WATER CONSERVATION FROM ROOFTOP RAINWATER HARVESTING IN AUSTIN, TEXAS

by

Darin Daniel Rice, B.S. Geography

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Committee Members:

Advisor: Timothy T. Loftus, Ph.D.

Nathan Allan Currit, Ph.D.

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ABSTRACT

Rooftop rainwater harvesting may provide an alternate supply of water for many household uses. There is a significant potential for supply from rooftop rainwater harvesting systems to offset the use of utility potable water used for outdoor irrigation demand from landscaped areas in Austin, Texas. To calculate the potential savings of these systems a supply and demand are needed. Monthly average rainfall totals, the area of building footprints of over two hundred thousand single-family residential parcels, and a roof material runoff coefficient were used to calculate the potential volume collected from rooftop rainwater harvesting. Monthly average evapotranspiration totals, the area of landscaped areas of over two hundred thousand single-family residential parcels, and a plant water use coefficient were used to calculate the potential volume conserved from rooftop rainwater harvesting. Object-based, supervised land-use classification was performed on sample areas to obtain the average landscaped area in Austin. The results of this study may help local, regional, and state water planners quantify the potential volume of water collected and conserved from the implementation of rooftop rainwater harvesting systems.

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1. Introduction

The world population is growing rapidly. The United Nations' World Urbanization Prospects: The 2018 Revision states the future world population growth will be made up primarily of city dwellers (United Nations 2019). This is evident in the capitol of Texas, Austin, a city located in the central part of the state. In July 2019, the city was designated the eleventh most populous city in the United States of America (USA) (United States Census Bureau 2020). The state projects by 2070 over 1.7 million people will reside in the Austin area, an increase from over nine hundred and seventy-six thousand in 2020 (Texas Water Development Board 2017).

As the city grows water planning becomes an important component to ensuring the water needs of the population are met. In Texas, state water planning is published in a report, the State Water Plan, every five years. The plan projects water supply and demand in the state assuming drought of record conditions. These conditions represent when supplies are their lowest and demands are their highest referencing a period in Texas known as the worst drought in state history, the drought of record. State water plans and the process of evaluating projected demands, current supplies, potential shortages, and feasible water management strategies are legislatively mandated. A state agency, the Texas Water Development Board (TWDB), compiles regional water planning reports and other data to produce projections over a fifty year period by regional water planning area, river basin, county, and water user group (TWDB 2017).

Water user groups are divided into six categories: irrigation, municipal, manufacturing, steam-electric power, livestock, and mining. The City of Austin represents one of the many municipal water user groups in the state. The Austin water user group is also known as the city of Austin's water utility, Austin Water. Austin Water, heretofore referred to as Austin, provides water for many uses including residential uses in Hays, Travis, and Williamson counties. In the most recent state water plan published in 2017, Austin supplies are projected to decrease by over 17 percent and demand is projected to increase by over 75 percent by 2070. By 2050, Austin is projected to have a potential water shortage due to demand outpacing supply. To meet water demands, due to population growth, water management strategies will be needed (TWDB 2017).

Water management strategies must identify a new source of water to be accepted in the water planning process (TWDB 2010). The strategies for Austin include, but are not limited to, aquifer storage and recovery, direct reuse, conservation, lake and dam improvements, drought management, and rainwater harvesting (TWDB 2017). Austin plans to supply 16,564 acre feet per year by 2070 from rainwater harvesting alone, an increase of over 16,000 acre feet per year from 2020 projections. For comparison, aquifer storage and recovery, conservation, and drought management are projected to provide 50,000, 36,899, and 28,937 acre feet per year, respectively, by 2070 (Lower Colorado Regional Water Planning Group 2016).

Though not as large a volume of projected supply as these other strategies, the rainwater harvesting strategy only represents supplemental non-potable water use from rainwater catchment by customers in Austin. The cost to meet the rainwater harvesting strategy is projected over $690 million by 2070, representing over 40 percent of the total capital cost of all recommended projects for Austin in the 2017 State Water Plan. The $690 million represents the cost incurred by Austin in the form of rebates to over one hundred and thirty-eight thousand water customers for implementation of rainwater harvesting systems and does not include the full cost of installation, operation, and maintenance incurred by the customers. These rebates help alleviate the customer cost burden while decreasing the use of surface water and groundwater, and the treatment cost associated (Lower Colorado Regional Water Planning Group 2016).

In this study, the potential volume of water collected and conserved from single-family residential rooftop rainwater harvesting in Austin will be evaluated. Just like state and regional water planning, calculating rainwater harvesting potential requires supply and demand. The volume collected from rainwater harvesting systems represents the supply and the water needs of plants in the landscaped area represent the demand. A cost to implement is also necessary however this study seeks to answer the rainwater harvesting potential without regard to cost. The goal of this study is, therefore, to identify whether implementing rooftop rainwater harvesting systems on all single-family residential properties can collect enough supply to conserve the large volume of valuable potable water currently used to irrigate these landscaped areas.

2. Literature Review

2.1 Rainwater harvesting: a background

The use of captured rainwater has been practiced for thousands of years. Dating back 10,000 years, early hunter-gatherers in the Chihuahuan Desert used water naturally collected in rock formations now known as the Hueco Tanks located in an area east of current day El Paso, Texas (Texas Parks and Wildlife Department 2021). Over 4,000 years ago the concept of rainwater harvesting is documented from archeological evidence of cisterns, or storage tanks, in Israel (TWDB 2005). Present-day rainwater harvesting is the collection of rainwater from a catchment surface and diverted to a storage facility for use in applications such as landscape irrigation, potable and non-potable indoor water uses, groundwater recharge, and storm and flood water reduction (Haq 2017).

Rainwater harvesting is seeing a resurgence due to contamination, drawdown, and increased demands on existing water supplies (Haq 2017). In 2005, the Texas Legislature established the Texas Rainwater Harvesting Evaluation Committee (TRHEC) to determine the potential and recommend guidelines for the use of rainwater harvesting for potable and non-potable indoor uses with the potential for conjunctive use with existing water utility supply for residential, commercial, and industrial customers in the state. The committee found rainwater harvesting has the potential to provide a significant additional source of water, particularly in urban and suburban areas (TRHEC 2006).

Austin included rainwater harvesting in their long-term water resource plan, called the Water Forward Integrated Water Resource Plan (Water Forward). Water Forward addresses limited water supply and increasing water demand in the city over the next one hundred years. The plan recommends water supply projects to alleviate limitations on existing supplies during drought conditions. It also recommends demand management and water reuse strategies to encourage, and in some cases require, water use efficiency. Nearly half of the non-potable drinking water demand in 2020 was projected to come from potable water supplies. By 2115, demand management strategies are projected to offset most of the potable supply for non-potable demands with non-potable supply for non-potable demands (City of Austin 2018). Rooftop rainwater harvesting at single-family, multi-family, and commercial lots for non-potable indoor and irrigation demands is one of many demand management strategies in the plan. Slated to be implemented by 2040 and yield 10,600 acre-feet per year by 2115, rooftop rainwater harvesting, on new and existing properties, will help alleviate non-potable demand on potable water supplies (City of Austin 2018).

Rainwater harvesting has many benefits and some limitations which must be considered when evaluating it as a source of water for any application. Rain is a free source of water if it can be captured, stored, and diverted for use. Water is generally free of most impurities in the atmosphere making rain a relatively clean source of water. However, it is necessary to note that rainfall collects contaminants as it falls as precipitation, when it lands on a contaminated surface such as the ground or the roof of a structure, and there is possible contamination that can occur during collection, storage, and use. In situ collection and storage of rainfall is generally more clean than other raw sources of water like surface or ground water (Haq 2017). The TRHEC (2006) found rainwater harvesting can provide a source of water which can offset use of limited or contaminated sources of water, reduces storm water runoff, nonpoint-source pollution, and erosion, and can reduce the threat and/or extent of flooding. The TRHEC (2006) also found rainwater catchment can provide an excellent source of water for irrigating landscapes, provides a decentralized source of water less susceptible to natural disasters or terrorism, lowers water utility customers' bills, can delay a utility's need for treatment and source expansion, and can reduce water utility peak demands which occur primarily in the hot summer months in Texas.

Rainwater harvesting is not a panacea for all water issues. Rainfall is not predictable because it is not distributed, temporally or spatially, even. This uneven distribution of water supply can limit the effectiveness of rainwater harvesting systems (Haq 2017). To collect the rainfall, it is necessary to store this water for times of need, preferably near the collection and use points. A storage tank can be above or below ground, made of different materials, and come in varying sizes relative to the user's demand and budget (TWDB 2005). The height, diameter, and volume of the storage tank should also be considered when determining a suitable location and use on a property.

Cost is also a limitation. The storage tank is the most expensive component of the harvesting system. Cost depends on size, materials, and construction. In Central Texas, it is estimated that an average of 33,000 gallons can be collected from each roof and adequate storage would be necessary to supply water needs for up to 80 days without rainfall for all potable and non-potable uses (TRHEC 2006). In arid regions a large storage tank is required to capture adequate supply for demand which may be limited in urban areas due to a lack of available land for siting a tank. The initial and ongoing costs of installing, operating, and maintaining such a system could be considered cost prohibitive to many water users (Haq 2017, Nachshon, Netzer and Livshitz 2016). If the rainwater is used for potable uses, then treatment is required which increases the cost further (TWDB 2005).

The cost of rainwater harvesting can be competitive, however, with other water supply sources in certain areas, including an arid area such as Iran (Hoseini and Hosseini 2020), and can be equivalent to the volume from a domestic groundwater well depending on the storage capacity (TRHEC 2006). In Austin, one of the many conservation programs available to their customers are rebates of up to $5,000 for the labor and materials required to install a rainwater harvesting system which could help offset the high initial cost (City of Austin 2021).

2.2 Rainwater harvesting: a calculation

Calculating rainwater harvesting generally requires the area of a catchment surface, the size of the landscaped area, precipitation and evapotranspiration values, and coefficients of runoff and plant water use (TWDB 2010). To collect rainfall from a roof, a storage tank, and a conduit to the storage tank (e.g., gutters and pipes) are required. In order to water plants, including turf grass, an irrigation system as basic as one that is gravity-fed and above-ground or as intricate as an automated in-ground system is required (TWDB 2005).

A water budgeting method is an effective tool for calculating the potential for water savings from rainwater harvesting using rainfall supply, catchment area size, demand from indoor and/or outdoor uses, storage volume, and coefficients of runoff and plant water use (Imteaz, Ahsan and Shanableh 2013). Water budgeting analyses can be accomplished using hourly, daily, monthly, quarterly, or yearly rainfall and water use data to determine the volume of supply necessary to meet demands and the adequate size of storage to meet demand in dry times (Imteaz, Ahsan and Shanableh 2013, TWDB 2005). This method has been studied at varying scales, from a university like Tamil Nadu Agricultural University in India for non-potable and laboratory uses (Manikandan, Ranhaswami and Thiyagarajan 2011) to small areas within a city like Tel-Aviv for domestic water use and aquifer recharge (Nachshon, Netzer and Livshitz 2016) to across different regions within a large city like Melbourne for potable and non-potable indoor and outdoor uses (Imteaz, Ahsan and Shanableh 2013).

Various studies calculated the water savings from rainwater harvesting in residential areas, the potable water demand offset by rainwater, to be between 15 and 73 percent. The savings were dependent on the size of the roof, the amount of rainfall and evapotranspiration, and the size of the tank. These studies included water demand from potable indoor uses which increases the demand parameters of a rainwater harvesting calculation (Herrmann and Schmida 1999, Hoseini and Hosseini 2020, Imteaz, Ahsan and Shanableh 2013). Other studies have looked at the potential of rooftop rainwater harvesting to meet outdoor water demand including landscaped-area water needs.

Mehrabadi, Saghafian and Fashi (2013) studied the efficiency of rainwater harvesting systems to meet outdoor demand in three cities and the surrounding areas in Iran representing different climatic conditions. The study used various scenarios based on the climate of the location, tank size, and roof area. They expected the combination of climate, roof area, tank size, and demand to play a key factor in the overall reliability of these systems. Their findings show that 75 percent of non-potable outdoor demand can be met 23 percent to 70 percent of the time in the study area depending on roof size and climate conditions (Mehrabadi, Saghafian and Fashi 2013).

Tamaddun, Kaira, and Ahmad (2018) used calculations obtained from the Texas Manual on Rainwater Harvesting, published by TWDB, to calculate the rooftop rainwater harvesting potential on supplying non-potable water for outdoor demand at residential households in nine states in the USA. Using a tank size of 1,000 gallons as storage, large enough to capture a months' worth of rainfall, they calculated all states were unable to meet demand all year, using monthly rainfall and demand. In dry times the storage tank would be emptied from an excess demand. In arid climate states, including Texas, emptying of tanks was most likely. Arid areas were unlikely to meet all outdoor water demands in most months using rainwater to offset potable water supply from water utilities. Outdoor demand for each state was calculated as a percent of monthly gallons per capita per day usage and population from 2014 (Tamaddun, Kaira and Ahmad 2018).

