ASSESSING URBAN RESIDENTIAL IRRIGATION PERFORMANCE USING A WATER BUDGET APPROACH

A Thesis

by

ALAN CHRISTOPHER LEWIS

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Chair of Committee,	Ronald A. Kaiser
Committee Members,	Ralph A. Wurbs
	Kelly Brumbelow
	Steven M. Quiring
Head of Department,	Ronald A. Kaiser

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ABSTRACT

Wasting water by excessive irrigation of urban residential landscapes is a ubiquitous problem. By reducing irrigation in excess of plant water needs, homeowners and cities save substantial quantities water. Although water utilities can use a variety of approaches to encourage customers to reduce their consumption, some residences may use water more efficiently than others. By understanding patterns of irrigation performance among customers, water utilities can develop more economical approaches for encouraging water conservation. Irrigation performance can be assessed by comparing outdoor water use with a landscape water budget. This requires an accurate estimate of irrigated landscape area, which can be difficult to obtain for citywide datasets. A bivariate approach using tax appraisal information is proposed, which can be applied in any county. Irrigation performance was assessed for 5,565 single-family residences by examining their conformance to monthly water budgets. Nonconformance was defined as outdoor water use exceeding the monthly budget volume. Large lots were found to overwater by significantly greater volumes than smaller lots. However, lots with smaller landscape areas tended to overwater more frequently and apply higher volumes per unit area. These findings suggest new management options for addressing consistently wasteful water use and improving efficiency.

DEDICATION

To late Dr. Valeen Silvy, whose passion for water education and strength of character inspired a generation of water scientists and professionals. And, to my family and loved ones, for their tireless encouragement and support.

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This thesis was made possible through generous time and support from several people. I am very grateful to my Dr. Ron Kaiser, for his patience, belief in my abilities as a student, and advice throughout my graduate studies. From the beginning of my studies at in the WMHS program, he encouraged me to explore my fullest intellectual potential. Were it not for the guidance and mentorship of Dr. Prakash Khedun, the quality of my thesis would have paled in comparison to the current work. His advice to always use data to tell a story will be indispensable for my future in science. I would also express my deep appreciation and respect for Dave Coleman and Jennifer Nations of College Station Utilities, who have greatly advanced College Station's approach to urban water management. Additionally, I would like to acknowledge Brett Blankner at the City of College Station and Miriam Olivares, at Texas A&M University Libraries, for granting me access to the GIS that made this research possible. Last but not least, my sincere gratitude goes to my friend Janet Torres, whose passion for science, social justice, youth leadership, and civic engagement inspired me to push my intellectual limits.

NOMENCLATURE

AWC	Average Winter Consumption
ET	Evapotranspiration
GIS	Geographic Information Systems
HOA	Homeowners Association
IR	Irrigation Requirement
SFR	Single-Family Residential
TWDB	Texas Water Development Board
TWRI	Texas Water Resources Institute
USGS	United States Geological Survey

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

1. INTRODUCTION

Urbanization and population growth are placing increased demands on public water supplies, everywhere. Whereas the task of urban water management historically focused on expansion of municipal and regional water infrastructure (Thompson 1999), concerns about water scarcity have shifted attention toward conservation and efficiency (Gleick 2000). Rising costs and political challenges associated with supply-side options, as well as additional stresses related to climate change and competition of resources (USEPA 2013; USGCRP 2014), have leveraged development of new technologies, alternative supplies, and demand-side management.

Changes in the national economic profile of the United States, environmental legislation, and more efficient irrigation practices in agriculture have contributed to an overall decline in overall freshwater withdrawals since 1980 (Kenny et al. 2009). However, estimated withdrawals for public supply have continually increased since 1950, closely following urban population growth trends (Figure 1). Over time and with sufficient growth, infrastructure expansions become inevitable. However, water supply augmentation typically happens periodically rather than continuously. Between capital projects, management approaches must often be altered to make existing supplies more sustainable.

According to the U.S. Geological Survey (USGS), water withdrawals for public supply represent the third-largest category of abstraction in the United States after agriculture and thermoelectric power (Kenny et al. 2009). Public-supply withdrawals in

California and Texas together comprised more than one-fourth of the nation's total in 2005, obtaining nearly 82% and 72% of their totals from surface water sources, respectively. Although relative dependency of municipal supplies on groundwater or surface water varies by location, statewide withdrawals in California and account for 57% and 67% of delivery from public suppliers, respectively. Whereas aquifer recharge rates place physical constraints on groundwater withdrawals, surface water is subject to substantial evaporative losses (Wurbs and Ayala 2014). Projections of more frequent and extended droughts throughout the state of Texas underscore the need for comprehensive water planning and urban water demand management (Banner et al. 2010).

Given the uncertainties about water availability, reducing waste and promoting conservation in all aspects of urban water use is crucial. Facing a growing water crisis, the California State Legislature has directed urban water suppliers to reduce urban per-capita water use by 20% by 2020, or nearly 2 million acre-feet (Guivetchi and Landis 2013). By comparison, the 2012 Texas Water Plan states that conservation could satisfy nearly 650,000 acre-feet in drought-induced annual water needs by 2060 (TWDB 2012). Although these plans do not indicate how the target reductions will be achieved, the most likely target is residential water use, which represents the largest urban water use category (Kenny et al. 2009).

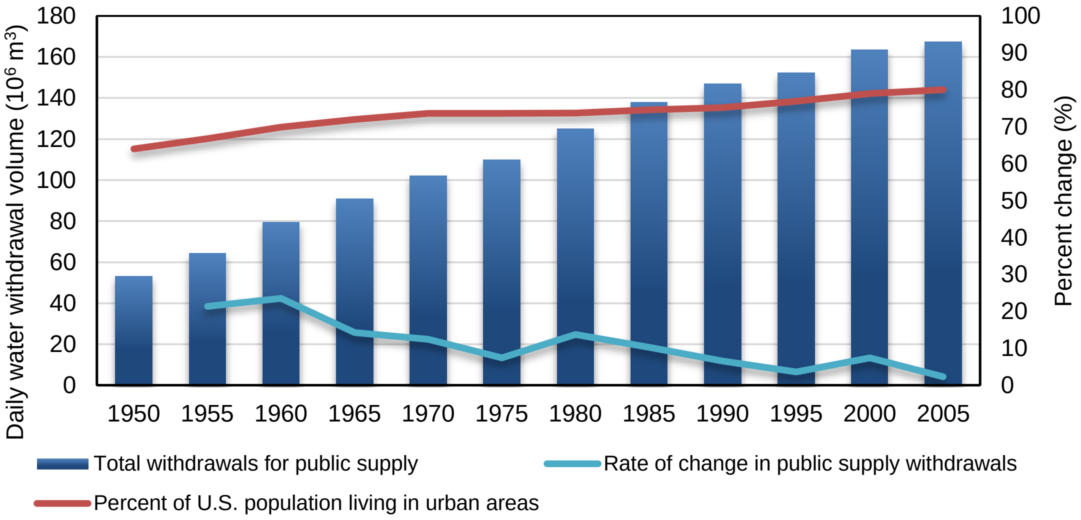

Figure 1. Water withdrawals for public supply since 1950 and their semi-decadal rates of increase versus percent urban population. Sources: (Kenny et al. 2009; U.S. Census Bureau 1995; U.S. Census Bureau 2012)

Demand-side water management offers numerous long-term benefits. Compared to expensive supply-side expansions of water infrastructure, demand-side measures can be implemented at much lower costs. The cost of planning and constructing a reservoir or desalination facility may be prohibitive for smaller cities or water management districts. Whereas supply-side projects may take years or even decades to complete, demand-side programs can be implemented quickly with immediate and sometimes lasting effects. For instance, rebate programs that provide homeowners with water-efficient fixtures have been shown to lead to permanent demand reductions (Price et al. 2014). Urban water demands vary with respect to seasonal temperature changes (Breyer et al. 2012; Halper et al. 2012; Vickers 2001). Typical peak seasonal demands can be reduced through demand-side management strategies, while critically high peaks induced by drought can managed for short periods through restrictions on outdoor water use

(Kenney et al. 2004). Capital projects and new water rights contracts can be delayed by maintaining consumer demands below supply and pumping capacity, and preparing customers for drought (Gleick 2000).

1.1 Urban Water Conservation

Residential water-use efficiency is showing signs of improvement. Rockaway et al. (2010) and DeOreo and Mayer (2012) noted declines in household per capita water use in cities throughout the United States and Canada following the Energy Policy Act of 1992. This has been a crucial development because of long-standing evidence indicating that indoor water use is inelastic (Howe and Linaweaver 1967), meaning that an increase in water price does not proportionately decrease demand (Espey et al. 1997; Klaiber et al. 2014; Rosenberg 2009; Stoker and Rothfeder 2014). The *Residential End Uses of Water* study by Mayer et al. (1999) supported evidence that indoor per capita water use does not greatly vary between households. These reductions in per capita usage have yielded declines in public water supply withdrawals despite continued urban population growth (Figure 1). Continued adoption of water-efficient devices and retrofit of old appliances could sustain the trend in decreasing household water use, particularly if demand-side measures targeting outdoor water use become widespread.

Despite the improvements to water-use efficiency inside the home, single-family residences often use more water around the exterior of the home than indoors. Outdoor water use represents a considerable portion of domestic water demand in many cities, with some homes dedicating up to 70% or more to outdoor uses (USEPA 2013).

