s*
96.6	3,190	30,000	*1950s*
110.4	3,760	30,000	*1950s*
124.2	4,330	30,000	*1950s*
138	4,900	30,000	*1950s*
151.8	5,470	30,000	*1950s*
165.6	6,040	30,000	*1950s*

Brownsville

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	3,181	4,870	*1950s*
41.4	3,181	7,970	*1950s*
55.2	3,181	11,800	*1990s*
69	3,181	18,800	*1950s*
82.8	3,181	30,100	*1950s*
96.6	3,181	45,300	*1950s*
110.4	3,181	110,000	*1950s*
124.2	3,181	-	-
138	3,181	-	-
151.8	3,181	-	-
165.6	3,181	-	-

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	910	30,000	*1950s*
41.4	1,370	30,000	*1950s*
55.2	1,820	30,000	*1950s*
69	2,470	30,000	*1950s*
82.8	3,190	30,000	*1950s*
96.6	3,970	30,000	*1950s*
110.4	4,880	30,000	*1950s*
124.2	5,830	30,000	*1950s*
138	6,790	30,000	*1950s*
151.8	9,170	30,000	*1990s*
165.6	11,800	30,000	*1990s*

Corpus Christi

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	3,181	3,520	*1970s*
41.4	3,181	6,690	*2000s*
55.2	3,181	11,300	*2000s*
69	3,181	15,900	*2000s*
82.8	3,181	22,900	*1960s*
96.6	3,181	37,100	*1960s*
110.4	3,181	51,300	*1960s*
124.2	3,181	76,400	*1960s*
138	3,181	92,600	*2010s*
151.8	3,181	-	-
165.6	3,181	-	-

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	825	30,000	*1950s*
41.4	1,260	30,000	*1950s*
55.2	1,690	30,000	*1950s*
69	2,190	30,000	*1960s*
82.8	2,850	30,000	*1960s*
96.6	3,510	30,000	*1960s*
110.4	4,170	30,000	*1960s*
124.2	4,850	30,000	*1960s*
138	6,490	30,000	*2010s*
151.8	8,170	30,000	*2010s*
165.6	9,840	30,000	*2010s*

Dallas

Firm Yield (gallons per day)	**Catchment (square feet)**	**Storage (gallons)**	**Defining drought**
27.6	3,181	4,520	*1990s*
41.4	3,181	6,820	*1990s*
55.2	3,181	9,110	*1990s*
69	3,181	13,300	*1990s*
82.8	3,181	17,700	*1990s*
96.6	3,181	22,200	*1990s*
110.4	3,181	27,000	*1990s*
124.2	3,181	31,900	*1990s*
138	3,181	63,000	*1950s*
151.8	3,181	97,600	*1950s*
165.6	3,181	133,000	*1950s*

Firm Yield (gallons per day)	**Catchment (square feet)**	**Storage (gallons)**	**Defining drought**
27.6	619	30,000	*2010s*
41.4	957	30,000	*1950s*
55.2	1,330	30,000	*1950s*
69	1,700	30,000	*1950s*
82.8	2,070	30,000	*1950s*
96.6	2,440	30,000	*1950s*
110.4	2,800	30,000	*1950s*
124.2	3,610	30,000	*1990s*
138	4,940	30,000	*1990s*
151.8	6,430	30,000	*1990s*
165.6	7,920	30,000	*1990s*

Del Rio

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	3,181	6,150	*2010s*
41.4	3,181	10,600	*2010s*
55.2	3,181	15,300	*2010s*
69	3,181	29,500	*2010s*
82.8	3,181	50,400	*2010s*
96.6	3,181	-	-
110.4	3,181	-	-
124.2	3,181	-	-
138	3,181	-	-
151.8	3,181	-	-
165.6	3,181	-	-

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	1,120	30,000	*2000s*
41.4	1,610	30,000	*2000s*
55.2	2,340	30,000	*2010s*
69	3,160	30,000	*2010s*
82.8	3,980	30,000	*2010s*
96.6	4,790	30,000	*2010s*
110.4	6,310	30,000	*2010s*
124.2	9,850	30,000	*2010s*
138	14,000	30,000	*2010s*
151.8	32,300	30,000	*2010s*
165.6	50,100	30,000	*2010s*