2.3 Outdoor water demand

Irrigation of residential outdoor landscapes constitutes a significant volume of water use in public water supplies (Gleick, et al. 2003). Outdoor irrigation use is supplied from water treated by the public water supply, also known as potable water. It is difficult to quantify the savings of outdoor water use from projected demand management strategies, also known as water conservation strategies, due to uncertainties in the varied land cover characteristics of properties, the differences in metering of water consumption, climate factors, and data not being available (Gleick, et al. 2003). Many methods have been developed to estimate the volume of residential outdoor usage including calculating landscape water use coefficients of different plant species, calculating outdoor water use from the difference of winter months usage and non-winter month usage, and use of remote sensing vegetation indices which identifies plant health and calculates a water use volume necessary to maintain the plant health (Mini, Hogue and Pincetl 2014).

The United States Environmental Protection Agency (2013) (EPA) estimates that 30 percent of household daily water use in the USA is used outdoors and can be as high as 60 percent in arid locations. Calculating outdoor demand can be done in varying methods ranging from simple to detailed, with varying levels of confidence. A simple method uses the difference of winter month usage (i.e., November to January), assumed as a constant indoor use volume, to non-winter month usage to obtain a percent of water used for outdoor uses, assuming all properties irrigate (Hermitte and Mace 2012). Hermitte and Mace (2012) found the average outdoor water use for single-family residential houses in Texas as 31 percent and in Austin as 33 percent of total household water use.

A detailed method studies a sample set of properties observed water usage coupled with inspecting irrigation through remote sensing techniques to determine a percentage of water used outdoors, adjusted by the percent of sample properties actively irrigating outdoors (DeOreo, et al. 2011). DeOreo, et al. (2011) found 87 percent of the properties in their sample area irrigated their properties, which can affect the calculation of outdoor demand. All homes accounted for an average of 82,000 gallons per household per year and homes with observed irrigation accounted for nearly 92,700 gallons of outdoor water use per household per year (DeOreo, et al. 2011).

Many factors affect the volume of outdoor demand including the size of homes, presence of irrigation systems, type of plants in the landscaped area, size of landscaped area, a homeowner’s knowledge of and behavior surrounding water use, and the season. Homes with higher square footage, homes with large-landscaped areas, and those with an irrigation system installed tend to have higher outdoor water use, a proposed correlation between affluence and higher water use (DeOreo, et al. 2011). Homeowners educated in the correlation between their water use behavior and their water use tend to decrease their water usage, while homeowners with little knowledge of their behavior tend to have higher water use, including outdoor water use (Landon, Kyle and Kaiser 2016). Hotter and drier weather is a large factor in high outdoor water use. As the temperature increases and rainfall declines plant water needs from irrigation increase, potentially requiring supplemental irrigation to maintain plant health (Gleick, et al. 2003).

Different plants have different water needs. The typical turf grass found in Texas, (bermuda, buffalo, St. Augustine, etc.), requires between 15 and 35 inches or more of rainfall without supplemental irrigation (TWDB 2016). Replacing the landscaped area cover of turf grass with drought tolerant or native landscaping, can provide significant savings of water use. Reducing the irrigated area by 10 percent can result in an 8 percent reduction in demand (DeOreo, et al. 2011). Increasing drought tolerant or native landscape from 20 percent to 50 percent coverage can result in a 14 percent savings (Tamaddun, Kaira and Ahmad 2018). Coupled with rainwater harvesting, retrofitting a portion of turf grass to drought tolerant landscape can result in a compound reduction in demand. In addition to rainwater harvesting rebates, Austin offers rebates of up to $1,750 for residents to convert a portion of their turf grass to native and adapted landscapes (City of Austin 2021).

The way in which outdoor watering is accomplished affects the volume of demand. Outdoor irrigation can be accomplished by hand-held bucket or hose watering, manual and automatic in-ground sprinkler systems, and drip irrigation. Over 33 percent less water is used by customers watering by hose than an average household that waters via other means. For example, the EPA (2013) found those customers with drip irrigation, manual sprinklers, or automatic irrigation sprinkler systems used 16, 35, and 47 percent more water than average households. Typically, irrigation systems use more water because of leaks, misdirection, or overwatering (EPA 2013).

Landon, Kyle, and Kaiser (2016) studied compliance with residential outdoor water conservation programs. A water budget analysis was conducted on select properties in College Station, Texas. Using information including landscaped area and outdoor demand they analyzed compliance. Landscaped area was calculated using geographic information systems (GIS) data including parcel area, building footprints, and driveway footprints. The irrigable area was determined as the remainder of parcel area after subtracting building and driveway. Outdoor demand was calculated as the difference between non-winter monthly usage and winter monthly usage. Winter monthly usage was assumed as an indoor only use. The study found that a positive and engaged attitude toward a customers' impact on water conservation increased compliance and lowered their outdoor water use when provided information about their water use and characteristics of their property (Landon, Kyle and Kaiser 2016). Landon, Kyle, and Kaiser (2016) illustrate that data used to calculate the volume from rainwater harvesting can also be used for compliance with conservation programs to reduce customer water use.

2.4 Classifying residential landscapes using remote sensing techniques

A GIS can be an effective tool in processing, analyzing, and classifying objects observed in orthoimages. An orthoimage is a corrected aerial image using remote sensing techniques such as orthorectification. Orthorectification removes distortion on an image from camera perspective and terrain relief (United States Geological Survey 2021). The practice of correcting an aerial image is a pre-processing step in the classification of an image using GIS or other software. Image classification assigns values to different land features of a remotely sensed image. Two types of image classification exist, supervised and unsupervised. Supervised classification requires the user to select sample classes by pixel or object segment for a computer to assign user-defined classes to the entire image. Unsupervised classification allows the computer to decide which classes are in an image and assigns the classes from a user-defined schema using the spectral characteristics of pixels (ESRI 2021). Other GIS techniques can be used to analyze an image in conjunction with classification.

Villar-Navascues, Perez-Morales, and Gil-Guirado (2020) used hotspot analysis to determine spatial distribution of roofs and supervised classification to determine slope of roofs in Spain to determine their potential as rainwater catchment areas. Ojwang, et al. (2017) used supervised classification to identify roof area and different roof materials for use in calculating rooftop rainwater harvesting in Mombasa, Kenya. Supervised classification can also be used to identify other landscape features including turf grass, trees, and swimming pools (Hof and Wolf 2014, Mathieu, Freeman and Aryal 2007, Gage and Cooper 2015).

Hof and Wolf (2014) used supervised classification of a WorldView-2 satellite imagery to identify characteristics of residential properties in areas of Spain to determine the highest water use features. They coupled the classified image results with landscape water use coefficients finding swimming pools made up a third of the footprint of a parcel compared to turf grass but made up 8 to 14 percent of the outdoor demand where turf grass made up 9 to 18 percent; trees and shrubs were the dominant feature of the outdoor area and made up most of the outdoor demand for water. Mathieu, Freeman, and

Aryal (2007) used object-oriented segmentation and supervised classification to classify vegetated garden areas in the United Kingdom. They found vegetated garden areas comprised 46 percent of the residential study area. Gage and Cooper (2015) also used object-oriented segmentation and supervised classification to identify land features influence on water use in Aurora, Colorado. They separated irrigated areas into low-height vegetation (e.g., grass) and trees, respectively covering on average 34.6 and 17.7 percent of the urban area. Vegetation was an important variable in determining water use (Gage and Cooper 2015).

Unfortunately, imagery, like those used in these studies, does not allow classification of two types of land cover per unit area, pixel. A pixel can only represent one land-use feature, typically the dominant feature. For instance, a tree may block or take up the majority area of turf grass when viewing from the bird's eye view of aerial imagery. The corresponding pixel would be classified as the tallest or most dominant feature, the tree. Despite these limitations it is possible to classify land features appropriately for this study using orthoimagery and GIS tools.

3. Data Acquisition and Application

The essential data to calculate the potential volume of water collected and conserved from residential rooftop rainwater harvesting in Austin includes numerous sources and strategies. Just like water planning in Texas, determining this requires supply and demand. This study used water system boundaries, land parcels, building footprints, orthoimagery, local precipitation and evapotranspiration figures, a roof runoff coefficient, and a plant water use coefficient to calculate supply for and demand of outdoor water uses.

In addition to existing datasets, GIS tools including supervised classification, kernel density analysis, extract features, and intersect were used. Supervised classification was used on orthoimagery to determine the landscaped area of sample parcels to calculate a percent of parcel land cover. The percent of land cover across the sample parcels was used to calculate the size of landscaped areas across all parcels in the study area.

3.1 Water system boundary

All water utilities in Texas are encouraged to provide their current retail service area boundaries using TWDB's Water Service Boundary Editor. This boundary represents the parcels served directly by the utility's water service infrastructure. Austin's water system boundary, updated with TWDB in February 2020, covers over 250 square miles primarily in Travis County. Small portions of the service area extend into Williamson, Hays, Caldwell, Bastrop, and Burnet counties (TWDB 2020). Figure 1 illustrates the footprint of the Austin service area boundary.

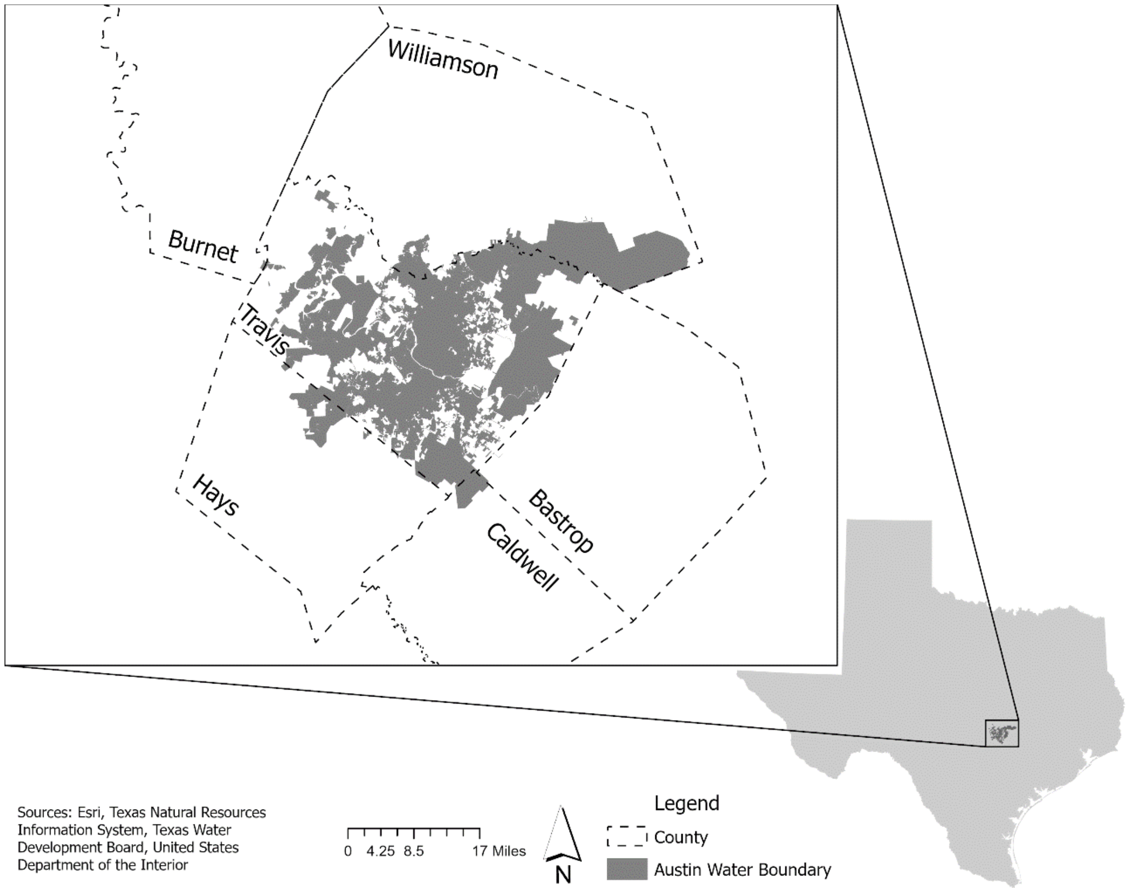

Figure 1. Austin water system boundary. Inset in Texas for location.

3.2 Land parcels

The Texas Natural Resources Information System (TNRIS) collects geographic data for the state. This data includes a repository of 228 of the 254 county level land parcel datasets, as of the publication of this study. Parcel data provides this study the area of the property, the occupancy type, and the property boundaries.