Hermitte and Mace (2012) showed that outdoor water use ranges from 13 to 65% of total average household water use by single-family homes in 256 cities throughout the State of Texas.

Seasonal patterns in residential water use are important considerations in water conservation programs because their effectiveness may vary depending on when certain water uses prevail and how sensitive residents are to change. Residential peak water demand is more elastic during the summer than off-peak demand during the winter (Lyman 1992). Numerous studies have shown that outdoor water use is more sensitive to changes in water price than indoor usage (Arbués et al. 2003). Voluntary strategies and temporary restrictions can lower demands (Fielding et al. 2013), but the reductions tend to dissipate over time if the restrictions or conservation programs cease (Kenney et al. 2004). With the exception of price-based approaches (i.e. block rate structures, seasonal pricing, surcharges) (Olmstead and Stavins 2009), demand-management strategies often have limited success unless they can specifically target outdoor uses over extended periods of time. These efforts are further complicated by the diversity of plant species, their water needs, and landscape watering behaviors.

1.2 Residential Lawns and Landscapes

Turf grass lawns are some of the most recognizable features of low-density urban development. Ground cover vegetation provides various functions and benefits, including soil erosion control, dust stabilization, previous area for infiltration, decomposition of organic chemicals, and surface temperature moderation (Beard and

Green 1994; Halper et al. 2012; Shashua-Bar et al. 2009). However, the widespread appeal of lawns has deep societal underpinnings. Some have contended that the desire for social conformity (whether by acceptance, solidarity, or conflict avoidance) may be partly responsible for the association between landscape appearance and home value (Ozan and Alsharif 2013; Robbins 2007).

Turf grass is the most widely irrigated crop in the United States, representing a significant portion of ground cover in urban areas (Claggett et al. 2013; Robbins and Birkenholtz 2003) and an estimated 1.9% of the total surface area in the United States (Milesi et al. 2005). In 2002, the total economic output of the environmental horticulture industry (Green Industry) was estimated to be $147.8 billion, of which $9.7 billion were generated in Texas (Hall et al. 2006). Unprecedented economic growth and new single-family home tracts throughout the state caused the industry to nearly double over the following decade (Palma and Hall 2013). With estimates that the Texas population could exceed 46 million by 2060 (TWDB 2012), the Green Industry may continue to experience considerable growth. Evidence that lawns can tolerate extended drought conditions better under specific management regimes suggests that the lawn aesthetic could persist despite climate change (Trudgill et al. 2010).

Landscape plants require irrigation when soil moisture is inadequate to maintain desired quality and appearance. A typical urban landscape features several varieties of plants with a range of water requirements. The water requirements of landscape plants are the respective quantities, or depths, needed to support growth at a baseline level. Climate variability and desired appearance influence the amount of water required in addition to precipitation. The irrigation water requirement (IR) of a lawn is the amount of water required to produce the desired yield and quality and to maintain an acceptable salt balance at the root zone (NRCS 1997). Soil conditions, fertility, plant type, growth stage, and local climate are all factors that determine a plant's response to irrigation. The quantity and timing of precipitation strongly influences IR. In sub-humid regions, such as East Texas, irrigation may only be required for part of the year since dry periods are short compared to arid and semi-arid regions. Seasonal climate patterns cause residential water demand to increase during the summer because homeowners must account for higher evapotranspiration (ET) rates and lower precipitation (Balling and Gober 2007).

Irrigation is the predominant outdoor water-using activity and represents a substantial portion of domestic water demand. The EPA notes that about half of water used outdoors is wasted from inefficient application (USEPA 2013). A recent study by the Texas Water Resources Institute (TWRI) estimates that landscape irrigation statewide accounts for 46.6% of municipal water use and 12.6% of the total annual water demand (Cabrera et al. 2013). Given the Texas Water Development Board's projections for future water demand (TWDB 2012), as well as estimated economic losses from the recent drought of record (Combs 2012), inefficient irrigation practices could have profound implications for the sustainability of public water supplies. Variations in landscape irrigation in cities can be due to local climate regimes (Breyer et al. 2012), irrigation practices (Mayer et al. 1999), and household demographics (Harlan et al. 2009).

The influence of homeowner associations (HOAs) has been debated (Ozan and Alsharif 2013; Turner and Ibes 2011). HOAs often require households to maintain the quality and appearance of their landscapes through covenants, conditions, and restrictions (CCRs). Although CCRs apply to all households in a HOA neighborhood, regardless of whether their occupants are the actual owners, many other factors may influence conformance to restrictions. Turner and Ibes (2011) found no significant differences in water use between neighborhoods with and without HOAs in Phoenix. However, Ozan and Alsharif (2013) found that communities in Tampa irrigated more during a drought while once-a-week watering restrictions were in place. The geographic and social context of non-adherence to irrigation restrictions may explain why diverse outcomes may be observed under similar circumstances (Turner and Ibes 2011). Regional water availability and drought severity could affect the influence HOAs have on demand.

Although the terms “water use efficiency” and “water conservation” are often used interchangeably in discussions of water management (Vickers 2000), they actually carry different meanings. The U.S. Environmental Protection Agency (EPA) distinguishes between water efficiency (use of improved technologies and practices that deliver equal or better service with less water) and water conservation (curtailment of water use and minimizing waste) (2012). Since plants require a minimum amount of water to prevent wilting, irrigation efficiency can be defined as the reduction of wasteful watering. Efficient landscape irrigation could substantially reduce domestic water demand (Gleick et al. 2003).

Reducing excessive irrigation through non-price measures, such as voluntary restrictions, has been especially challenging. Improper irrigation scheduling (i.e. watering after recent rainfall or certain sections for too long), inadequate distribution uniformity (inadequate overlap of sprinkler radius), and system leakage are all factors that can contribute to overwatering (Vickers 2001). Water audits can help to resolve problems with a sprinkler system, but irrigation scheduling is ultimately the responsibility of the homeowner or landscape manager. Landscape irrigation performance is typically not measured with a quantifiable yield but rather how well it meets the homeowner's expectations (Kjelgren et al. 2000). Preferences regarding landscape appearance (Carrow 2006), and willingness to pay (Hensher et al. 2006), can strongly influence domestic water demand for outdoor use.

The use of improved technology alone does not necessarily lead to more efficient irrigation. In a review of price and non-price conservation studies, Boyer et al. (2014) indicated that proper scheduling and irrigation uniformity yielded between 7 and 53% reductions in water use. Furthermore, homeowners who irrigate using a hose tend to use 33% less water than others who irrigate using automated systems (Mayer et al. 1999). Consequently, technology intended to facilitate landscape irrigation scheduling often lead to higher water consumption due to improper use. Proper knowledge about irrigation scheduling and landscape IRs can help homeowners and commercial landscape managers irrigate more efficiently.

1.3 Landscape Water Budgets

A water budget is an application of the consumptive use equation, which was originally used to compute irrigation requirements for crops (Blaney and Criddle 1962). The two approaches are mathematically similar but differ with respect to dimensionality. By assuming that a plant's water requirement is equivalent to the amount of water it transpires over a fixed period, irrigation requirements can computed by multiplying potential evapotranspiration (ET_o) by a crop coefficient (K_c) and subtracting effective precipitation. This provides an estimate of a plant's water deficit, or required irrigation depth. The quantity can be made more precise by accounting landscape-specific characteristics, such as mixed vegetation and irrigation system design (USEPA 2013). To compute a water budget, the irrigation requirement for a landscape, computed in units of depth (typically inches or millimeters), can be multiplied by an estimate of irrigation area (square feet or square meters) to obtain volumetric units (gallons or cubic meters). The precision of a water budget depends on how precisely landscape area can be computed.

Water budgets are versatile tools in water management and widely applicable because they can be developed using data available in most cities. White et al. (2004) used living area from county appraisal records and locally-recorded ET and P estimate plant water deficit. In their water budget approach, coefficients were applied universally to estimate landscape area and plant evapotranspiration. Research has indicated that the approach used to develop water budgets can be useful for assessing conservation potential of households (White et al. 2004), as well as developing conservation-based pricing structures (Hildebrand et al. 2009; Mayer 2009). Others have proposed that cities can reduce water waste by furnishing water budgets to residents in the form of letters with budget tables or charts (Kenney et al. 2004; St. Hilaire et al. 2008; White et al. 2004). Interactive web water budget tools can be instrumental towards helping residents, developers, and landscape professionals determine the water needs for any landscape given climate data, information about plant types or landscape features, and the application efficiency of irrigation water (Al-Kofahi et al. 2012; Dobbs et al. 2013; USEPA 2013).

Numerous methodologies developed and improved the consumptive use equation have made possible the construction of water budgets that more accurately reflect the water needs of urban landscape vegetation. Use of a crop coefficient (k_c) provides an approximation of the water requirement for a single plant species (Carrow 1995; Pannkuk et al. 2010). However, urban landscapes are generally composed of a mixture of trees, shrubs, and turf grasses. More accurate estimates of irrigation requirements can be obtained by accounting for heterogeneous landscapes, vegetation density, microclimate conditions, and water application efficiency (Costello and Jones 2000; Nouri et al. 2013). This typically involves the substitution of k_c with landscape coefficient (k_L). Nouri et al. (2013) compared estimates several practical approaches to estimating k_L, including the Water Use Classification of Landscape Species (WUCOLS), plant factor (PF), and Irrigated Public Open Space (IPOS). They concluded that the WUCOLS method produced the best approximation of urban vegetation water requirements. Adjustment factors can be computed with additional levels of complexity while accounting for non-uniformities in landscape water application. Remote sensing techniques have also been used to develop adjustment factors based on features found on individual landscapes (Farag et al. 2011; Johnson and Belitz 2012).