El Paso

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	3,181	12,900	*1950s*
41.4	3,181	-	-
55.2	3,181	-	-
69	3,181	-	-
82.8	3,181	-	-
96.6	3,181	-	-
110.4	3,181	-	-
124.2	3,181	-	-
138	3,181	-	-
151.8	3,181	-	-
165.6	3,181	-	-

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	2,620	30,000	*1970s*
41.4	3,970	30,000	*1950s*
55.2	5,580	30,000	*1950s*
69	7,340	30,000	*1950s*
82.8	9,100	30,000	*1950s*
96.6	11,900	30,000	*1950s*
110.4	14,700	30,000	*2010s*
124.2	33,700	30,000	*2010s*
138	53,000	30,000	*2010s*
151.8	72,300	30,000	*2010s*
165.6	91,600	30,000	*2010s*

Fort Davis

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	3,181	8,350	*2010s*
41.4	3,181	18,500	*2010s*
55.2	3,181	32,800	*2010s*
69	3,181	91,800	*1960s*
82.8	3,181	-	-
96.6	3,181	-	-
110.4	3,181	-	-
124.2	3,181	-	-
138	3,181	-	-
151.8	3,181	-	-
165.6	3,181	-	-

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	1,490	30,000	*1960s*
41.4	2,280	30,000	*1960s*
55.2	3,480	30,000	*2010s*
69	5,120	30,000	*2010s*
82.8	6,750	30,000	*2010s*
96.6	8,430	30,000	*2010s*
110.4	42,100	30,000	*2010s*
124.2	83,600	30,000	*2010s*
138	125,000	30,000	*2010s*
151.8	-	30,000	-
165.6	-	30,000	-

Hallettsville

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	3,181	2,620	*1920s*
41.4	3,181	4,930	*1920s*
55.2	3,181	9,190	*1920s*
69	3,181	14,000	*1920s*
82.8	3,181	19,100	*1920s*
96.6	3,181	25,900	*1920s*
110.4	3,181	32,800	*1920s*
124.2	3,181	39,700	*1920s*
138	3,181	46,700	*1920s*
151.8	3,181	75,300	*1950s*
165.6	3,181	166,000	*1950s*

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	640	30,000	*1930s*
41.4	930	30,000	*1950s*
55.2	1,250	30,000	*1950s*
69	1,570	30,000	*1950s*
82.8	1,890	30,000	*1950s*
96.6	2,650	30,000	*1920s*
110.4	3,530	30,000	*1920s*
124.2	4,430	30,000	*1920s*
138	5,460	30,000	*1920s*
151.8	6,840	30,000	*1920s*
165.6	8,210	30,000	*1920s*

Houston

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	3,181	2,600	*2010s*
41.4	3,181	4,160	*2010s*
55.2	3,181	6,320	*2010s*
69	3,181	8,490	*2010s*
82.8	3,181	10,700	*2010s*
96.6	3,181	12,900	*2010s*
110.4	3,181	15,000	*2010s*
124.2	3,181	18,200	*2010s*
138	3,181	21,800	*2010s*
151.8	3,181	25,500	*2010s*
165.6	3,181	32,100	*1950s*

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	491	30,000	*1950s*
41.4	717	30,000	*1950s*
55.2	974	30,000	*1950s*
69	1,240	30,000	*1950s*
82.8	1,510	30,000	*1950s*
96.6	1,770	30,000	*1950s*
110.4	2,030	30,000	*1950s*
124.2	2,290	30,000	*1950s*
138	2,550	30,000	*1950s*
151.8	2,910	30,000	*1950s*
165.6	3,290	30,000	*1950s*

Laredo

Firm Yield (gallons per day)	**Catchment (square feet)**	**Storage (gallons)**	**Defining drought**
27.6	3,181	6,260	*1970s*
41.4	3,181	10,100	*1970s*
55.2	3,181	17,200	*2010s*
69	3,181	30,900	*2010s*
82.8	3,181	44,700	*2010s*
96.6	3,181	119,000	*2010s*
110.4	3,181	-	-
124.2	3,181	-	-
138	3,181	-	-
151.8	3,181	-	-
165.6	3,181	-	-