Single-family residential property land-use types were identified and extracted from the full parcel datasets and county parcel data were merged. Travis county parcel data classifies single-family residential properties separate from multi-family residential properties; therefore, only single-family residential properties, classified as A1, were included for analysis. Williamson county parcel data does not separate single-family and multi-family residential properties. Manual separation of these property types was conducted. Parcel size, property type, and verification using ancillary satellite imagery was used to remove multi-family residential properties from single-family residential properties. Hays County parcels were not included in this study due to a lack of land-use type in the dataset. Only a small portion of the Austin water system boundary is in Hays County with an estimated six hundred parcels being excluded. Burnet, Bastrop, and Caldwell county parcels were also not included in this study due to the small number of parcels (less than one hundred) within the water system boundary. Additionally, an even smaller number of these properties are small enough to meet the maximum parcel size used in this study.

Sample properties were selected during the supervised classification process to calculate land-use percentages. These samples represented a median single-family residential size lot, 0.2 acres, calculated from the full single-family residential dataset. Only properties like the sample properties were sought for this study. Properties with a legal area greater than 0.5 acres were removed from analysis. Over 236,000 parcels meet these criteria (TNRIS 2019). Figure 2 shows a sample view of single-family residential parcels with 0.5 acres or less on top of orthoimagery from a sample area tile, discussed later.

Figure 2. Single-family parcels of 0.5 acres or less example from northwest Montopolis orthoimagery tile.

Limitations do exist when using parcel polygon features in GIS. Parcels do not cover all the property that may be irrigated by the homeowner. For instance, a parcel polygon feature may not cover the area from the street curb to the sidewalk, but grass may exist here. This small area of irrigable land should not largely influence the calculation of outdoor water demand. Additionally, even after reprojection of the parcel shapefiles, property lines observed in the orthoimagery do not accurately align with parcel lines in all places. Sample parcels were chosen for their near accurate alignment. This misalignment should not significantly influence the rainwater harvesting calculation because the sum of all parcels' legal area was used, and collective and individual parcel landscaped area was adjusted by multiplying the average percent of landscaped area from sample parcel areas.

3.3 Building footprints

Microsoft's open source computer generated building footprints of Texas were obtained from their GitHub repository (Microsoft 2019). The data format was adjusted from GeoJSON to shapefile using ArcGIS Pro 2.7.2 and projected to match the parcel dataset. A North American Datum (NAD) 1983 Texas Statewide Mapping System projected coordinate system with a Lambert Conformal Conic projection was used.

Building footprint polygon features provide the area of the catchment surface, the roof. The area of the roof is multiplied by the average monthly rainfall, in gallons per square feet, to calculate the potential volume of water from the collection area. A runoff coefficient is applied to this volume to determine the estimated supply to the collection tank. Using the intersect tool in ArcGIS Pro, 202,074 single-family residential parcels with 0.5 acres or less intersect building footprints. The building footprints dataset was joined with intersecting parcels to establish total catchment area and total parcel area. Figure 3 shows a sample view of building footprints.

Figure 3. Single-family building footprints on parcels of 0.5 acres or less in northwest Montopolis orthoimagery tile.

There are limitations in using these computer-generated building footprints to determine catchment area. The building footprints do not accurately align with footprints of buildings observed from orthoimagery. In most cases the computer-generated building footprints are smaller than the actual footprint meaning the calculations of catchment area are undervalued in this study however, this can only mean a greater potential could be realized if building footprints with greater accuracy were available. Typically, the computer-generated footprints do not include detached structures, like storage sheds, or roof covered porch areas. The difference in actual to computer-generated building footprints was determined to have only minor effect on the outcome of the study.

3.4 Precipitation and evapotranspiration

Rainfall is the most important variable in the rainwater harvesting. Calculating the potential volume of water from the collection area requires the volume of average rainfall for the region. Precipitation data was obtained from the monthly climate normals determined by the National Oceanic and Atmospheric Administration (NOAA) (see table 1). The Austin Camp Mabry station was used as it represented a central location in the study area. Between 1981 and 2010, the Austin area averaged 34 inches of precipitation, or 21 gallons per square foot (NOAA 2011). The average rainfall is also used to determine total monthly demand of irrigated areas. Rainfall directly on irrigated areas decreases the demand from the rainwater harvesting system.

Table 1. Average monthly rainfall totals for Camp Mabry station in central Austin, Texas.

Month	Average rainfall (in.)	Month	Average rainfall (in.)
January	2.22	July	1.88
February	2.02	August	2.35
March	2.76	September	2.99
April	2.09	October	3.88
May	4.44	November	2.96
June	4.33	December	2.40
	Annual		**34.32**

Source: Data from NOAA 2011.

Note: Average of 1981 to 2010 climate normals.

Evapotranspiration is the volume of water plants need to grow. Texas A&M AgriLife Extension calculates a standard evapotranspiration rate for different stations across Texas. The Austin (LCRA Redbud) weather station's Potential Evapotranspiration of a Grass Reference Crop (ETo) averages were used. Over 70 years of climatic data determine the ETo for this station. Table 2 shows the Austin area averages over 57 inches of ETo annually (Texas A&M AgriLife Extension 2021). Figure 4 illustrates the relationship between rainfall and ETo.

Table 2. Average monthly evapotranspiration for LCRA (Redbud) station in Austin, Texas.

Month	Average evapotranspiration (in.)	Month	Average evapotranspiration (in.)
January	2.27	July	7.22
February	2.72	August	7.25
March	4.34	September	5.57
April	5.27	October	4.38
May	6.39	November	2.74
June	7.15	December	2.21
	Annual		**57.51**

Source: Data from Texas A&M AgriLife Extension 2021.

Note: Average of 70 years of evapotranspiration data.

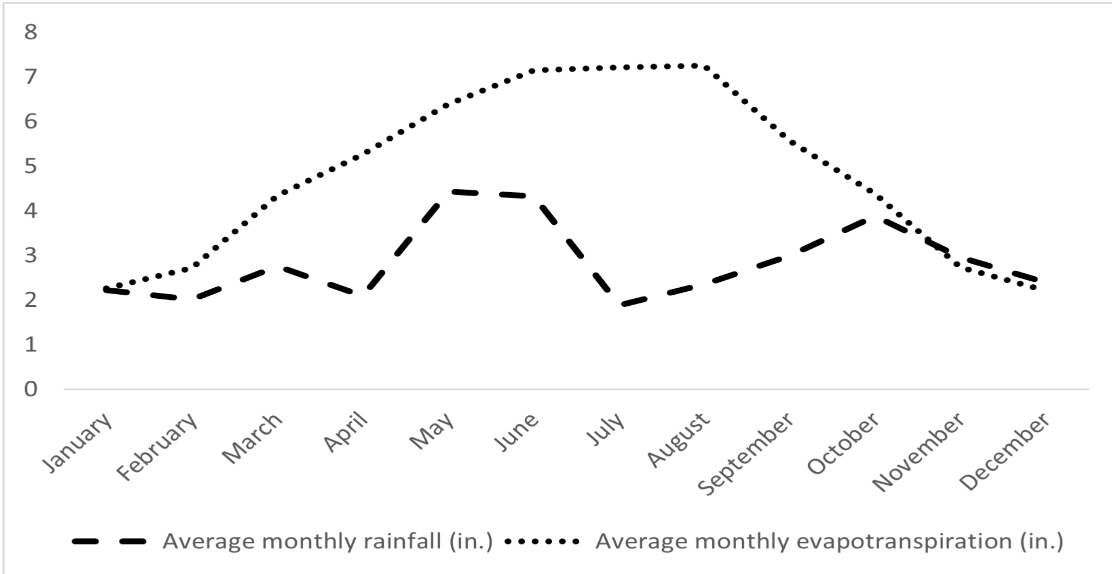

Figure 4. Stacked line chart of average monthly rainfall and average monthly evapotranspiration for weather stations in Austin, Texas.

A plant water use coefficient is multiplied by the average ETo to determine the average plant water needs, 34 inches or 21 gallons per square foot annually. The difference between average rainfall and average plant water needs coupled with the size of the landscaped area provides outdoor irrigation demand. Calculated annually, average rainfall and average plant water needs are almost identical. However, when calculated monthly there are times when plant water needs are lower than rainfall and vice versa (see figure 5). For example, the summer season has low rainfall and significantly higher ETo; plants require more water in the hotter summer months.

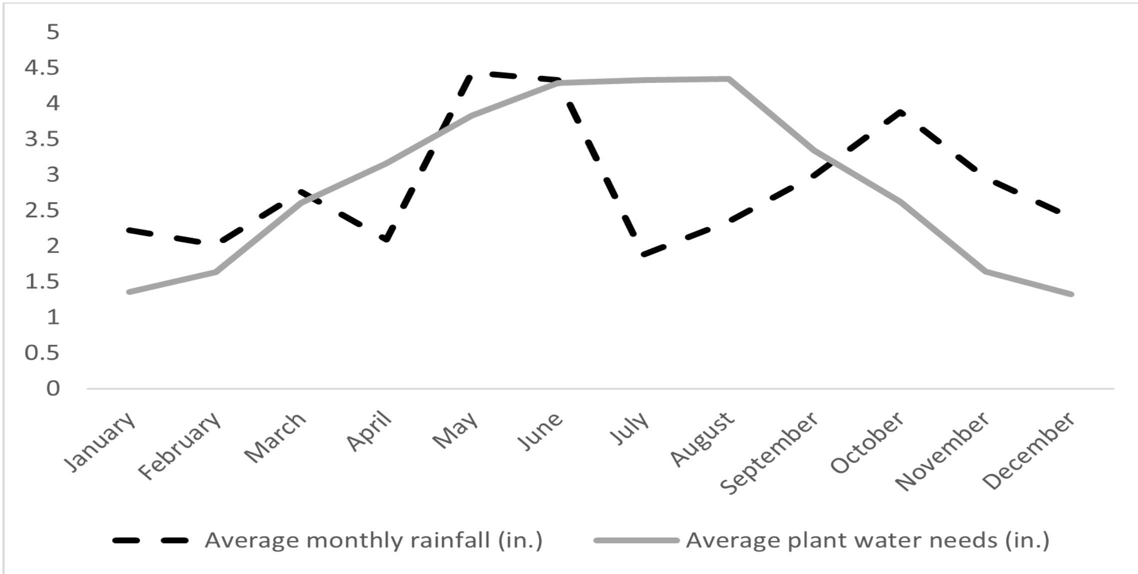

Figure 5. Stacked line chart of average monthly plant water needs and average monthly rainfall in Austin, Texas.

3.5 Runoff and plant water use coefficients

Seven tiers of coefficients correspond to the primary type of roofing material: metal or glass, rubber, asphalt shingle, tar and gravel, cement tile, clay tile, or green roof. These constitute runoff coefficients between 0.95 for metal or glass and 0.28 for green roof (TWDB 2010). The higher the coefficient the more water can be collected from the roof material assuming the gutter and collection system are installed correctly. The Roof-Reliant Landscaping Manual states "asphalt shingle roofs, which are very popular because they are relatively inexpensive, can be efficient for water harvesting" (Downey 2009). For this study asphalt shingle is used as the primary roof material when considering the runoff coefficient. Observations from orthoimagery during supervised classification suggest this is the primary roof material in the study area. The coefficient is 0.9, meaning it is a relatively efficient roof material for rainwater harvesting.

Suitable grasses for the central Texas climate include bermuda, paspalum, St.

Augustine, zoysia, and buffalo. These turf grass can tolerate summer heat and high humidity and require little to no supplemental irrigation (Chalmers and McAfee 2010). Five tiers of coefficients correspond to plant water use: very low, low, medium, high, and very high. Very low corresponds to desert like plants, medium corresponds to most warm climate turf grasses and trees, and very high corresponds to garden vegetables. A plant water use coefficient is multiplied by the average ETo to calculate outdoor water use demand. Some properties in the study area have xeriscape or desert-like landscaped areas and some properties have gardens for growing vegetables. On one end of the spectrum is very low outdoor water use demand and on the other is very high outdoor water use demand. Most properties in the study area have turf grass covering much of the landscaped area of their property. A medium plant water use coefficient, 0.6, was used for this study corresponding to the primary component, and average, of landscaped areas in the study area. The term landscaped area is used throughout referring to areas of a property requiring supplemental irrigation where rainfall does not meet plant water needs, assumed as a majority turf grass in this study.

3.6 Water use

Austin reports annually on the water production and usage in TWDB's water use survey. In 2019, over fifty billion gallons of surface water was produced or purchased. Over two and a half billion gallons were sold to other water systems and over forty-one billion gallons were sold to retail customers or used by the utility. Over fourteen billion gallons of the forty-one billion was sold to 214,949 single-family residential connections. The number of parcels, before intersecting with building footprints, discussed earlier exceeds the number of single-family connections listed in Austin's annual water use survey (2019). This may be due to differences in the classification of properties between the water system and the appraisal district.