Computing landscape irrigation requirements (or irrigation rate) in volumetric units requires irrigated land area. This can be measured or estimated using aerial imagery or derived from property appraisal data. Digital surveys using high-resolution aerial images or ground measurements can be useful for computing water budgets for a small number of lots (Salvador et al. 2011). Remote sensing and GIS can provide robust estimates of pervious area for large numbers of lots (Farag et al. 2011; Wolf and Hof 2012; Xie 2009). Estimates of pervious area can also be derived indirectly as the difference between total lot area and impervious area. Building area and living area (also called interior floor space or heated/cooled area) can be applied as surrogates but require assumptions about other impervious features, such as driveways, paved footpaths, and decks (Robbins and Birkenholtz 2003; Romero and Dukes 2013; Romero and Dukes 2011).

Various methods of indirectly estimating pervious area using as have been applied in studies of urban residential water use. The approach used by White et al. (2004) estimated landscape area for each lot as the difference between total area and 1.5 times heated/cooled living area, or interior floor space. Robbins and Birkenholtz (2003) estimated building footprint, or impervious area, by dividing living area by the number of floor of floors. Other studies attempted to estimate non-building impervious area to yield closer approximations of landscape area, calculating the different between total lot area and the sum of building area and a percentage of lot area (to account for driveways, sidewalks, etc.) (Mayer et al. 1999; Romero and Dukes 2013). Research indicates that there is a lack of information concerning the accuracy of these approaches (Claggett et al. 2013; Robbins and Birkenholtz 2003; Romero and Dukes 2013). Improving estimates of water budgets or residential irrigation rates can provide a better understanding of how much water is wasted in urban areas.

There is limited information about irrigation performance between single-family residential (SFR) lots relative to landscape water budgets or irrigation requirements. A comparison of the number of customers who over-irrigate with those who under-irrigate reveals how extensive excess irrigation might be (Romero and Dukes 2013; Romero and Dukes 2011), but not how intensive. Salvador et al. (2011) computed the quantities of water applied to landscapes relative to IRs, but did not analyze how these results compared to the actual quantity of water used. The capacity to conduct research on irrigation performance is limited by precision of data pertaining to water consumption, irrigated landscape area, plant water needs, rainfall, climate, and irrigation system operation and performance (Gleick et al. 2003).A better understanding of the relationship between irrigation performance and property characteristics could help water utilities to more effectively address wasteful water use.

1.4 Research Objectives

Efficiency standards and new technologies have been instrumental towards reducing indoor water consumption. However, promoting conservation or efficiency in outdoor water use has been considerably more challenging since outdoor activities are driven by homeowner preferences rather than human needs (Kjelgren et al. 2000; Syme et al. 2004). Addressing wasteful water use is an important goal in urban water management urban irrigation is the largest domestic water use category for many households. Irrigating no more than what is needed can conserve substantial quantities of water (Kjelgren et al. 2000; White et al. 2004).

Assessing irrigation performance is important for qualifying and understanding where overwatering might be a problem. Overwatering can be defined as applying more water to a landscape than what is theoretically necessary to maintain healthy plants. Since numerous factors can lead households to apply more water to landscapes than necessary, it is crucial to distinguish between infrequent and frequent overwatering. It is important to differentiate overwatering in terms of quantity. It may not be worth addressing small volumes exceeding the water budget compared to large volumes. This study will help to understand what constitutes frequent overwatering behavior and problematic overwatering.

The purpose of this study was to investigate irrigation performance for a major water users in College Station using a water budget approach. Performance was assessed at the residential lot level based on conformity with estimated irrigation requirements. This is accomplished through the following four objectives:

1. Developing a method for determining pervious area based on property data from county appraisal district records and geographic information systems (GIS),

2. Calculating water budgets and comparing with estimated outdoor use,
3. Assessing the extent of conformity with budgets, and
4. Determining if there are differences in conformity with irrigation requirements based on lot size.

Methodologies pertaining to the four objectives of this study are addressed in Section 3, with each of the major headings corresponding to an objective. Table 1 provides definitions for key terms discussed throughout the study.

Table 1. Summary of key terminology for this this study.

Term	Definition	
Water Budget	Estimated quantity of water required to support normal plant growth based on rainfall and evapotranspiration over a given period	
Irrigation performance	How well irrigation behavior conforms with a water budget based on the following indicators:	
	• Overwatering frequency	How often a household exceeds its landscape water budget
	• Volume over budget	How much water is applied in excess of the landscape water budget
	• Volume over budget per unit area	Uniform comparison of how much water is applied based on landscape area
Irrigation efficiency	Application of a volume of water less than the landscape water budget or proximity to the water budget if it is exceeded	
Net irrigation	Difference in aggregate water consumption and aggregate water budget for all households in the study	
Gross excess irrigation	Aggregate of irrigation exceeding the water budget for all households in the study	

2. STUDY AREA

The city of College Station, located Central Texas, has an area of 49.6 mi^2 (128.5 km^2) and a population of approximately 100,000 (U.S. Census Bureau 2012). The local climate is humid, infratemperate (Cress and Sayre 2009), characterized by mild winters and warm, hot summers. Daily high temperatures range from 61°F in January to 96.2°F in August. Based on 47 years of data recorded by the Texas ET Network, precipitation and evapotranspiration in College Station have annual means of 40 inches and 56 inches, respectively. Monthly average rainfall is highest in October, followed by May and June. July and August typically have the lowest precipitation.

Between 2008 and 2013, College Station Utilities Water Services reported the total annual residential water use to be between 2.85 and 3.4 billion gallons, or 63-67% of the flows from the city's pumping station (Figure 2). Although these quantities were well below the permitted annual limit of 25,000 acre-feet (8.14 billion gallons), record drought conditions drove peak demands to their highest levels in the city's history in August 2011. Demand patterns suggest that outdoor water use, particularly landscape irrigation, is a major contributing factor. About 60% of the city's residential water use occurs between April and September, coinciding with the growing season for warm season cool grasses common to this region of the United States (Figure 3). Peak residential water use typically occurs in August and is more than double the total use in January, when water use is lowest. Due to gradual demand growth, the Water Services division of College Station Utilities projected that peak demands could exceed production capacity by 2025 without tighter conservation measures.

In response to severe drought, forecasted infrastructural limitations, and conservation requirements mandated by the Texas Commission on Environmental Quality, College Station has instituted several measures to mitigate the risk of emergency shortages. In 2008, the first residential block rate structure was implemented with 5 tiers. Additional programs have since been implemented to encourage customers to conserve, including rebates for high-efficiency toilets and rainwater harvesting barrels, as well as free irrigation system audits.

In efforts to reduce water waste, College Station Utilities Water Services has collaborated with the Urban Water Conservation Research Group at Texas A&M University to furnish landscape water budgets to the major water users throughout the city. A total of 5,565 single-family households located in 15 neighborhoods (Figure 4) were identified based on total water consumption greater than 100,000 gallons during the peak growth period for warm season turf grasses (April through September). Water consumption by these households represents about 30% of citywide residential demand and is predominantly driven by landscape irrigation. As of 2014, the city has prohibited residential use of automatic in-ground or hose-end sprinkler systems between 10am and 6pm (City of College Station 2014). Voluntary water conservation guidelines have also been established to encourage customers to limit non-essential water uses during the peak season (May 1st to September 30th). These measures, in addition to the block rate structure, may lead to lower water use in years to come.

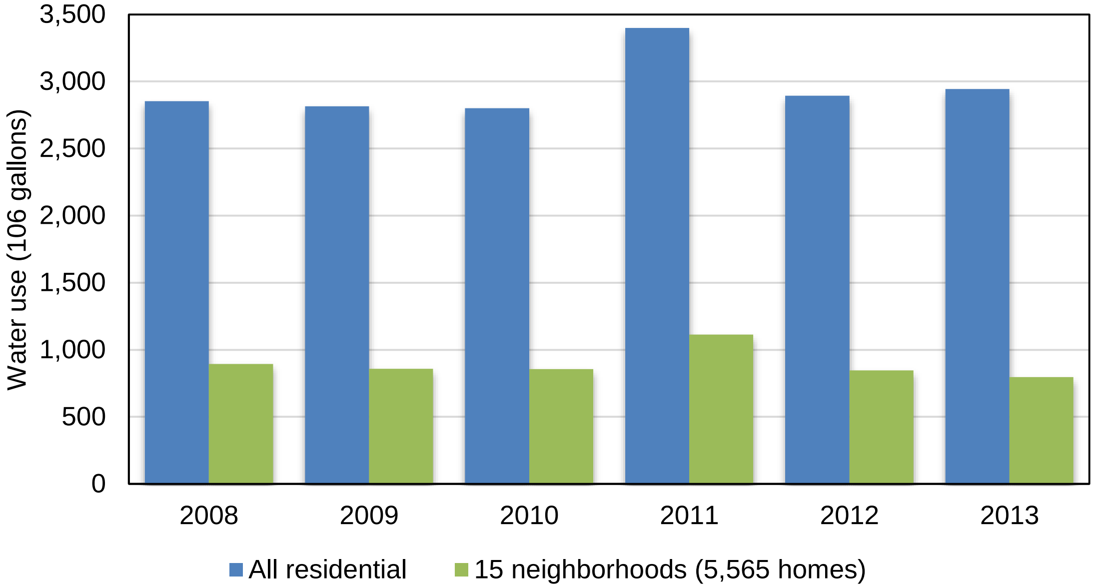

Figure 2. Comparison of aggregate water use by the 5,565 households with citywide residential water use