Firm Yield (gallons per day)	**Catchment (square feet)**	**Storage (gallons)**	**Defining drought**
27.6	1,050	30,000	*2010s*
41.4	1,550	30,000	*2000s*
55.2	2,190	30,000	*2010s*
69	3,250	30,000	*2010s*
82.8	4,320	30,000	*2010s*
96.6	5,370	30,000	*2010s*
110.4	6,820	30,000	*2010s*
124.2	8,780	30,000	*2010s*
138	14,500	30,000	*1970s*
151.8	21,100	30,000	*1970s*
165.6	27,700	30,000	*1970s*

Lubbock

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	3,181	7,000	*2010s*
41.4	3,181	11,900	*2010s*
55.2	3,181	24,300	*2010s*
69	3,181	43,300	*2010s*
82.8	3,181	164,000	*1960s*
96.6	3,181	-	-
110.4	3,181	-	-
124.2	3,181	-	-
138	3,181	-	-
151.8	3,181	-	-
165.6	3,181	-	-

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	1,230	30,000	*1950s*
41.4	1,830	30,000	*2010s*
55.2	2,870	30,000	*2010s*
69	3,910	30,000	*2010s*
82.8	4,940	30,000	*2010s*
96.6	6,210	30,000	*2010s*
110.4	8,260	30,000	*2010s*
124.2	13,200	30,000	*2010s*
138	18,700	30,000	*2010s*
151.8	24,400	30,000	*2010s*
165.6	30,100	30,000	*2010s*

Lufkin

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	3,181	1,570	*1950s*
41.4	3,181	2,650	*1990s*
55.2	3,181	3,970	*1990s*
69	3,181	5,530	*1990s*
82.8	3,181	7,100	*1990s*
96.6	3,181	8,670	*1990s*
110.4	3,181	10,300	*1990s*
124.2	3,181	13,000	*1970s*
138	3,181	17,500	*1980s*
151.8	3,181	23,700	*1970s*
165.6	3,181	34,800	*1970s*

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	540	30,000	*1980s*
41.4	770	30,000	*1970s*
55.2	1,000	30,000	*1970s*
69	1,240	30,000	*1970s*
82.8	1,490	30,000	*1970s*
96.6	1,730	30,000	*1970s*
110.4	2,020	30,000	*1970s*
124.2	2,330	30,000	*1970s*
138	2,660	30,000	*1970s*
151.8	3,000	30,000	*1970s*
165.6	3,400	30,000	*1970s*

Midland

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	3,181	9,500	*2010s*
41.4	3,181	17,400	*1950s*
55.2	3,181	49,900	*2000s*
69	3,181	267,000	*2020s*
82.8	3,181	-	-
96.6	3,181	-	-
110.4	3,181	-	-
124.2	3,181	-	-
138	3,181	-	-
151.8	3,181	-	-
165.6	3,181	-	-

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	1,650	30,000	*1950s*
41.4	2,610	30,000	*2000s*
55.2	3,690	30,000	*2000s*
69	4,990	30,000	*1950s*
82.8	6,780	30,000	*1950s*
96.6	26,300	30,000	*2010s*
110.4	69,100	30,000	*2010s*
124.2	-	30,000	-
138	-	30,000	-
151.8	-	30,000	-
165.6	-	30,000	-

San Angelo

Firm Yield (gallons per day)	**Catchment (square feet)**	**Storage (gallons)**	**Defining drought**
27.6	3,181	4,950	*1960s*
41.4	3,181	9,620	*1950s*
55.2	3,181	21,500	*1950s*
69	3,181	45,200	*1950s*
82.8	3,181	107,000	*1960s*
96.6	3,181	-	-
110.4	3,181	-	-
124.2	3,181	-	-
138	3,181	-	-
151.8	3,181	-	-
165.6	3,181	-	-

Firm Yield (gallons per day)	**Catchment (square feet)**	**Storage (gallons)**	**Defining drought**
27.6	1,250	30,000	*1950s*
41.4	1,940	30,000	*1950s*
55.2	2,740	30,000	*1950s*
69	3,670	30,000	*1950s*
82.8	4,750	30,000	*1950s*
96.6	5,820	30,000	*1950s*
110.4	6,890	30,000	*1950s*
124.2	8,150	30,000	*1950s*
138	9,900	30,000	*1950s*
151.8	12,200	30,000	*1950s*
165.6	15,200	30,000	*1950s*