An average of 68,203 gallons of water are used annually per connection. Appendix A provides a copy of the 2019 Water Use Survey. The outdoor use as a percentage of total use from Hermitte and Mace (2012), stated above, is 33 percent for Austin. Of the 68,203 gallons annually used per connection, roughly 22,506 gallons would be estimated as outdoor use. This represents a significant volume of water which could be conserved from the use of rainwater harvesting and other conservation techniques.

3.7 Orthoimagery and land-use classification

Orthoimagery of the study area was used to conduct supervised land classification. Land-use classification of sample areas provided an average percent land cover of landscaped areas. The average landscaped-area land-use percentage provided an estimated area of turf grass for 202,074 single-family residential properties in the Austin service area, representing 94 percent of the single-family residential accounts identified in the water use survey from 2019 (City of Austin 2019).

Orthoimagery was collected from TNRIS's Strategic Mapping Program's CapArea Imagery 2019. The imagery was flown during leaf-off conditions in January 2019 providing 6-inch pixel spatial resolution tiles with 4-band spectral resolution (RGBIR). Each pixel represents 6-inch spatial resolution which provides very detailed imagery to identify small features. Features in residential properties such as cars, sidewalks, fences, and gardens are all identifiable with this level of resolution (Strategic Mapping Program 2019).

The orthoimagery collected is packaged in sets of tiles. Each tile set contains multiple tiles, representing one square mile per tile. Each tile represents a section of imagery flown during the CapArea Imagery project. One tile from each tile set, a total of six, were selected. Using ESRI's ArcGIS Pro 2.7.2, land-use classification was performed in a sample of individual single-family residential parcels from the six tiles within the study area.

To best represent most single-family residential properties in Austin, the six tiles were chosen by performing a kernel density spatial analysis on points created from over 236,000 single-family residential building footprints within Austin. Kernel density calculates the density of point or polyline features per unit area (ESRI 2021). Figure 6 shows the density of these points per square mile of the Austin water system boundary classified into ten equal interval classes. The darker the color the denser the single-family residential buildings per square mile.

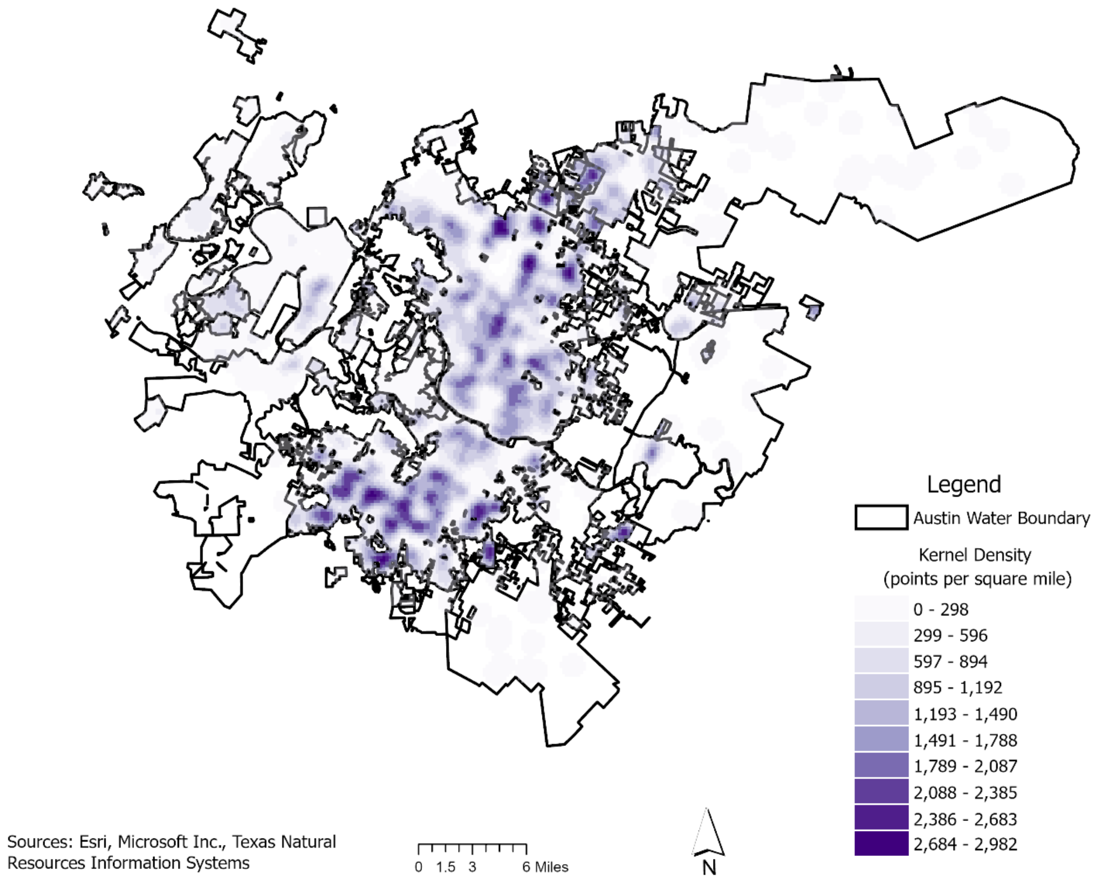

Figure 6. Kernel density of building footprint points per square mile classified into ten equal-interval classes.

The six tiles chosen from TNRIS tile sets correspond to a high density of single-family residential homes as represented in the kernel density spatial analysis. These tiles are named by TNRIS for their location. They are all located within the Austin water system boundary though the name may not suggest. The tiles include northeast Oak Hill, northwest Oak Hill, northwest Montopolis, east southeast Austin, east northwest Austin, and west southwest Pflugerville (Strategic Mapping Program 2019). Figure 7 shows the location of these six tiles.

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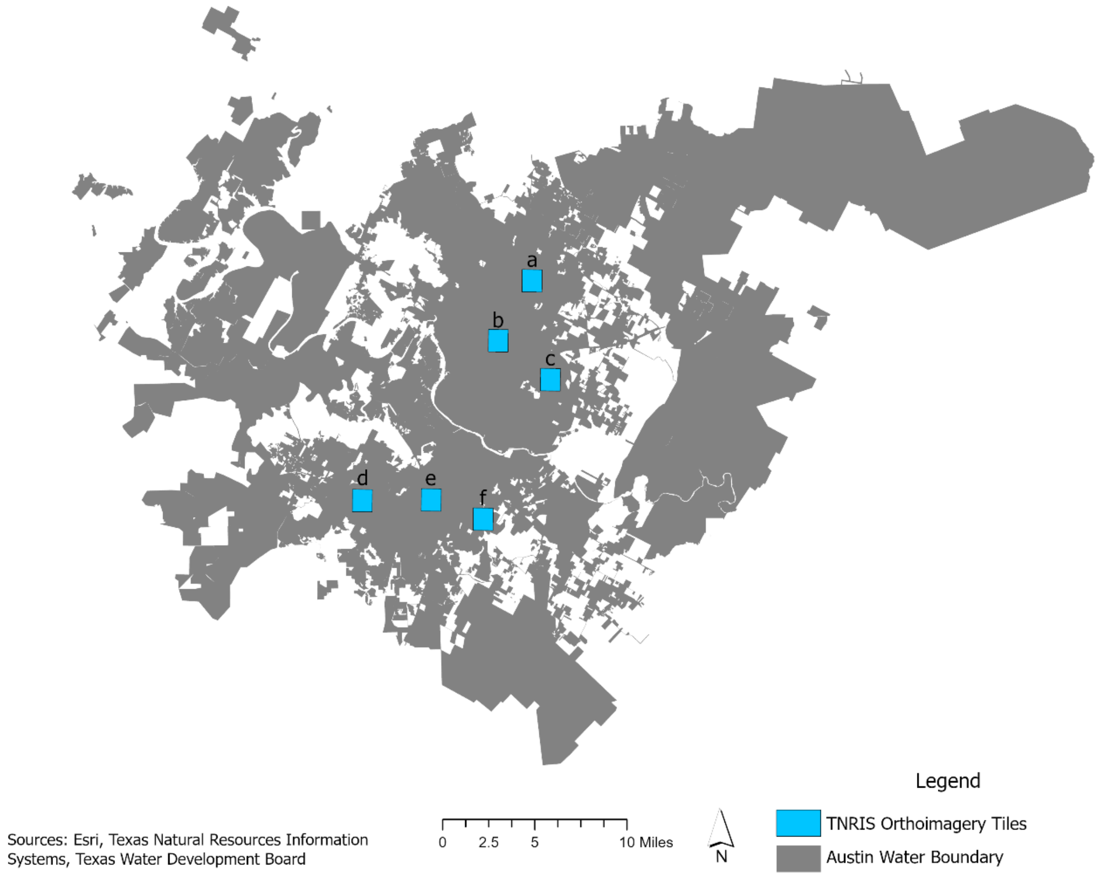

Figure 7. TNRIS orthoimagery tile locations. Each polygon is the name of the original orthoimagery tile set: (a) west southwest Pflugerville, (b) east northwest Austin, (c) east southeast Austin, (d) northeast Oak Hill, (e) northwest Oak Hill, and (f) northwest Montopolis.

4. Method

Building footprint square footage, precipitation, and a runoff coefficient provide data for a rainwater harvesting system supply. Evapotranspiration, precipitation, landscaped area square footage, and a plant water use coefficient provide data for the outdoor water demand of landscaped areas. Irrigated area square footage is not a readily available dataset. Parcel square footage is available, however. An object-based, supervised land-use classification using ESRI's ArcGIS Pro was conducted on sample areas within the selected orthoimagery tiles. Other ArcGIS Pro tools were used in pre-processing and post-processing of the orthoimagery tiles. From the classified images, sample parcels were selected to calculate the average percent of landscaped area.

4.1 Supervised classification

Object-based, supervised classification is a machine learning method that segments a multiband remote sensing image then acquires user training inputs that represent land cover types selected from a classification schema to classify an image. Image segmentation groups similar neighboring pixel values together into objects. From this segmented image, the user inputs the observed land cover type from the classification schema. From these training samples the software classifies the objects based on their similarity to the training pixel values within the image. Some land cover features are identified incorrectly, either from a low number of training samples per land cover type or the land cover types pixel values being more like other land cover types than their own class. An accuracy assessment, further discussed below, is calculated identifying the class assignment accuracy. To elaborate, the assessment identifies which land cover features were classified incorrectly and what class they were placed in by the machine learning model. The image can then be reclassified by the user to correct any observed errors (ESRI 2021).

Using ESRI's ArcGIS Pro tool, Create Features, polygon features were created within each location tile representing sample areas with a high density of single-family residential homes, per the kernel density spatial analysis. These sample areas were extracted using the polygon features as mask. Figure 8 shows the six sample areas.

Sources: Esri, Texas Natural Resources Information Systems - Strategic Mapping Program

Figure 8. Orthographic imagery of extracted residential areas used for supervised classification in six orthoimagery areas within Austin Water boundary: (a) west southwest Pflugerville, (b) east northwest Austin, (c) east southeast Austin, (d) northeast Oak Hill, (e) northwest Oak Hill, and (f) northwest Montopolis.

Object-based, supervised classifications was performed on each of the six sample areas. First segmentation was performed, while maintaining the clipping extent, with a spectral detail of 15.5, a spatial detail of 15, and a minimum segment size in pixels of 5. Spectral detail is the level of significance the user chooses to give to the difference in spectral characteristics of pixels on a scale of 1.0 to 20.0 when identifying object segments. A higher spectral detail directs the model to create smaller object segments representing high detail of varying classes, and vice versa (ESRI 2021). A relatively high value was used to reduce grouping grass, tree, and green hue features into the same object segment. Spatial detail is the level the user defines so the program can determine whether a proximate pixel should be included with neighboring pixels when creating object segments. A range of 1 to 20 is used where a higher value indicates small and clustered pixels of varying classes exist in relative proximity (ESRI 2021). A relatively high spatial value was used to distinguish between buildings and roads as separate classes. A minimum size of segment relates to the limit at which the program should merge segments below the minimum size with best-fitting neighboring segments (ESRI 2021).

After segmentation, the user manually selected land cover types per the classification schema. The classification schema was user generated for the purpose of this study and included land cover types found in single-family residential neighborhoods. It included light, medium, and dark colored buildings (or roofs), light and dark colored roads (or other non-roof impervious covers like sidewalks and driveways), trees, pools, and turf grass. Between 50 and 150 objects were classified by the user per land cover type from the schema as training samples.

Shadows were also included, as large portions of parcels were covered in shadows. An average of between 5 and 15 percent of the sample parcels' area, within the sample areas, were covered by shadow after classification. Shadows make it difficult to identify the actual land cover type without ground truth data; however, reclassification was conducted on sample parcels and shadows were removed before obtaining the percent of landscaped area.