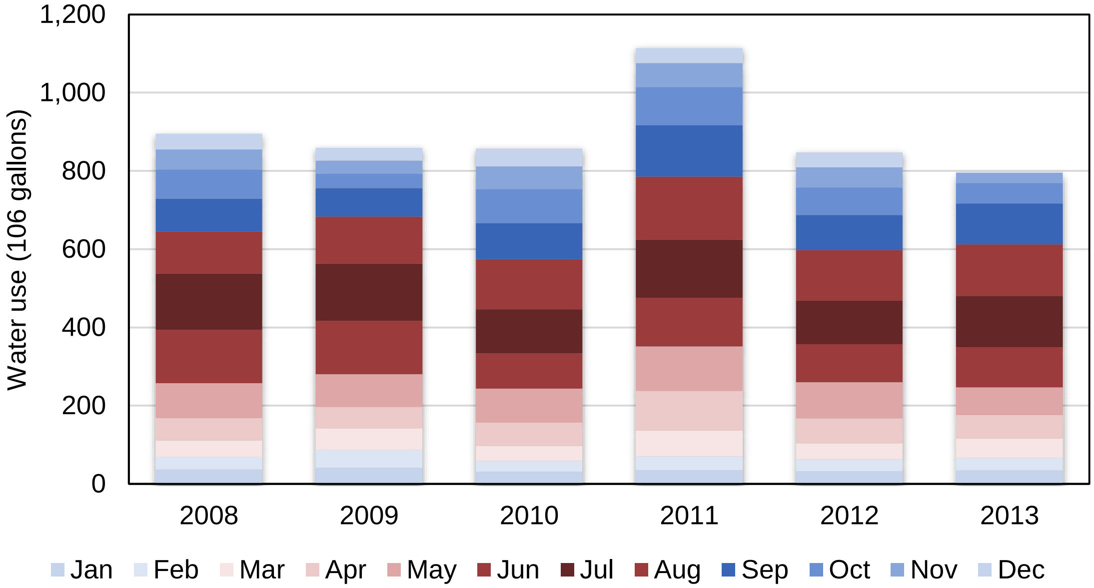

Figure 3. Annual aggregate water use (colored by month) for the study households

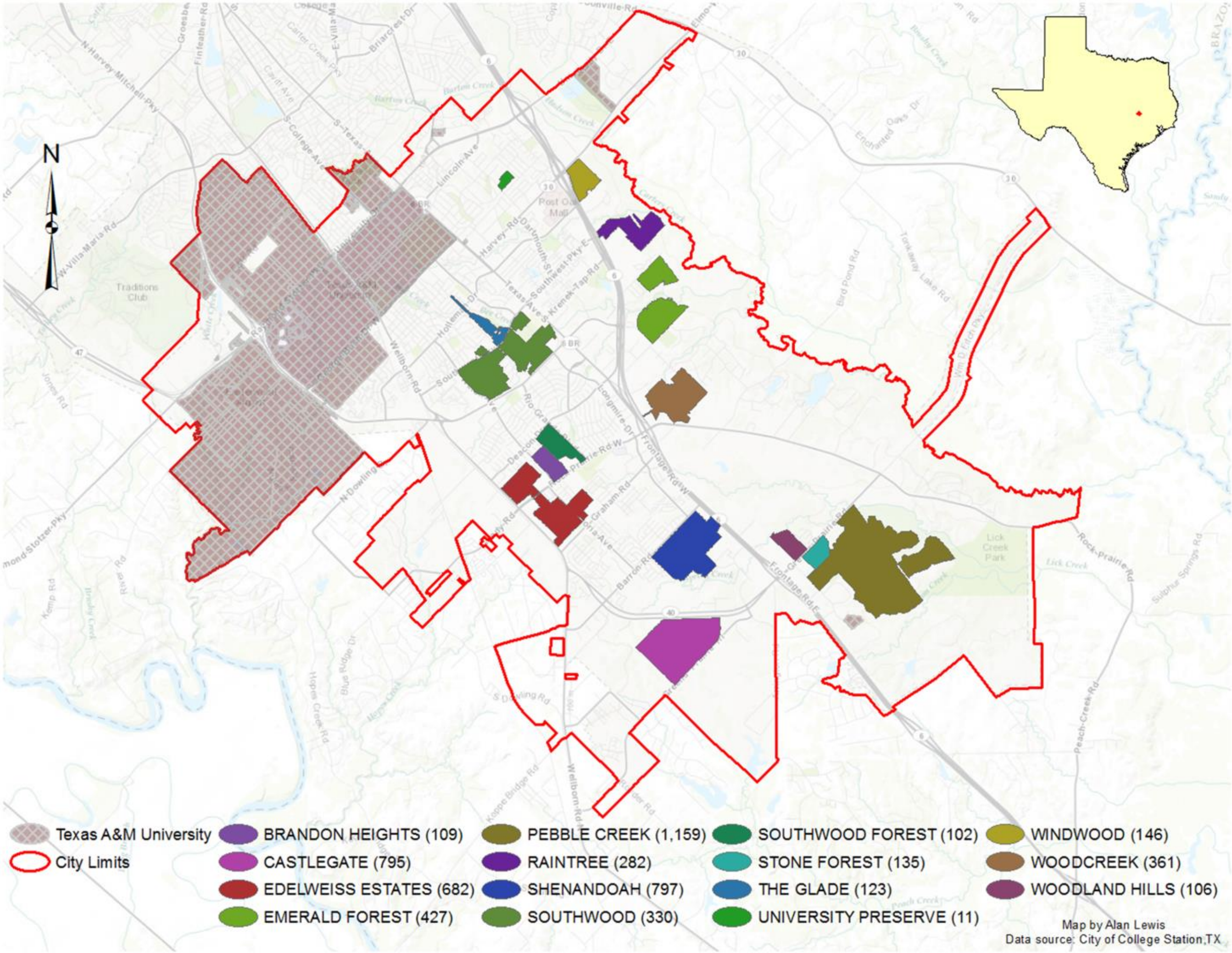

Figure 4. College Station neighborhoods and the number of SFR lots selected for study of irrigation performance

3. METHODS

3.1 Determining Irrigable Landscape Area

Computing a residential water budget requires a measurement of irrigated area on a property. This can be accomplished by (1) on-site lot measurement, (2) estimating area from property tax appraisal records, or (3) digital surveys using high-resolution aerial images. On-site measurements is the most accurate approach for estimating irrigated area. However, it is economically impractical for a large number of lots (Salvador et al. 2011). Alternative approaches cannot determine irrigated area directly and thus rely on assumptions about the layout. Since irrigated area cannot be measured, irrigable area is estimated instead based on pervious area. Irrigable landscape area can be assumed equivalent to pervious area a fraction thereof.

A second approach is to use property appraisal data to estimate irrigable area. Impervious area comprises the footprint of the home and exterior structures, driveways, decks, sidewalks, and even footpaths and swimming pools. Several studies estimated non-building impervious area to yield closer approximations of landscape area, calculating the difference between total lot area and the sum of building area and a percentage of lot area (to account for driveways, sidewalks, etc.) (Mayer et al. 1999; Romero and Dukes 2013). In these studies, pervious area was assumed inversely proportional to impervious area, permitting estimation of pervious area as the difference between total lot area and impervious area. However, this approach is nuanced by the variability of SFR lot size and layout. The approach used by White et al. (2004)

estimated landscape area for each lot as the difference between total area and 1.5 times heated/cooled living area, or interior floor space. Robbins and Birkenholtz (2003) estimated building footprint, or impervious area, by dividing living area by the number of floor of floors.

A third approach is to use remote sensing and GIS can provide robust estimates of pervious area for large numbers of lots. Estimates of pervious area can be derived directly using spectral signatures of ground surface classes. Normalized Difference Vegetation Index (NDVI) has also been used to estimate irrigated area (Farag et al. 2011; Wolf and Hof 2012; Xie 2009). Pervious area can also be estimated indirectly using GIS data in a manner similar to the approach using county appraisal data. Building area and living area (also called interior floor space or heated/cooled area) can be applied as surrogates but require assumptions about the prominence of impervious features, such as driveways, paved footpaths, and decks (Robbins and Birkenholtz 2003; Romero and Dukes 2013; Romero and Dukes 2011).

The first objective of this study was to show that it is possible to infer pervious area from property tax appraisal data and develop a new approach for estimating landscape area. Living area has been used as a surrogate for impervious area. Property appraisal records obtained from the Brazos Central Appraisal District provided total lot size and the living area (heated/cooled interior space) for residences. These lots were then compared with GIS images to derive pervious area measurement. In 2005, the Geographic Information Services Department contracted with GIS Landmark, LLC to acquire planimetric data for all existing lots and right of way using orthorectified aerial photography with 1-ft spatial resolution. The final product included highly accurate delineations for all buildings, driveways, and sidewalks (Figure 5).