San Antonio

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	3,181	3,810	*1970s*
41.4	3,181	6,410	*1970s*
55.2	3,181	8,960	*1970s*
69	3,181	12,800	*1970s*
82.8	3,181	22,800	*2000s*
96.6	3,181	41,500	*2000s*
110.4	3,181	70,900	*1950s*
124.2	3,181	139,000	*1950s*
138	3,181	-	-
151.8	3,181	-	-
165.6	3,181	-	-

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	840	30,000	*1950s*
41.4	1,270	30,000	*1950s*
55.2	1,800	30,000	*1950s*
69	2,330	30,000	*1950s*
82.8	2,910	30,000	*1950s*
96.6	3,490	30,000	*1950s*
110.4	4,170	30,000	*2010s*
124.2	4,900	30,000	*2010s*
138	5,640	30,000	*2010s*
151.8	6,380	30,000	*2000s*
165.6	7,220	30,000	*2000s*

Texarkana

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
10	3,181	2,410	*1890s*
15	3,181	3,900	*1890s*
20	3,181	5,300	*1890s*
25	3,181	7,000	*1890s*
30	3,181	9,300	*1890s*
35	3,181	11,600	*1890s*
40	3,181	14,000	*1890s*
45	3,181	19,000	*1890s*
50	3,181	25,000	*1890s*
55	3,181	31,400	*1890s*
60	3,181	50,300	*1890s*

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
10	530	30,000	*1900s*
15	780	30,000	*1900s*
20	1,030	30,000	*1900s*
25	1,300	30,000	*1890s*
30	1,610	30,000	*1890s*
35	1,920	30,000	*1890s*
40	2,240	30,000	*1890s*
45	2,550	30,000	*1890s*
50	2,890	30,000	*1890s*
55	3,250	30,000	*1890s*
60	3,750	30,000	*1890s*

Waco

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	3,181	2,770	*1960s*
41.4	3,181	4,870	*1960s*
55.2	3,181	6,980	*1960s*
69	3,181	9,310	*1960s*
82.8	3,181	12,400	*1950s*
96.6	3,181	18,300	*1950s*
110.4	3,181	24,900	*1950s*
124.2	3,181	49,500	*1950s*
138	3,181	91,600	*1950s*
151.8	3,181	159,000	*1980s*
165.6	3,181	-	-

Firm Yield (gallons per day)	Catchment (square feet)	Storage (gallons)	Defining drought
27.6	699	30,000	*1950s*
41.4	1,070	30,000	*1950s*
55.2	1,440	30,000	*1950s*
69	1,830	30,000	*1950s*
82.8	2,220	30,000	*1950s*
96.6	2,620	30,000	*1950s*
110.4	3,070	30,000	*1950s*
124.2	3,510	30,000	*1950s*
138	4,020	30,000	*1950s*
151.8	4,740	30,000	*1950s*
165.6	5,460	30,000	*1950s*

Wichita Falls

Firm Yield (gallons per day)	**Catchment (square feet)**	**Storage (gallons)**	**Defining drought**
27.6	3,181	3,730	*2010s*
41.4	3,181	7,270	*2010s*
55.2	3,181	12,000	*2010s*
69	3,181	16,800	*2010s*
82.8	3,181	21,500	*2010s*
96.6	3,181	30,500	*2010s*
110.4	3,181	50,100	*2010s*
124.2	3,181	69,800	*2010s*
138	3,181	-	-
151.8	3,181	-	-
165.6	3,181	-	-

Firm Yield (gallons per day)	**Catchment (square feet)**	**Storage (gallons)**	**Defining drought**
27.6	804	30,000	*1970s*
41.4	1,160	30,000	*1950s*
55.2	1,580	30,000	*2010s*
69	2,120	30,000	*2010s*
82.8	2,660	30,000	*2010s*
96.6	3,200	30,000	*2010s*
110.4	3,740	30,000	*2010s*
124.2	5,290	30,000	*2010s*
138	7,230	30,000	*2010s*
151.8	9,060	30,000	*2010s*
165.6	10,900	30,000	*2010s*