After user input training samples, the images were trained using the machine learning model support vector machine. A maximum number of samples per class of 500 was selected to train the classifier. Once training was complete, the images were classified per the training model. Light, medium, and dark colored buildings and light and dark colored roads were then merged into buildings and roads, respectively, to combine like features. Figure 9 shows the classified images of the sample areas. Appendix B provides higher detailed versions of these classified images.

Figure 9. Orthographic imagery of extracted residential areas classified in six orthoimagery areas within Austin Water boundary: (a) west southwest Pflugerville, (b) east northwest Austin, (c) east southeast Austin, (d) northeast Oak Hill, (e) northwest Oak Hill, and (f) northwest Montopolis.

To identify errors in the classified images, over 100 accuracy assessment points were generated for each sample-area classified image. Each point was manually assigned a ground truth value corresponding to the classification schema. The user hides the classified value and assigns the ground truth value with the aid of the original orthoimagery and ancillary data (e.g., Google Earth Pro 7.3.3.7786) (Gao 2009). A stratified random-sample method accuracy assessment was performed on over 100 points of the ground truthed accuracy assessment points (Gao 2009, ESRI 2021). The accuracy assessment produced a table, known as a confusion matrix, of the accuracy of the classifier in classifying land cover type (Gao 2009). The six individual confusion matrices, shown in appendix C, show an overall accuracy between 58.7 and 77.3 percent.

The west southwest Pflugerville tile sample area confusion matrix, shown in table 3, provides an example of the overall and individual land cover type accuracies. The overall accuracy is 77.3 percent. An overall accuracy is calculated from the sum of the diagonal accurately classified points divided by the total classified points (Gao 2009).

Table 3. West-southwest Pflugerville tile sample area confusion matrix.

	Pool	Roof	Road	Tree	Grass	Shadow	Total	User's Accuracy	Kappa
Pool	**9**	1	0	0	0	0	10	90%	
Building	0	**16**	1	0	7	0	24	67%	
Road	0	1	**18**	0	0	0	19	95%	
Tree	0	3	0	**10**	0	1	14	71%	
Grass	0	1	1	6	**23**	1	32	**72%**	
Shadow	0	1	0	1	0	**9**	11	82%	
Total	9	23	20	17	30	11	**110**		
Producer's Accuracy	100%	70%	90%	59%	**77%**	82%		**77.3%**	
Kappa									**0.72**

A user's and producer's accuracy are calculated for each individual land cover type. The user's accuracy shows where land-use types were erroneously classified, or included, in another class (Gao 2009). For example, the computer classified nine non-grass land-uses incorrectly as grass. An accuracy of 72 percent of classified land types were correctly classified as grass. The producer's accuracy shows where land-use types were erroneously classified as other land-use types (Gao 2009). For example, the computer excluded seven non-grass land-use types from the grass land-use type. An accuracy of 77 percent of classified grass types were classified correctly as grass, or 23 percent of points were classified as buildings but were grass in this example. A user's accuracy of 72 percent and a producer's accuracy of 77 percent indicate a moderate accuracy of classification for the grass land-use type. Individually, the sample imagery tiles' user's accuracy ranges from 50 to 76 percent and producer's accuracy ranges from 67 to 100 percent.

Congalton (2001) explains a Cohen's kappa coefficient, or kappa coefficient, is also calculated with the accuracy assessment. A kappa coefficient shows the agreement between the classified image and the reference image classification results on a scale of zero to one. The more agreement between the classified and reference image, the closer a kappa coefficient will be to one; with less of an agreement, the kappa coefficient will be closer to zero. A kappa coefficient value below 0.4 represents poor agreement, a value of 0.4 to 0.8 constitutes a moderate agreement, and a value above 0.8 constitutes a strong agreement (Congalton 2001). In this study, the Cohen's kappa coefficient ranged from 0.5 to 0.72 across the six sample imagery tiles. This indicates the classification of all samples were within moderate agreement with the expected outcome for land-use type.

4.2 Reclassification and landscaped area square footage

A moderate accuracy for classification of turf grass could be higher for this study. Accuracy assessment identified most of the errors in classifying grass were classified as trees and vice versa. This could be due to tree spectral characteristics similar to turf grass spectral characteristics (Gao 2009). From observation, trees over turf grass should not significantly affect the usefulness of the turf grass area from being irrigated from rainwater harvesting systems or receiving precipitation. To correct this and obtain a more accurate percent of parcel covered by turf grass, random points were generated within each imagery tile. Ten parcels from each sample area orthoimagery tile were selected corresponding to the random points. A total sixty parcels were extracted from the sample areas using the parcels as the mask. Pixel counts were then collected for each land-use type.

Each of the 60 parcels were reclassified using ESRI's ArcGIS Pro tool, Pixel Editor. Manual correction was applied to these areas using observation of the original orthoimagery and ancillary data. All shadows and trees were reclassified as the observed feature below. For instance, areas with trees over grass area were reclassified using images from Google Earth Pro, where tree leaf density was lower compared to the orthoimagery used in this study and grass areas could be observed. Other misclassified areas were reclassified as their observed land cover type. A recount of the pixels was performed with the reclassified images. Figure 10 shows the progression of a sample parcel from original orthoimagery to classified to reclassified using the above method.

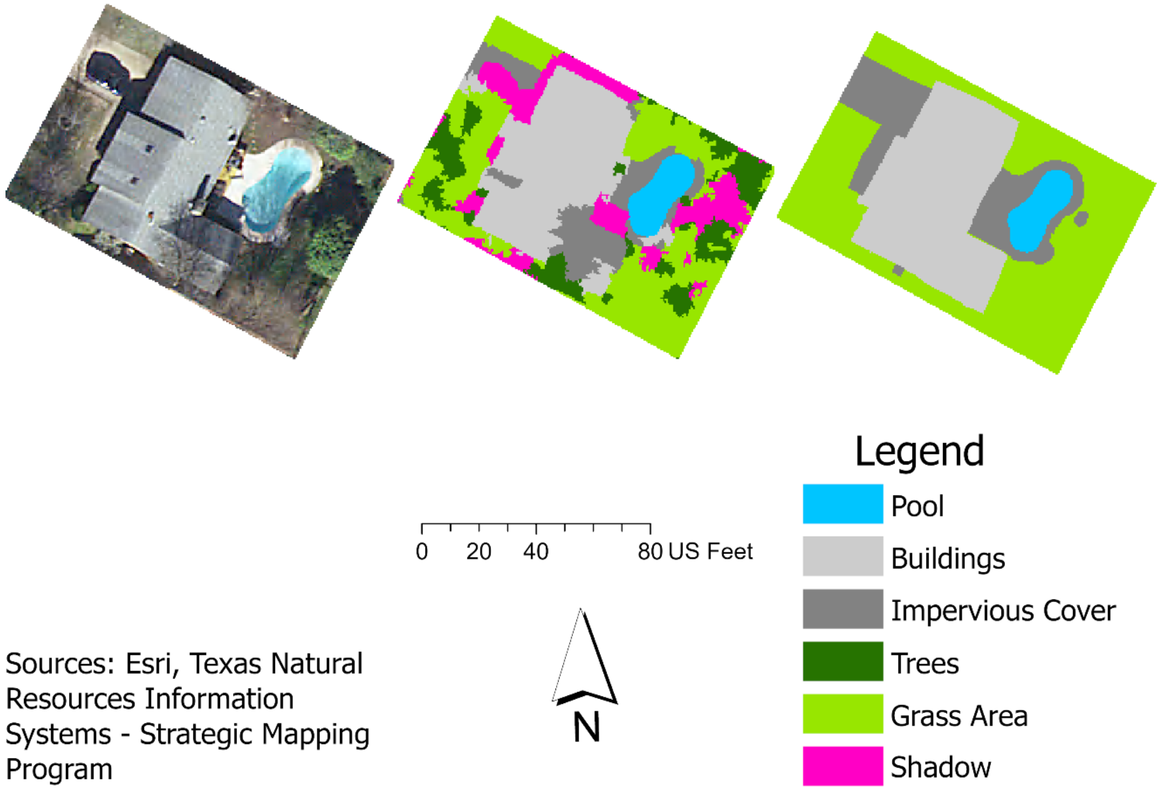

Figure 10. Progression of a sample parcel from orthoimagery to classified to reclassified.

After reclassification, grass area became the landscaped area. The percentage of landscaped area coverage per parcel was calculated by dividing the number of landscaped area pixels from the total parcel pixel count. An average of all sixty parcels' percent landscaped area coverage was then calculated to be 60 percent. This percentage was applied to the total legal area of the 202,074 parcels in the study, 1.87 billion square feet. The landscaped area was calculated as 1.1 billion square feet across all parcels in the study area.

4.3 Outdoor demand

Calculating outdoor demand in landscaped areas is dependent on climate, soil, and plant type. Plant water needs are calculated using a plant water use coefficient multiplied by ETo (Texas A&M AgriLife Extension 2021). Plant water needs are typically met in wetter months, with sufficient rainfall, or during a dormant growth period and associated low demand. ETo data is expressed in inches per month. To adjust to the unit of area for the landscaped area, square feet, ETo is converted to gallons per square feet per month by multiplying ETo by 0.62 gallons per square foot. The following equations are adapted from the Texas Rainwater Harvesting Calculator (TWDB 2010).

Equation (1.1) shows average plant water needs, N_{aw}, is equal to average monthly potential evapotranspiration of a grass reference crop, ETo_m, multiplied by the plant water use coefficient, PWU_{coeff}, then adjusted to gallons per square feet, by multiplying by 0.62 (gallons per square foot).

$$N_{aw} = ETo_m \times PWU_{coeff} \times 0.62 \tag{1.1}$$

Equation (1.2) calculates the monthly outdoor demand of plants. Monthly outdoor demand (gallons), $D_{om,}$ is equal to N_{aw} multiplied by the total landscaped area (square feet), A_{Irr}.

$$D_{om} = N_{aw} \times A_{irr} \tag{1.2}$$

Equation (1.3) calculates the monthly potential volume of water from rainfall directly on landscaped areas. The potential volume of water from rainfall directly on landscaped areas (gallons), P_{im}, is equal to A_{Irr} multiplied by the product of average monthly rainfall (inches), R_m, and 0.62 gallons per square foot.

$$P_{im} = A_{irr} \times (R_m \times 0.62) \tag{1.3}$$

Equation (1.4) represents the total monthly irrigation demand of landscaped areas. Total monthly irrigation demand (gallons), D_{tmi}, is equal to D_{om} minus P_{im}.

$$D_{tmi} = D_{om} - P_{im} \tag{1.4}$$

If P_{im} is greater than D_{om}, then D_{tmi} would equal zero. A negative D_{tmi} is not appropriate for this calculation therefore D_{tmi} would equal zero. Monthly rainfall may meet or exceed demand in one month, but this volume is not banked. In subsequent months plants require additional rainfall or irrigation. This is important when calculating total annual irrigation demand. It is the sum of D_{tmi}, not the difference of annual potential volume of water from rainfall directly on landscaped areas (sum of P_{im}) and annual outdoor demand of plants (sum of D_{om}) (see appendix D).

4.4 Collected supply

The potential volume of water on the catchment area provides a starting point for determining the volume that can be supplied to storage tanks for use on landscaped areas. The type of roof materials and whether the roof is pitched are factors in the efficiency of rainfall being collected from rooftops. The area of the rooftop, volume of rainfall, and a runoff coefficient provide the estimated supply to the storage tanks.

Equation (2.1) shows the potential volume of water from the collection area, V_{cam}, is equal to building footprint (square feet), BF_a, multiplied by the product of R_m and 0.62 gallons per square feet.

$$V_{cam} = BF_a \times (R_m \times 0.62) \tag{2.1}$$

Equation (2.2) shows the monthly supply to collection tank (gallons), S_{ectm}, is equal to V_{cam} multiplied by the runoff coefficient, RO_{coeff}.

$$S_{ectm} = V_{cam} \times RO_{coeff} \tag{2.2}$$

5. Results and Discussion

As mentioned, rainwater harvesting requires a supply to meet eventual demand. Supply calculations require minimal data manipulation, and the inputs are readily available with some customization. Demand estimation requires knowledge of the study area. Though most inputs are readily available, estimating the size of landscaped areas required machine learning techniques using orthoimagery with high spatial resolution. This step in the process provides the most room for error. The percent coverage of an average parcel was calculated and found to be like sample parcels. Areas of land-use types were reasonably correct when compared to their sample to obtain an estimate of landscaped area.

5.1 Outdoor demand

The 202,074 parcels in this study, representing 94 percent of single-family connections in Austin, cover 1.9 billion square feet. The average single-family parcel is 9,256 square feet. The average percent of landscaped area, obtained from object-based supervised classification of sample parcels, is 60 percent. Sixty percent of the 1.9 billion square feet of the parcels' lot size was classified as landscaped area, 1.1 billion square feet. The average landscaped area of a single-family parcel is 5,553 square feet.