Pervious and impervious areas were determined for each lot by using planimetric mapping data furnished by the City of College Station. Features missing from the dataset, which included all developments after 2005, were hand-delineated using aerial imagery with 6-inch resolution from the Texas Natural Resources Information System. Citywide, a total of 10,851 SFR lots were identified containing nonzero impervious area. This sample included the 5,565 SFR lots from the 15 neighborhoods identified in Figure 4. To minimize errors caused by buildings and driveways found to cross lot boundaries, polygon features were converted to points and joined by lot.

Pervious area was computed by taking the difference between lot area and the sum of building footprint area and driveway area. These values were then compared with Brazos Central Appraisal District property data to develop a table of coefficients for determining pervious area based on ranges of lot area and living area. The average fraction of pervious area was computed for each range of lot area and living area. The accuracy of pervious area computed using tabular approach was examined by determining the extent to which pervious area estimates computed using the coefficients differed from to actual values derived from College Station GIS data.

Figure 5. Close-up of GIS layers indicating delineations of lot boundaries, structures, and driveways.

3.2 Estimating Water Budgets and Outdoor Water Use

Once the irrigation area for each lot was determined, monthly irrigation budgets could be computed based on a plant water balance. For each of 5,565 lots from the neighborhoods shown in Figure 4, irrigable area was assumed to be equivalent to pervious area computed in the first objective. Furthermore turf grass was assumed to comprise irrigable landscape area entirely. This was considered reasonable since warm season turf grasses are commonly found on SFR lots throughout the southeast and Gulf Coast regions of the United States. Additionally, obtaining information about specific plant varieties found on each lot was beyond the scope of this study. System moisture inputs included precipitation and irrigation while the output was crop evapotranspiration. St. Augustine grass, which has a relatively high water requirements relative to other species of turf, was taken to be a conservative estimate of minimum irrigation requirements for single-family residential landscapes.

Estimated irrigation requirement was computed from the moisture deficit, or the difference between crop evapotranspiration (ET_c) and precipitation (P). Modified evapotranspiration was computed using the crop coefficient (k_c) for St. Augustine grass. It was not necessary to consider moisture retention or abstractions since the k_c incorporates the mean effects of soil evaporation and crop transpiration (Allen et al. 1998). Average monthly ET_o was computed as the average of daily values multiplied by the number of days in the month. Monthly P was computed as the sum of daily totals. Using irrigable area estimated previously and converting to volumetric units, the monthly irrigation requirement for each lot was computed

$$Q_{IR}(t) = cA_{irr}(k_c ET_o(t) - P(t)) \tag{1}$$

where,

Q_{IR} is the water budget volume for month t (gallons),

c is a conversion factor to volumetric units (7.48 gal/ft^3),

A_{irr} is the irrigable landscape area (ft^2),

k_c is the crop coefficient for St. Augustine grass (0.65).

ET_o is the average monthly potential evapotranspiration (in), and

P is the cumulative monthly precipitation (in)

Weather data recorded by the Texas ET Network were obtained in daily format for the period January 1, 2008 to November 31, 2013. The dataset included precipitation (P), reference evapotranspiration (ET_o), maximum and minimum temperature, relative humidity, solar irradiance, and instantaneous wind speed (4am and 4pm). Reference evapotranspiration was calculated using the standardized Penman-Monteith equation (Allen et al. 1998). The station located at the TAMU Golf Course provided the closest available estimate of weather conditions. Between January 10, 2013 and June 28, 2013 station was taken offline while the golf course underwent renovation. The missing range was substituted with data from the TAMU Turf Lab, located about 2 miles away. Another 33 nonconsecutive days for the TAMU Golf Course station found to have missing data. These were substituted by the average of values from years in which data was available. According to differences in ET and P summarized in Table 2, the years 2009 and 2011 featured the wettest and driest conditions, respectively.

Table 2. Annual averages of meteorological data for study period (2008-2013)

Meteorological parameters	Units	2008	2009	2010	2011	2012	2013
Annual reference ET	in	54.0	53.0	52.4	61.8	54.8	58.5
Annual precipitation	in	27.0	37.9	27.2	17.5	38.6	42.0
Maximum temperature	°C	79.4	78.1	77.3	80.8	80.2	77.9
Minimum temperature	°C	59.4	59.2	58.5	60.1	61.2	58.9
Average relative humidity	%	39.6	41.9	40.7	34.5	43.3	43.9
Average solar radiation	$MJ/m^2 \cdot day$	16.2	14.5	15.2	16.0	16.3	16.1
U_{10} wind speed at 4pm	mph	4.5	4.3	4.5	4.9	4.3	5.8
U_{10} wind speed at 4am	mph	2.0	2.2	2.0	2.1	2.0	3.4

Monthly water billing data for residential customers was provided by College Station Utilities for the period January 1, 2008 to November 31, 2013. The original files, separated by year, contained records for around 21,109 residential customers. Fields in the dataset providing consumption in thousands of gallons, read date, and unique location and property identification numbers corresponding to each address. A sample of 5,565 single-family residential (SFR) lots was chosen with complete data from 2008 to 2013. A summary of the data used in this study can be found in Table 3.

Table 3. Summary data sources for variables explored in this study

Category	Variable	Definition	Units	Source
Water Usage	Monthly Consumption	Total water use per household	1,000 gal/month	CS Utilities – Water Services
Climate	Evapotranspiration	Cumulative daily evapotranspiration	in/day	Texas ET Network
	Precipitation	Cumulative daily precipitation	in/day	Texas ET Network
Property	Lot Area	Appraised area of residential lot	ft^2	BCAD
	Living Area	Appraised area of heated/cooled interior space	ft^2	BCAD

Residential water use on SFR lots can be disaggregated into indoor and outdoor components. Since indoor consumption is not subject to seasonal variation (DeOreo 2011), outdoor use can be computed as the residual of total consumption and indoor use. Depending on regional climate, household demographics, and water availability, some methodologies may provide better estimates of indoor use. The minimum month has been applied in regions with mild winters (such as California and Florida) where outdoor water consumption can potentially occur year-round (Romero and Dukes 2013). White et al. (2004) used the average winter consumption (AWC) method to estimate indoor consumption for households in College Station. This method has been shown to yield better approximation of indoor water demand in regions with well-defined winters, characterized cold weather and increased precipitation (DeOreo and Mayer 2012). Additionally, this method corrects for possible winter months in which no consumption occurred.

Household water consumption was shown to be lowest between November and February. The AWC was computed for each household as the average of three of the four months between November and February with the lowest consumption. Outdoor water use Q was then computed for each month by subtracting the AWC corresponding to the preceding winter. Outdoor consumption was assumed to be zero wherever computations produced negative values. Although 700 swimming pools were identified in the dataset, we assumed that landscape irrigation comprised all outdoor use.

Utility providers calculate water use as the difference between the current and prior meter readings and bill for the month the meter is read. This method, while expedient for billing purposes, presents certain analytical problems. Billing cycles typically do not coincide with the first day of each the month, reflecting consumption that occurred during different months. Additionally, the number of days in a billing cycle may vary for different neighborhoods yielding disproportionate consumption totals relative to the number of days in a calendar month. For example, if consumption is recorded on the 25th of May and corresponds to the 25th of April month, then 5 days of water consumption billed for May actually occurred in April. Likewise, 6 days of consumption billed in June would have occurred in the month of May. Water meter readings for the College Station water use dataset occurred on cycles of 26-32 days, but at times yielded multiple readings in a single month or duplicate zero readings. Explaining climate-driven consumption may be difficult on monthly or shorter time scales without proper alignment of water consumption and climate data.

An algorithm was developed to realign residential consumption data with the proper month according to the meter read date. Monthly consumption values were realized sequentially by applying one portion corresponding to the present month and another portion to the month prior. Read dates were converted to percentages based on the number of days in the month and/or since the prior reading. This procedure yielded one consumption value per month. Water consumption was shifted to earlier times in the series and based on proportionate amounts of time between each reading and the months on which they fell.

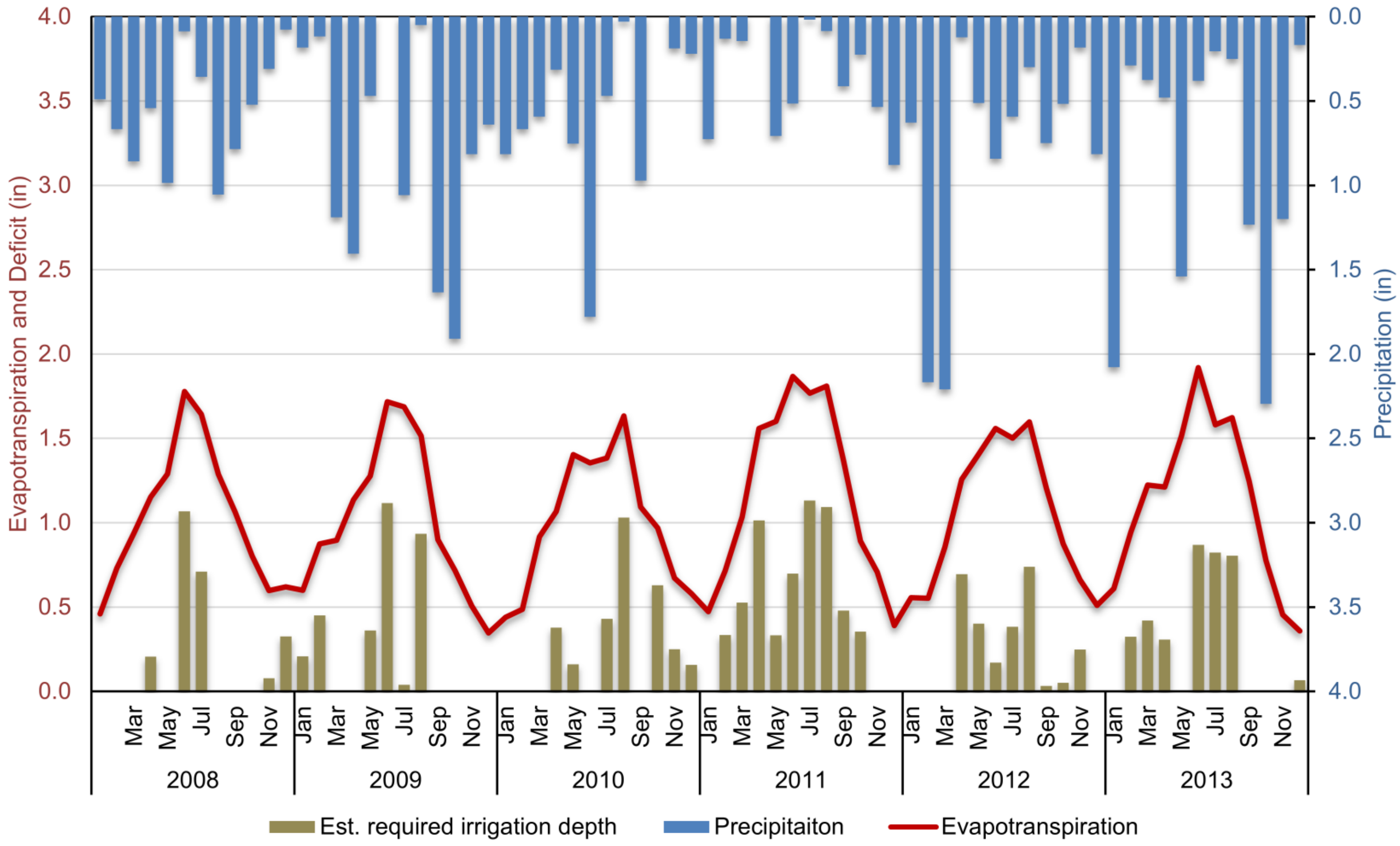

Figure 6. Time series plot of monthly meteorological parameters, with precipitation on the inverse vertical axis and evapotranspiration and estimated irrigation requirement for St. Augustine grass on the left vertical axis

3.3 Conformity with Water Budgets

Applying less than the monthly requirement can be assumed to be efficient since it does not waste water. Excess irrigation was therefore defined as the quantity of water applied to a landscape greater than the monthly water budget (Q_{WB}). Since warm season turf grasses experience the most active growth during the summer but become effectively dormant during the winter (Agriculture and Natural Resources 2014), we focused only on irrigation during the growing season (April—September). Monthly quantities less than Q_{WB} indicated when households irrigated efficiently and were assigned a value of zero. Figure 7 summarizes monthly household use and irrigation.

$$Q_E(t) = \begin{cases} Q(t) - Q_{WB}(t) & \text{if Q} > Q_{WB} \\ 0 & \text{if } Q \leq Q_{WB} \end{cases} \tag{2}$$

Irrigation performance was assessed using three metrics of overwatering computed for each lot: (1) overwatering frequency, or how often that a residence exceeded its water budget; (2) total volume; and (3) volume per square foot of irrigable area. Overwatering frequency (N_{over}) is the total number of times per growing season that that a residence over-irrigated. A binary variable N was developed to count each time a residence's irrigation exceeded Q_{WB} and was assigned a value of 1 if monthly Q exceeded Q_{WB} and 0 if otherwise:

$$N_{over} = \sum_{i=1}^{6} N_i \tag{3}$$

For any given year, N_{over} ranged from 0 to 6. Total volume of excess irrigation that occurred during the growing season was computed as the sum. Excess irrigation volume was computed as the sum of each month i (April—September):

$$Q_{E,total} = \sum_{i=1}^{6} Q_{E,i} \tag{4}$$

Finally, excess volume per unit of irrigable area $\hat{Q}_{E,total}$ was used as a uniform comparison of excess irrigation based on lawn size. Unit excess volume quantity was computed by dividing $Q_{E,total}$ by A_{irr} for each lot to produce a normalized quantity in units of gallons per square feet:

$$\hat{Q}_{E,total} = \frac{Q_{E,total}}{A_{irr}} \tag{5}$$

3.4 Conformity with Budget Based on Size of Irrigation Area

A multiple regression analysis was used examine the relationship between irrigable area and each of the irrigation performance measures. Irrigation performance was qualitatively analyzed through separate treatments based on ranges of estimated irrigable area. Percentiles of irrigable area for the 5,565 lots were used as a guide for arranging households by category. The data was divided into seven categories, as shown in Figure 8.

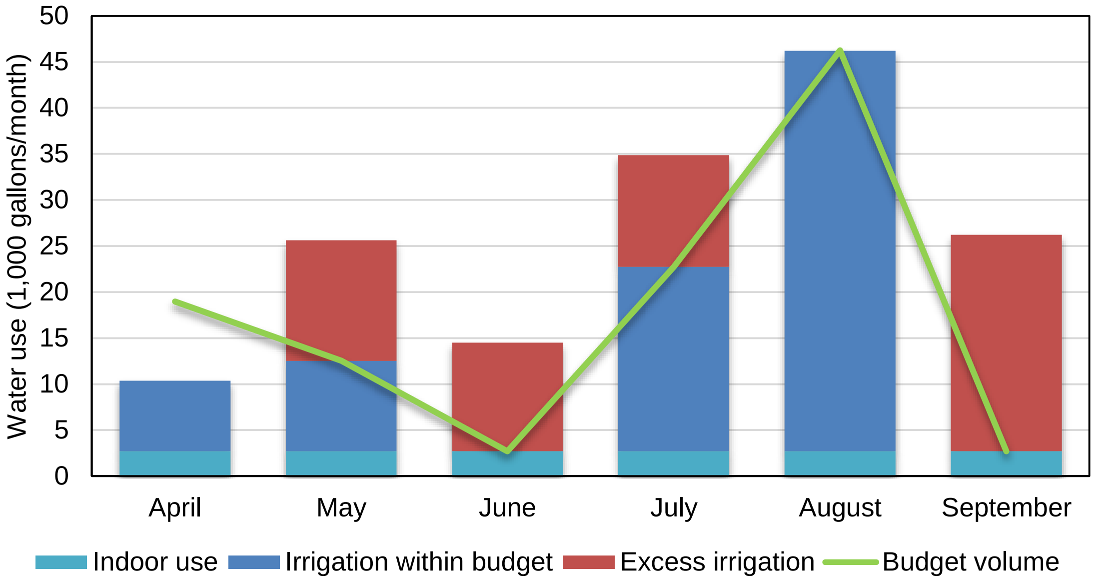

Figure 7. Example comparison of a household's water consumption (blue) versus their landscape water budget (black), with months of nonconformity indicated by excess irrigation (red)

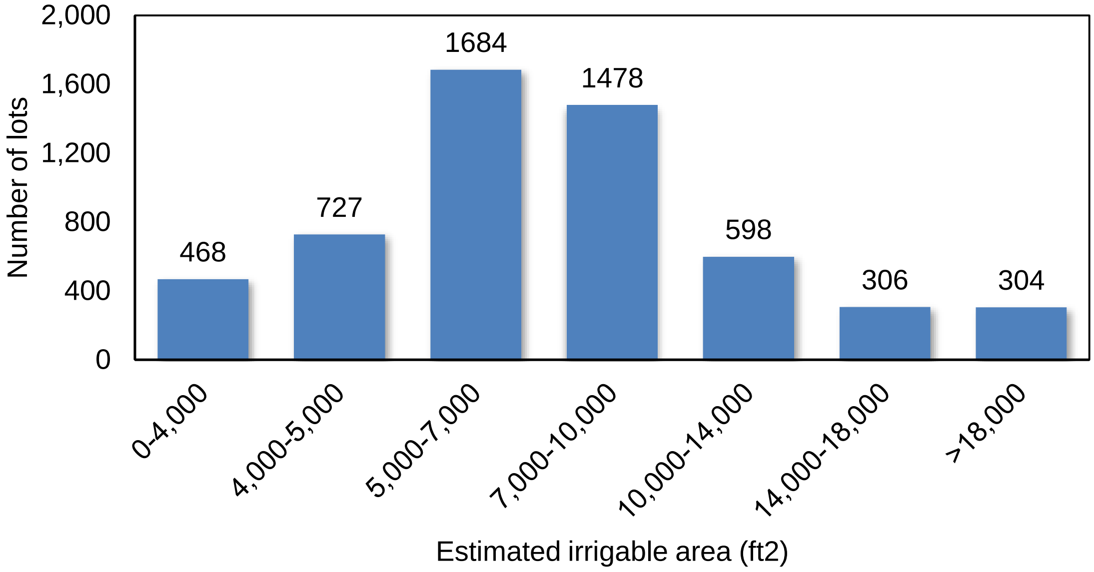

Figure 8. Histogram indicating number of lots within each range of irrigable area.