The annual outdoor demand from landscaped areas is 24 billion gallons, calculated as the sum of D_{om}. The potential volume of water from rainfall that falls directly on landscaped areas is 23.9 billion gallons, calculated as the sum of P_{im}. As discussed earlier, the difference between the annual figures is not used because supply and demand vary by season or month. For instance, there is a deficit of rainfall for landscaped area plant water needs in April, July, August, and September, using the average of 30 years of rainfall data (NOAA 2011). In Austin, apparently the adage April showers bring May flowers does not apply, unless irrigation is provided. The sum of the total monthly irrigation demand, D_{tmi}, for these four months is 4.1 billion gallons. This volume represents how much supplemental water is needed from harvested/stored rainwater to irrigate landscaped areas at single-family residential properties in Austin beyond what average rainfall provides.

5.2 Collected supply

Single-family residential building footprints cover nearly 470 million square feet of catchment area in Austin. An average single-family parcel's building(s) covers 2,326 square feet. The annual potential volume of water from the collection area is 10 billion gallons, calculated from the sum of V_{cam}. Including the runoff coefficient of 0.9 for asphalt shingle roof material, 9 billion gallons of water is the supply available for collection, calculated from the sum of S_{ectm}. This amount represents the volume of water all 202,074 single-family residential parcel buildings in Austin can supply.

5.3 How much water can be collected and conserved?

If all houses identified in this study had the proper rainwater harvesting equipment, 9 billion gallons of water could be collected. If homeowners only irrigated their landscaped area with the volume of water the plants need then nearly 4.1 billion gallons could be conserved from the potable water system. An average storage tank of 12,500 gallons would be necessary at each house if each homeowner wanted to meet all plant water needs in all months with harvested rainwater alone. A smaller tank would not be sufficient to capture and store enough water to meet outdoor irrigation demand. Stated earlier, Tamaddun, Kaira, and Ahmad (2018) found a 1,000 gallon storage capacity is not sufficient to meet water use demand during dry months.

Some homes do not irrigate their landscaped areas and may not need to irrigate depending on their landscape-plant types, while others may overwater their landscaped area resulting in more water than necessary being used for irrigation (EPA 2013, Landon, Kyle and Kaiser 2016). A 2012 report by the TWDB found the average outdoor water use as a percentage of total water use for Austin was 33 percent, using water use data from 2004 to 2011 (Hermitte and Mace 2012). This percent can be applied to an adjusted 2019 volume of total water use for Austin. The houses in this study represent 94 percent of the 214,949 single-family properties in the annual water use survey (City of Austin 2019). Adjusting the 14 billion gallons of the collective single-family residential usage in the 2019 annual water use survey (City of Austin 2019) and multiplying by 94 percent yields an approximate 13.8 billion gallons of total water usage for the 202,074 properties in this study.

Thirty-three percent of the 13.8 billion gallons of the collective single-family residential adjusted usage in 2019 is approximately 4.5 billion gallons. By this calculation, roughly 459 million gallons of water is used beyond the average plant water needs at these properties. Even if properties overwater their landscaped areas, with a collected supply of 9 billion gallons, from a 12,500 gallon tank, there is adequate supply, a surplus of over 4.5 billion gallons, for plant water needs and other uses. Homeowners could water their turf grass twice as much as the estimated outdoor irrigation demand illustrated by Hermitte and Mace (2012) and over two times the plant water needs using collected rainwater with a cistern size of 12,500 gallons at each home in this study. This surplus water, if captured could be used for other purposes beyond outdoor irrigation. Table 4 illustrates the comparison of outdoor irrigation demand between watering for plant water needs versus overwatering at 33 percent of total water use for the collective single-family residential properties.

Table 4. Comparison of collective single-family residential outdoor irrigation demand.

Outdoor water use	Annual single-family residential total water use (gallons)	Annual single-family residential outdoor irrigation demand (gallons)	Estimated supply to storage tank[a] (gallons)
Plant water needs met[b]	13,781,275,140	4,088,353,476	8,999,521,267
33 percent of total use[c]	13,781,275,140	4,547,820,796	8,999,521,267
Difference	-	459,467,320	

[a] Assuming a 12,500 gallon storage tank.

[b] If plant water needs were met with rainfall and rainwater harvesting, illustrated from this study's calculations.

[c] If 33 percent of total household water use was used outdoors, illustrated by Hermitte and Mace (2012).

A total water savings from rainwater harvesting systems and the difference in outdoor irrigation demand between two studies may illustrate findings relevant to water planning regions and governments; however, it is also of concern how this could be implemented for the average household. The average annual total water demand of a single-family residential property in Austin, calculated from the collective adjusted total water use, 13.8 billion gallons, divided by 202,074 properties, is 68,199 gallons. For an average property, 44,537 gallons could be collected annually, and 20,233 gallons would be needed to irrigate the landscaped area to meet plant water needs not met by rainfall. If these properties overwatered at 33 percent of total water use, an estimated 22,506 gallons would be for outdoor irrigation. There is adequate supply from collected rainwater annually, 44,537 gallons, to conserve valuable potable water supplies. Of note, if the average homeowner is overwatering or has a landscaped area larger than the average single-family residential property, then a larger storage tank than 12,500 gallons would be necessary to meet peak outdoor irrigation demand in summer months, when plant water needs are not met by rainfall alone. Also of note, if the landscaped area is smaller than the average single-family residential property then a smaller storage tank than 12,500 gallons could be sufficient to meet peak outdoor irrigation demand in summer months. Table 5 illustrates the comparison of outdoor irrigation demand between watering for plant water needs versus overwatering at 33 percent of total water use for an individual single-family residential property.

Table 5. Comparison of individual single-family residential outdoor irrigation demand.

Outdoor water use	Annual single-family residential total water use (gallons)	Annual single-family residential outdoor irrigation demand (gallons)	Estimated supply to storage tank[a] (gallons)
Plant water needs met[b]	68,199	20,233	44,537
33 percent of total use[c]	68,199	22,506	44,537
Difference	-	2,273	-

[a] Assuming a 12,500 gallon storage tank.

[b] If plant water needs were met with rainfall and rainwater harvesting, illustrated from this study's calculations.

[c] If 33 percent of total household water use was used outdoors, illustrated by Hermitte and Mace (2012).

A 12,500 gallon storage tank takes up a large footprint of the landscaped area. This size tank would require either a minimum diameter of 12 feet at a height of around 16 feet or a minimum diameter of 18 feet at a height of around 8 feet (TWDB 2005). A 12-foot diameter tank would cover a minimum of 113 square feet of area while an 18 foot diameter tank would cover a minimum of 254 square feet of area (see figure 11). The average property has an estimated 9,256 square foot lot and 5,553 square feet of landscaped area available for a tank with these diameters. Ultimately a storage tank could reduce the area required for irrigation and provide a catchment area for rainwater. However, the height of these tanks is not feasible at most properties because of the size limitations on a property. Additionally, tall structures could require the removal or transfer of trees or other land features on many properties, unsightly and large structures may lower the aesthetics of the property, and tall structures are potential hazards should they collapse, falling on and/or flooding homes.

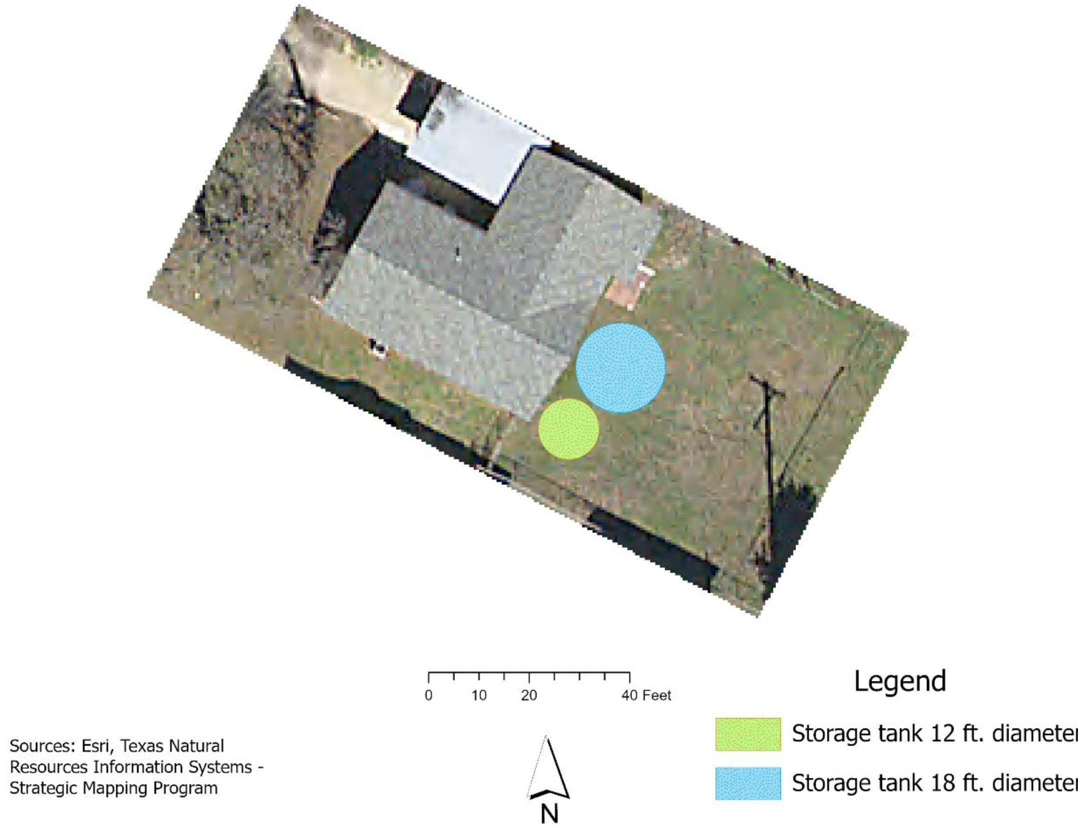

Figure 11. Comparison of storage tank diameters on average sized study area parcel.

An alternative to a single large structure is installing two or more storage tanks equivalent to 12,500 gallons of storage. The use of multiple storage tanks could alleviate the burden of storage tank and rainwater harvesting appurtenances maintenance. During April, June, July, and August outdoor irrigation demand is high; however, during the other months of the year the storage tanks are refilling, and plant water needs are met by rainfall without supplemental irrigation. Taking a storage tank off-line during this period for maintenance may be more manageable for a homeowner, the proprietor of the rainwater harvesting system and components. Installing two or more storage tanks also reduces the area of landscape to be irrigated, a negative feedback loop. Additionally, situating multiple storage tanks at different sides of a home can increase roof runoff and conduit efficiency by reducing travel distance from catchment and storage. If two 6,250 gallon storage tanks were installed, each tank would still have a footprint with a diameter of 12 feet or roughly 113 square feet, but with a height of 8 feet or less; that is, each tank is half as tall as a 12,500 gallons storage tank with the same diameter footprint. For reference, the percent reduction in landscaped area from installing two tanks is less than 5 percent of the average properties' landscaped area, resulting in a very low decrease in outdoor irrigation demand.

Replacing the landscaped area with low water use plants, a drought tolerant or native landscape, can also reduce the outdoor irrigation demand. By reducing the outdoor irrigation demand, the size of the tank can be reduced. For example, drought tolerant or native landscapes water demand can be met by rainfall without the need for supplemental irrigation (Tamaddun, Kaira and Ahmad 2018), reducing the need for a larger storage tank. Austin provides a rebate of up to $1,750 for its residential customers to replace a minimum of 500 square feet of turf grass with native and adapted plants. The converted area must have at least 50 percent plant coverage when plants are mature (City of Austin 2021). Other areas have set similar requirements or set limitations for the installation of a drought tolerant landscape. In Nevada, a maximum of 50 percent of the side and rear landscaped area of a property can be converted to a drought tolerant landscape (Tamaddun, Kaira and Ahmad 2018).

Assuming 12,500 gallons of storage were installed on a property, conversion of a portion of the landscaped area to drought tolerant or native landscape would yield a reduction in the annual outdoor irrigation demand. Table 6 shows the average properties annual outdoor irrigation demand, the volume of outdoor irrigation demand not met by 12,500 gallons of storage (i.e., deficit), the months with a deficit, represented by the number for the month (i.e., 1 = January), and the volume of potable water conserved by using rainwater in the storage tank. Even without converting any portion of the landscaped area to a drought tolerant or native landscape no deficit in water exists because this size of storage is adequate to meet peak outdoor irrigation demand in the drier months and not drawdown the storage to empty, as expressed in Tamaddun, Kaira, and Ahmad (2018).

Table 6. Outdoor irrigation demand conserved by 12,500 gallons of storage before and after landscape conversion on an average Austin single-family residential property.