For the purposes of the regression analysis, the categories shown in Figure 8 were defined (in order from left to right) as exceptionally small, very small, small, medium, large, very large, and exceptionally large. Exceptionally small lawns were treated as the intercept and while the six remaining ranges were treated as regressors. Dummy variables were assigned to each of the six treatments. The multiannual averages for each of the three variables defined in the third objective of this study were computed and used in to assess differences in irrigation performance with respect to lot size. An error term ε_i was included to account for unobserved factors occurring at the lot-level.

$$\begin{Bmatrix} \bar{Q}_{E,total} \\ \hat{Q}_{E,total} \\ \bar{N}_{total} \end{Bmatrix}_i = \beta_0 + \beta_1 VSL_i + \beta_2 SL_i + \beta_3 MED_i + \beta_4 LG_i + \beta_5 VLG_i + \beta_6 XLG_i + \varepsilon_i \quad (6)$$

4. RESULTS AND DISCUSSION

4.1 Pervious Area and Coefficient Analysis

The first objective of this study was to develop a method for more accurately estimating pervious area on single-family residential (SFR) lots. While SFR lot layout widely varies we hypothesize that it is possible to infer pervious area using living area as a surrogate for impervious area. Multiple regression analysis revealed that pervious area computed using the GIS-aided approach (from building and driveway area) was strongly predicted by both lot area and living area (Adjusted $R^2 = 0.99$). Regression variable coefficients for both lot area and living area were significant, with *t*-statistic values of 962.06 and -117.12, respectively ($p < 0.001$) (see Appendix). This indicating that property appraisal data could be used as a surrogate for impervious area while estimating pervious area.

By assuming that pervious area is proportional to lot size, it is possible to directly estimate pervious area. In previous methodologies, pervious area was computed indirectly using a two-step approach whereby impervious area was first estimated then subtracted from total lot area. Here, the sum of building and driveway area was assumed to comprise nearly all of the impervious area on an SFR lot. Figure 9 indicates that the fraction of a lot that is pervious has a strong dependence on pervious area ($r^2 = 0.625$). Pervious area can be estimated by directly multiplying lot area by the fraction of pervious area ($F_{pervious}$) to quickly and accurately estimate pervious area. These values can be multiplied by lot area to compute pervious area.

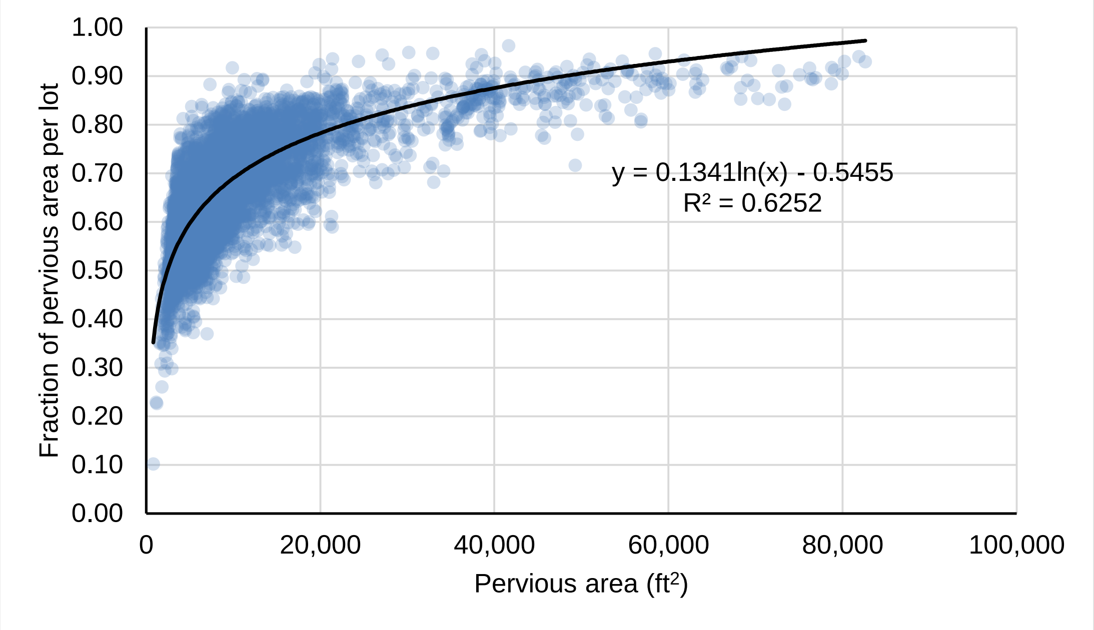

Figure 9. Pervious area computed using GIS-aided approach versus percentage pervious area per lot

It is important to compare how accurately living area can be used to predict pervious area versus building area and driveway area. Ordinary least squares (OLS) regression analyses were used to assess the compare the predictive power of the impervious factors (living area versus driveway building area). The trend shown in Figure 9 suggests a logarithmic trend between $F_{pervious}$ and the area variables. OLS regressions were performed for the common logarithm of total lot area and the impervious factors. Multiple regression analysis shows that $F_{pervious}$ is strongly predicted by lot area, building area, and driveway area (Adjusted $R^2 = 0.923$). Repeating the regression, but substituting building and driveway area with living area from the Brazos Central Appraisal District dataset, also showed a strong positive relationship (Adjusted $R^2 = 0.677$). In each of the regression analyses, variable coefficients were found to be significant (see Appendix). These findings indicate that it is possible to determine pervious area for SFR lots from area and living area. Values of $F_{pervious}$ can be adapted into coefficients.

A table of coefficients was developed to quickly estimate pervious area on SFR lots using lot area and living area. Analysis of the distribution of lot area and living area for the 10,851 SFR lots revealed five distinct ranges percentiles. Both distributions exhibited positive skew due to large numbers of outliers. The smallest and largest ranges were further separated with pervious to produce 10 ranges of lot size and 9 ranges of living area (Figure 10 and Figure 11). Average $F_{pervious}$ was computed for each of the ranges of lot area and living area to yield the coefficients found in Table 4. An OLS regression analysis of the coefficients showed that the table coefficients strongly determine pervious area (Adjusted $R^2 = 0.625$). The mean difference between pervious area computed using the GIS-aided approach and the table coefficients was 16.4 ft^2 with a standard deviation of 786 ft^2. This result was determined to be significant ($p = 0.03$) using a paired t-test. The coefficient table offers potential in terms of accuracy and ease in computing pervious area.