Landscaped area converted (% | sq. ft.)	Annual outdoor irrigation demand (gallons)	Annual deficit of water (gallons)	Months with a deficit	Annual volume conserved by storage (gallons)
0 | 0	20,233	-	-	20,233
10 | 555	18,208	-	-	18,208
25 | 1,388	15,173	-	-	15,173
50 | 2,777	10,116	-	-	10,116
75 | 4,165	5,058	-	-	5,058

Note: Annual volume conserved decreases due to lower demand from conversion of landscaped area to low water use plants.

Another alternative is to compound reducing the storage size and replacing a portion of the landscaped area with drought tolerant or native plants. Using the rainwater harvesting calculations and adjusting for the conversion of landscaped area to drought tolerant landscape, a minimum tank size can be calculated. If 50 percent of the average property were converted, a 5,000 gallon tank would still be required to meet plant water needs over all months of the year. Up to 10,116 gallons of potable water could be conserved. A 5,000 gallon storage tank would still require at least a 12-foot diameter tank at a height of 6 feet. Two 2,500 gallon storage tanks would require at least a 6-foot diameter footprint at a height of 12 feet. Table 7 shows the average properties annual outdoor irrigation demand, the volume of outdoor irrigation demand not met by 5,000 gallons of storage (i.e., deficit), the months with a deficit, represented by the number for the month (i.e., 1 = January), and the volume of potable water conserved by using rainwater in the storage tank.

Table 7. Outdoor irrigation demand conserved by 5,000 gallons of storage before and after landscape conversion on an average Austin single-family residential property.

Landscaped area converted (% | sq. ft.)	Annual outdoor irrigation demand (gallons)	Annual deficit of water (gallons)	Months with a deficit (number for month, i.e., 1 = January)	Annual volume conserved by storage (gallons)
0 | 0	20,233	7,280	7, 8	12,953
10 | 555	18,208	5,746	7, 8	12,462
25 | 1,388	15,173	3,446	7, 8	11,727
50 | 2,777	10,116	-	-	10,116
75 | 4,165	5,058	-	-	5,058

Note: Annual volume conserved decreases due to lower demand from conversion of landscaped area to low water use plants.

A 1,000 gallon tank used in the calculations by Tamaddun, et al. (2018), could be appropriate for many homeowners. At a diameter of 6 feet only 24 square feet of space is required. At a height of six feet a 1,000 gallon tank is more manageable and less likely to create a hazard on the property. For comparison, a 10-foot diameter above-ground pool at a 3-foot depth holds more water than these tanks. Table 8 shows an average properties’ annual outdoor irrigation demand, the volume of outdoor irrigation demand not met by 1,000 gallons of storage (i.e., deficit), the months with a deficit, represented by the number for the month (i.e., 1 = January), and the volume of potable water conserved by using rainwater in the storage tank.

Table 8. Outdoor irrigation demand conserved by 1,000 gallons of storage before and after landscape conversion on an average Austin single-family residential property.

Landscaped area converted (% | sq. ft.)	Annual outdoor irrigation demand (gallons)	Annual deficit of water (gallons)	Months with a deficit (number for month, i.e., 1 = January)	Annual volume conserved by storage (gallons)
0 | 0	20,233	16,233	4, 7, 8, 9	4,000
10 | 555	18,208	14,208	4, 7, 8, 9	4,000
25 | 1,388	15,173	11,264	4, 7, 8	3,909
50 | 2,777	10,116	6,510	4, 7, 8	3,606
75 | 4,165	5,058	1,832	7, 8	3,226

Note: Annual volume conserved decreases due to lower demand from conversion of landscaped area to low water use plants.

These results illustrate there can be many components to computing the outdoor irrigation volume conserved through rainwater collection. The volume of water from rainfall, the area of roofs available for rainwater catchment, the area of landscapes, the type of plants on the landscape, the plant water needs, the volume of storage required to store the rainwater, the size of the storage that is appropriate for the property, and so on. It may require a lot of data, but the benefits of rainwater harvesting are high, including the conservation of potable water resources. Depending on a homeowner's tank size and landscape preference, between 3,226 and 20,233 gallons could be conserved. A larger volume of storage can provide adequate supply to meet outdoor irrigation demand in dry times and conserve large volumes of potable water. Also, compounding rainwater harvesting with a landscape conversion to drought tolerant or native plants can result in a decreased outdoor irrigation demand, a decrease in the volume of outdoor irrigation demand not met by stored rainwater (i.e., deficit), and a decrease in the number of months with a deficit, if a homeowner installs a tank without adequate storage to meet outdoor irrigation demand without landscape conversion.

6. Conclusion

This study presents a method for calculating rainwater harvesting potential supply and outdoor irrigation demand volumes. Collective single-family residential parcels, 202,074, and individual single-family residential parcels were analyzed to determine these volumes. The calculations and GIS techniques performed, in this project report, on various data sources produced results showing a significant volume of water could be collected to supplant and therefore conserve potable water supply in Austin.

This study found a collective and individual volume of water, nearly 9 billion gallons and 44,537 gallons, respectively, could be collected with adequately sized storage. This volume exceeds plant water needs; therefore, a storage capacity of 12,500 gallons, at an average single-family residence, is necessary to meet outdoor irrigation demand in all months of the year. With adequately sized storage to meet outdoor irrigation in all months of the year a collective and individual total volume of water, nearly 4.1 billion gallons and 20,233 gallons, respectively, of water could be conserved. Collectively and individually a surplus of rainfall on roofs, 4.9 billion gallons and 24,304 gallons, respectively, exists due to lower outdoor irrigation demand than the potential volume of rainfall collected from roof.

Additionally, due to storage and property limitations, it is appropriate to consider the potential versus reality of rainwater harvesting systems for conserving potable water supply in Austin. Rainfall may be plenty to meet outdoor irrigation demands using rooftop rainwater harvesting with leftover supply for other water uses; however, storage space and size may be a limiting factor for many homeowners. Reducing the storage size, or splitting the storage capacity across multiple tanks, can still provide water supply for outdoor irrigation demand and result in conservation of potable water supply; though, a deficit of water may exist in some months if demand exceeds supply. It may be necessary to consider combining rainwater harvesting with other conservation strategies, such as landscape conversion. This study found, by increasing drought tolerant and native plants outdoor irrigation demand decreased resulting in less needed supply/storage. The right combination of conservation strategies is necessary to meet demands in all months of the year.

Further study is warranted to determine the volume of other demands besides outdoor irrigation, identify other storage alternatives, and develop other costs and benefits of rooftop rainwater harvesting in Austin. Additionally, it is important to note, rooftops exist on other properties besides single-family residences. Multi-family residential, commercial, and industrial properties exist in Austin as well. These sites may have greater potential for rainwater harvesting due to their larger building footprints. They may also have more resources and land area to accommodate larger storage facilities for rainwater. Another study could assess their potential among these and other factors. Finally, rooftops are not the only catchment surfaces in the study area. Further research could identify the potential for rainwater harvesting from non-rooftop surfaces.

Rainwater harvesting has a history of use and a great potential for offsetting water demand on public water supplies. It should be implemented more broadly by homeowners and utilities to achieve sustainable water supply. Additionally, state, regional, and local governments and other stakeholders should continue to research the potential of this alternate supply of water.

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APPENDIX A

City of Austin, Annual Water Use Survey (2019)

Date/Time Survey Submitted: 2/28/2020 9:49:13 AM

TEXAS WATER DEVELOPMENT BOARD
WATER USE SURVEY

WATER USE IN CALENDAR YEAR: 2019

SYSTEM NAME:	GENERAL DISTRIBUTION SYSTEM	**SURVEY NUMBER:**	0041010
OPERATOR NAME:		**PRIMARY USED COUNTY:**	TRAVIS
MULTIPLE SURVEY ORG:	CITY OF AUSTIN	**PRIMARY USED RIVER BASIN:**	COLORADO
MAILING ADDRESS 1:	PO BOX 1088	**ORGANIZATION MAIN PHONE:**	512-972-0423
MAILING ADDRESS 2:		**MAIN EMAIL:**	helen.gerlach@austintexas.gov
CITY/STATE/ZIP:	AUSTIN TX 78767-	**WEB:**	www.austintexas.gov
PWS NAME:	CITY OF AUSTIN WATER & WASTEWATER	**PWS CODE:**	2270001

INTAKE:

Water Type	County	Basin	Reservoir / River	Water Right #	% Consumed	Metered or Estimated	Brackish / Saline (Y or N)	% Treated Prior to Intake	Total Volume (gallons)
SURFACE WATER SELF SUPPLIED	TRAVIS	COLORADO	TOWN LAKE/RESERVOIR	05471-0-A	100.00	M	N	0.00	39,736,551,897

JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
2,796,127,431	2,539,356,843	2,792,868,921	3,012,166,644	3,339,321,048	3,411,008,268	4,017,742,830	4,398,988,500	3,859,705,095	3,426,649,116	3,045,077,595	3,097,539,606

Water Type	County	Basin	Seller Name and/or Seller System	River / Reservoir	Metered or Estimated	Brackish / Saline (Y or N)	% Treated Prior to Intake	Total Volume (gallons)
SURFACE WATER PURCHASED			LOOP 360 WSC		M	N	100.00	867,000

JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
100,000	115,000	102,000	106,000	74,000	73,000	47,000	49,000	43,000	48,000	43,000	67,000

Water Type	County	Basin	Seller Name and/or Seller System		River / Reservoir	Metered or Estimated	Brackish / Saline (Y or N)	% Treated Prior to Intake	Total Volume (gallons)
SURFACE WATER PURCHASED	TRAVIS	COLORADO	LOWER COLORADO RIVER AUTHORITY	LCRA LAKE TRAVIS 14230	COLORADO-LAVACA RUN OF RIVER	M	N	0.00	11,105,979,633

JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
624,330,516	678,421,782	900,978,015	727,625,283	718,827,306	652,679,553	882,078,657	1,392,361,323	1,553,005,866	1,458,834,927	825,706,434	691,129,971

Water Type	County	Basin	Metered or Estimated	% Reuse for Industrial	% Reuse for Landscape	% Reuse for Agriculture	% Reuse for Other	Total Volume (gallons)
REUSE SELF SUPPLIED DIRECT NON-POTABLE	TRAVIS	COLORADO	M	48.70	51.20	0.00	0.10	1,607,200,000

SALES:

BUYER	SALE TYPE (MUNICIPAL or INDUSTRIAL)	COUNTY NAME	BASIN NAME	WATER TYPE	AQUIFER NAME (if GW)	SURFACE WATER Name (if SW)	RAW or TREATED	TOTAL VOLUME (GALLONS)
SKORPIOS TECHNOLOGIES INC	I			SURFACE WATER			Treated	73,201,000
MORNINGSIDE SUBDIVISION	M			SURFACE WATER			Treated	2,233,500
SAMSUNG AUSTIN SEMICONDUCTOR LLC	I			SURFACE WATER			Treated	2,334,790,600
ED BLUESTEIN BLVD FACILITY	I			SURFACE WATER			Treated	406,911,000
TRAVIS COUNTY WCID 10	M			SURFACE WATER			Treated	834,001,000
SPANSION LLC	I			SURFACE WATER			Treated	325,633,000
CREEDMOOR MAHA WSC	M			SURFACE WATER			Treated	76,340,700
NIGHTHAWK WSC	M			SURFACE WATER			Treated	11,173,800
MARSHA WSC	M			SURFACE WATER			Treated	12,668,500
NORTH AUSTIN MUD 1	M			SURFACE WATER			Treated	421,927,400
WELLS BRANCH MUD	M			SURFACE WATER			Treated	457,948,300
RIVERCREST WATER SYSTEM	M			SURFACE WATER			Treated	120,228,500
CITY OF ROLLINGWOOD	M			SURFACE WATER			Treated	128,386,800
VILLAGE OF SAN LEANNA	M			SURFACE WATER			Treated	4,357,000
CITY OF SUNSET VALLEY	M			SURFACE WATER			Treated	100,337,200
HIGH VALLEY WSC	M			SURFACE WATER			Treated	5,759,800
NORTHTOWN MUD	M			SURFACE WATER			Treated	304,936,800
CITY OF MANOR	M			SURFACE WATER			Treated	1,000
WINDERMERE UTILITY COMPANY	M			SURFACE WATER			Treated	313,000
OAK HILL FAB	I			SURFACE WATER			Treated	242,088,200
MID-TEX UTILITIES - AVANA SUBDIVISION	M	TRAVIS	COLORADO	SURFACE WATER		AUSTIN LAKE/RESERVOIR	Treated	63,885,000
SAND HILL POWER PLANT	I	TRAVIS	COLORADO	REUSE				0

COUNTY CONNECTIONS:

COUNTY NAME	TOTAL CONNECTIONS
HAYS	39
TRAVIS	225,375
WILLIAMSON	14,582

CONNECTIONS & USAGE:	CONNECTIONS	VOLUME (GALLONS)
TOTAL METERED RETAIL:	240,141	41,933,277,400
Residential - Single Family	214,959	14,660,931,000
Residential - Multi Family	6,480	9,964,763,500
Institutional	535	1,216,558,500
Commercial	18,012	11,101,200,600
Industrial	10	3,382,623,800
Agriculture	0	0
Reuse	145	1,607,200,000
TOTAL UNMETERED:	0	47,867,383

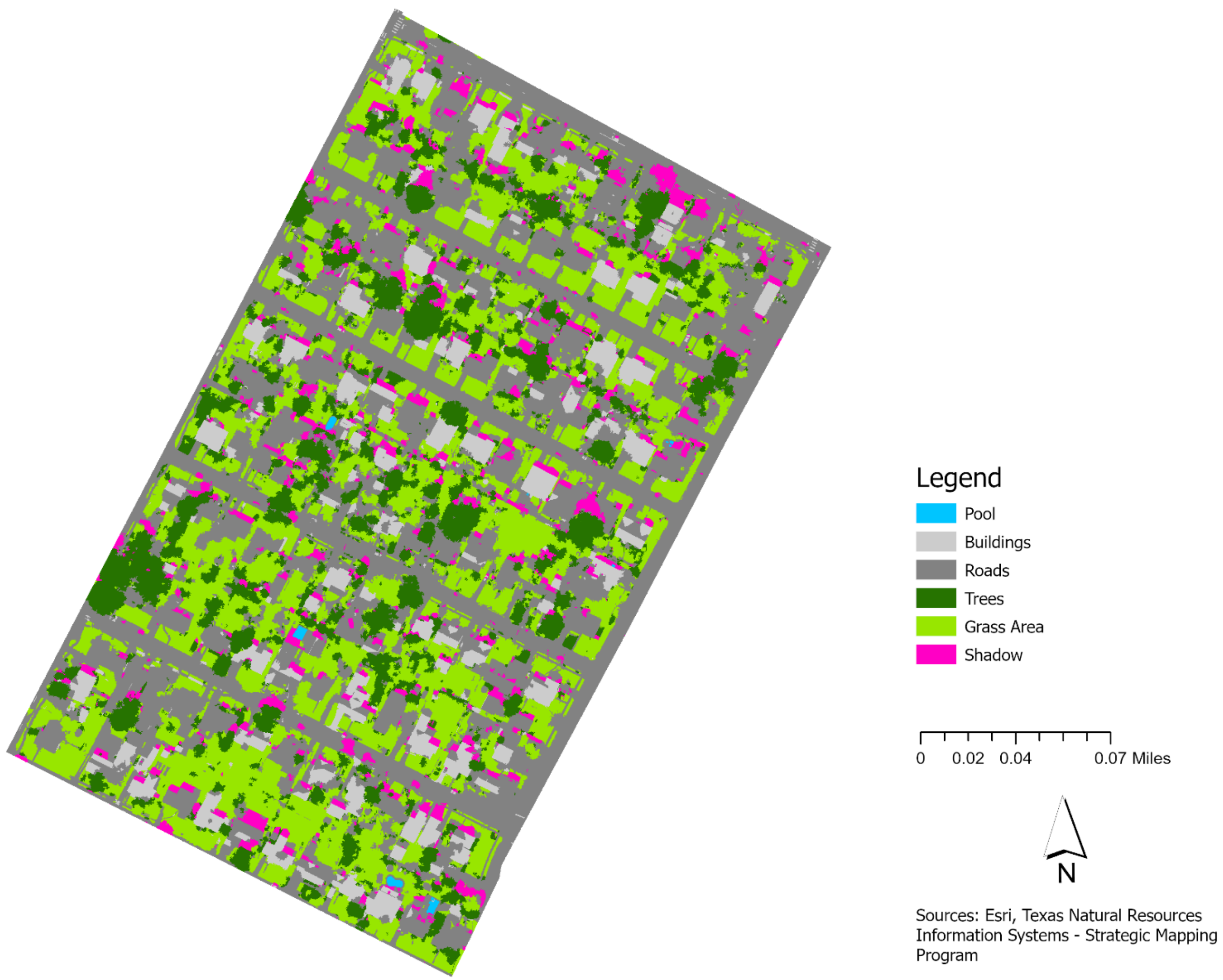
WATER SYSTEM INFORMATION:

Estimated full-time residential population served directly by this system	1,083,596

APPENDIX B

Six Study Sample Area Classified Images

Classified orthoimagery of sample tile area within Austin boundary: west southwest Pflugerville.



Classified orthoimagery of sample tile area within Austin boundary: east northwest Austin.

Classified orthoimagery of sample tile area within Austin boundary: east southeast Austin.

Classified orthoimagery of sample tile area within Austin boundary: northeast Oak Hill.

Classified orthoimagery of sample tile area within Austin boundary: northwest Oak Hill.

Classified orthoimagery of sample tile area within Austin boundary: northwest Montopolis.

APPENDIX C

Six Study Sample Area Classified Image Confusion Matrices

West southwest Pflugerville confusion matrix

	Pool	Roof	Road	Tree	Grass	Shadow	Total	User's Accuracy	Kappa
Pool	**9**	1	0	0	0	0	10	90.0%	
Roof	0	**16**	1	0	7	0	24	66.7%	
Road	0	1	**18**	0	0	0	19	94.7%	
Tree	0	3	0	**10**	0	1	14	71.4%	
Grass	0	1	1	6	**23**	1	32	**71.9%**	
Shadow	0	1	0	1	0	**9**	11	81.8%	
Total	9	23	20	17	30	11	**110**		
Producer's Accuracy	100.0%	69.6%	90.0%	58.8%	**76.7%**	81.8%		**77.3%**	
Kappa									**0.72**

East northwest Austin confusion matrix

	Pool	Roof	Road	Tree	Grass	Shadow	Total	User's Accuracy	Kappa
Pool	**10**	0	0	0	0	0	10	100.0%	
Roof	0	**10**	0	0	0	0	10	100.0%	
Road	0	15	**15**	4	4	5	43	34.9%	
Tree	0	0	0	**9**	2	3	14	64.3%	
Grass	0	0	0	6	**20**	3	29	**68.9%**	
Shadow	0	0	1	0	0	**9**	10	90.0%	
Total	10	25	16	19	26	20	**116**		
Producer's Accuracy	100.0%	40.0%	93.8%	47.4%	**76.9%**	45.0%		**62.9%**	
Kappa									**0.55**

East southeast Austin confusion matrix

	Pool	Roof	Road	Tree	Grass	Shadow	Total	User's Accuracy	Kappa
Pool	**8**	2	0	0	0	0	10	80.0%	
Roof	0	**10**	7	1	0	1	19	52.6%	
Road	0	4	**11**	1	0	0	16	68.8%	
Tree	0	0	0	**9**	1	0	10	90.0%	
Grass	0	2	3	13	**25**	2	45	**55.6%**	
Shadow	0	0	0	4	1	**9**	14	64.3%	
Total	8	18	21	28	27	12	**114**		
Producer's Accuracy	100.0%	55.6%	52.4%	32.1%	**92.6%**	75.0%		**63.2%**	
Kappa									**0.55**

Northeast Oak Hill confusion matrix

	Pool	Roof	Road	Tree	Grass	Shadow	Total	User's Accuracy	Kappa
Pool	**3**	7	0	0	0	0	10	30.0%	
Roof	0	**14**	2	1	0	0	17	82.4%	
Road	0	12	**12**	4	0	0	28	42.9%	
Tree	0	0	0	**10**	0	0	10	100.0%	
Grass	0	2	0	14	**17**	1	34	**50.0%**	
Shadow	0	0	1	1	0	**8**	10	80.0%	
Total	3	35	15	30	17	9	**109**		
Producer's Accuracy	100.0%	40.0%	80.0%	33.3%	**100.0%**	88.9%		**58.7%**	
Kappa									**0.50**

Northwest Oak Hill confusion matrix

	Pool	Roof	Road	Tree	Grass	Shadow	Total	User's Accuracy	Kappa
Pool	**2**	3	3	1	1	0	10	20.0%	
Roof	0	**16**	2	0	0	0	18	88.9%	
Road	0	1	**13**	0	0	0	14	92.9%	
Tree	0	1	3	**14**	5	0	23	60.9%	
Grass	0	2	1	6	**16**	0	25	**64.0%**	
Shadow	0	3	0	4	2	**11**	20	55.0%	
Total	2	26	22	25	24	11	**110**		
Producer's Accuracy	100.0%	61.5%	59.1%	56.0%	**66.7%**	100.0%		**65.5%**	
Kappa									**0.58**

Northwest Montopolis confusion matrix

	Roof	Road	Tree	Grass	Shadow	Total	User's Accuracy	Kappa
Roof	**21**	4	1	1	0	27	77.8%	
Road	7	**8**	0	2	0	17	47.1%	
Tree	2	0	**16**	4	1	23	69.6%	
Grass	1	1	4	**19**	0	25	**76.0%**	
Shadow	0	0	0	0	**10**	10	100.0%	
Total	31	13	21	26	11	**102**		
Producer's Accuracy	67.7%	61.5%	76.2%	**73.1%**	90.9%		**72.5%**	
Kappa								**0.65**

APPENDIX D

Collective and Individual Single-Family Residential Rainwater Harvesting Calculations (Austin)

Collective single-family residential rainwater harvesting calculation (Austin).

Month	Average monthly rainfall (gal. per sq. ft.)	Estimated monthly supply to collection tank (gal.)	Average plant water needs (gal. per sq. ft.)	Monthly outdoor demand (gal)	Potential volume of water from rainfall directly on irrigated areas (gal.)	Total monthly demand (gal.)
January	1.38	582,136,865	0.84	947,640,816	1,544,612,784	-
February	1.25	529,692,103	1.01	1,135,499,128	1,405,458,479	-
March	1.71	723,737,724	1.61	1,811,789,049	1,920,329,407	-
April	1.3	548,047,769	1.96	2,200,029,560	1,454,162,486	745,867,074
May	2.75	1,164,273,730	2.38	2,667,588,024	3,089,225,568	-
June	2.68	1,135,429,111	2.66	2,984,859,839	3,012,690,700	-
July	1.17	492,980,769	2.69	3,014,082,243	1,308,050,466	1,706,031,777
August	1.46	616,225,961	2.70	3,026,606,131	1,635,063,082	1,391,543,049
September	1.85	784,049,201	2.07	2,325,268,434	2,080,356,858	244,911,576
October	2.41	1,017,428,395	1.63	1,828,487,566	2,699,593,514	-
November	1.84	776,182,487	1.02	1,143,848,386	2,059,483,712	-
December	1.49	629,337,152	0.82	922,593,041	1,669,851,658	-
Annual	21.28	**8,999,521,267**	21.39	24,008,292,217	23,878,878,714	**4,088,353,476**

Coefficients and areas	Values
Parcel area (sq. ft.)	1,870,353,560
Irrigation area (sq. ft.)	1,122,212,136
Building footprint (sq. ft.)	469,935,149
Runoff coefficient	0.9
Plant water use coefficient	0.6

Individual single-family residential rainwater harvesting calculation with an average 12,500 gallons of storage (Austin).

Month	Average monthly rainfall (gal. per sq. ft.)	Estimated monthly supply to collection tank (gal.)	Average plant water needs (gal. per sq. ft.)	Monthly outdoor demand (gal)	Potential volume of water from rainfall directly on irrigated areas (gal.)	Total monthly demand (gal.)	Estimated volume of water left in tank (or deficit) at end of month (gal)
January	1.38	2,881	0.84	4,690	7,644	-	2,881
February	1.25	2,621	1.01	5,619	6,955	-	5,502
March	1.71	3,582	1.61	8,966	9,503	-	9,084
April	1.3	2,712	1.96	10,887	7,196	3,691	8,105
May	2.75	5,762	2.38	13,201	15,288	-	12,500
June	2.68	5,619	2.66	14,771	14,909	-	12,500
July	1.17	2,440	2.69	14,916	6,473	8,443	4,057
August	1.46	3,050	2.70	14,978	8,091	6,887	220
September	1.85	3,880	2.07	11,507	10,295	1,212	2,888
October	2.41	5,035	1.63	9,049	13,359	-	7,923
November	1.84	3,841	1.02	5,661	10,192	-	11,764
December	1.49	3,114	0.82	4,566	8,264	-	12,500
Annual	21.28	**44,537**	21.39	118,811	118,169	20,233	

Coefficients and areas	Values
Parcel area (sq. ft.)	9,256
Irrigation area (sq. ft.)	5,553
Building footprint (sq. ft.)	2,326
Runoff coefficient	0.9
Plant water use coefficient	0.6
Storage size (gal.)	12,500