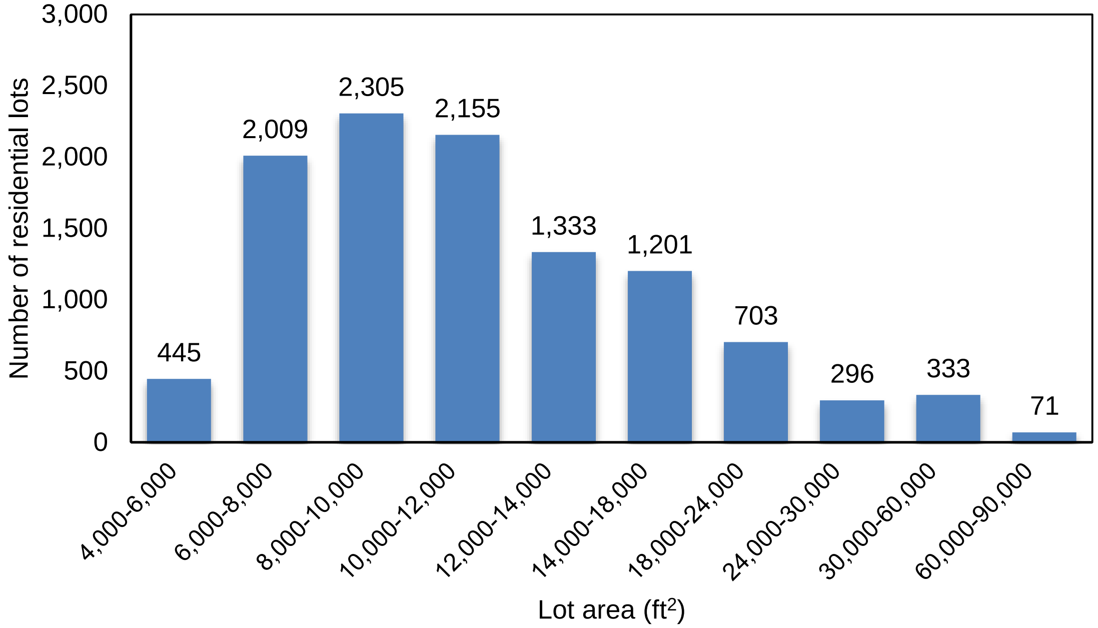

Figure 10. Histogram of ranges of lot area for the 10,851 SFR lots

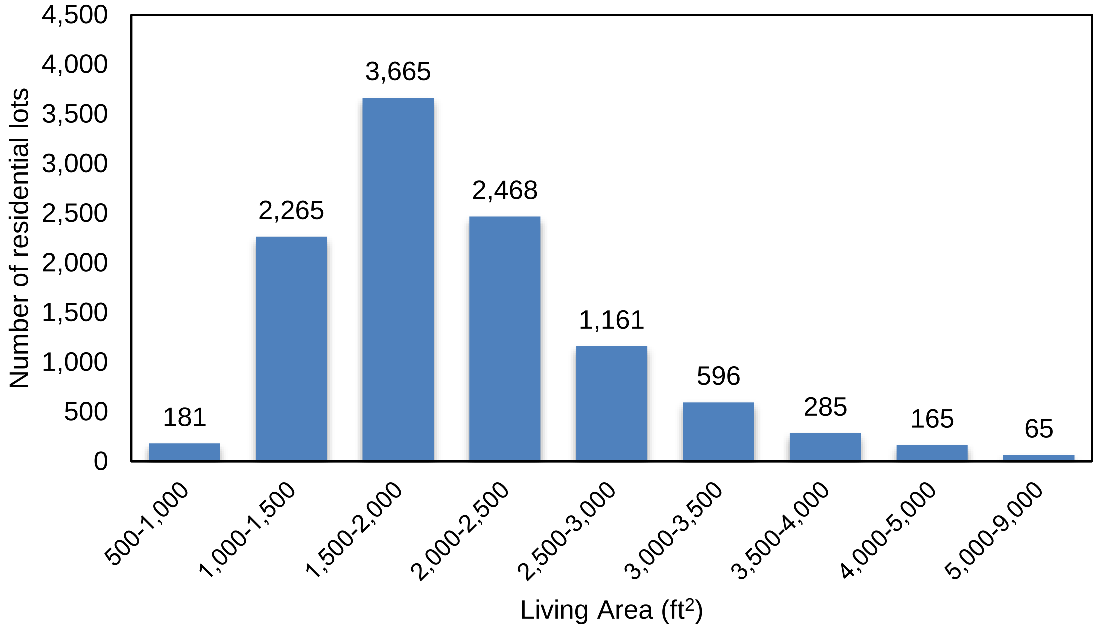

Figure 11. Histogram of ranges of living area for the 10,851 SFR lots

Table 4. Table of bivariate coefficients that can be multiplied by lot area to produce more precise estimates of pervious area on a single-family residential lots (color ranges from green to red to indicate properties that have more pervious area)

		Lot Area (ft^2)									
		4,000-6,000	6,000-8,000	8,000-10,000	10,000-12,000	12,000-14,000	14,000-18,000	18,000-24,000	24,000-30,000	30,000-60,000	60,000-90,000
Living Area *(Heating and Cooling)* **(ft^2)**	500-1,000	0.66	0.69	0.77	0.82	0.84	0.88	0.88	0.94	0.95	
	1,000-1,500	0.55	0.60	0.66	0.72	0.75	0.78	0.84	0.86	0.92	0.92
	1,500-2,000	0.50	0.56	0.62	0.67	0.71	0.76	0.80	0.84	0.87	0.90
	2,000-2,500	0.53	0.53	0.57	0.61	0.65	0.70	0.76	0.81	0.86	0.90
	2,500-3,000	0.50	0.54	0.57	0.58	0.60	0.66	0.73	0.77	0.84	0.89
	3,000-3,500		0.52	0.53	0.55	0.58	0.61	0.70	0.75	0.83	0.89
	3,500-4,000			0.54	0.53	0.56	0.60	0.67	0.72	0.80	0.88
	4,000-5,000					0.59	0.60	0.66	0.67	0.75	0.83
	5,000-9,000					0.50	0.60	0.61	0.64	0.74	0.85

4.2 Estimated Irrigation and Water Budget

The remainder of this study focused on 5,565 SFR lots from the 15 neighborhoods. Based on the assumption that irrigable area on an SFR lot was equal to pervious area, monthly water budget volumes were computed for each household. Outdoor water use was computed monthly by subtracting estimated indoor use based on volumes for the preceding winter. Annual water consumption for these lots decreased from about 509 million gallons in 2008 to approximately 481 million gallons in 2013. Each year, outdoor water use during the growing season (April—September) accounted for 76-86% of the total consumption. This indicates that households in these neighborhoods use the majority of water outdoors and predominantly during the summer.

Exceptionally high irrigation and water budget volumes observed in 2011, could be explained by extreme drought conditions as reported by the U.S. Drought Monitor. An approximately 40% increase in total irrigation for the 15 neighborhoods coincided with a 10% increase in reference evapotranspiration and a 56% decrease in recorded precipitation with respect to the historical means (see Section 3.2.2). Although total irrigation generally exceeded total water budget volume for the 5,565 lots, irrigation actually fell below the budget that year.

Based on the assumption that maintaining water use below budget could be considered efficient, the data suggests that the neighborhoods tended to use water inefficiently except during 2011 during the drought. Following the drought, however, the households again used more water than the overall budget, but exceeded by smaller amounts than before the drought. Figure 12 suggests that irrigation has slightly decreased. These trends were found to be statistically significant when volumes for 2011 were excluded. The obscuring effect of the 2011 drought on the data indicates one of the limitations of having a small period of analysis (6 years). The aggregated irrigation and budget data in Figure 12 does not distinguish between accidental overwatering and consistent wasteful behavior. Thus, this figure must be approached with caution because it essentially treats all overwatering equally. With the exception of 2011, gross excess irrigation declined consistently each year from 2008 and 2013. This might provide evidence that homeowners gradually are becoming sensitive to the block rates implemented in 2008. Table 5 summarizes irrigation and water budget volume for the 15 neighborhoods with respect to annual consumption. Computing the difference of irrigation and budget volumes produced the net irrigation amount. Between 2008 and 2013, net irrigation fell from 160 million gallons to 45 million gallons. Excess irrigation volumes were found to be lower following the 2011 drought. Although irrigation and budget both increased during the drought, the total quantity of irrigation water applied by households in these neighborhoods was 39 million gallons below the total water budget.

Assessing irrigation performance based on aggregate net irrigation can be misleading since it does not reveal the extent of wasteful irrigation. Looking at net irrigation offers an estimate of the minimum potential savings that can occur for a neighborhood or group of lots. However, assessing the total volume of excess irrigation as the sum of monthly quantities exceeding the water budget reveals additional potential for savings. Aggregate gross excess irrigation shown in the last column of Table 5 does not distinguish between accidental overwatering and consistent wasteful behavior. This figure also must be approached with caution because it essentially treats all overwatering equally. With the exception of 2011, gross excess irrigation declined consistently each year from 2008 and 2013. This might provide evidence that homeowners gradually are becoming sensitive to the block rates implemented in 2008.

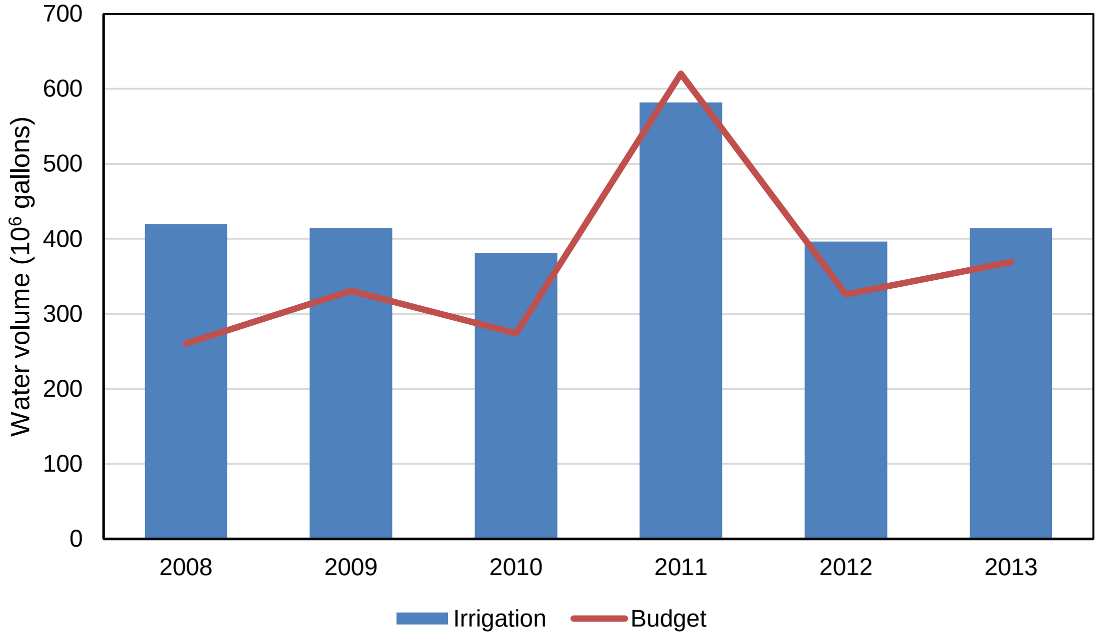

Figure 12. Total irrigation and total budget for the 15 neighborhoods (5,565 lots)

Table 5. Annual water consumption and growing season irrigation, budget, and over-irrigation (10^6 gallons)

Year	Annual consumption (Jan-Dec)	Growing season (Apr-Sep)				
		Consumption	Irrigation	Budget	Net irrigation	Gross excess irrigation
2008	895	618	420	260	160	244
2009	859	614	415	331	84	201
2010	857	568	381	274	107	205
2011	1,114	781	582	620	-39	158
2012	847	583	396	326	70	191
2013	797	601	414	369	45	181

4.3 Household Conformity with Water Budgets

Over-irrigation was a common practice among households within the 15 neighborhoods, with 78-95% of households exceeding their water budget annually. Each year a small number of households did not over-irrigate. According to the average total excess irrigation volume for 2008-2013, about 99% of the households over-irrigated during the study period. This indicated that households that did not over-irrigate in any one year did not necessarily repeat this behavior the following year. The rate of over-irrigation was much higher among these single-family homes compared to the 45-64% of homeowners reported by Romero and Dukes (2013) for Orange County Water Utilities (OWU), Florida. Although the current study was much smaller in scale than the OWU study, which contained over 100,000 SFR homes, the latter did not report on the quantities over-irrigated or the frequency of excessive application.

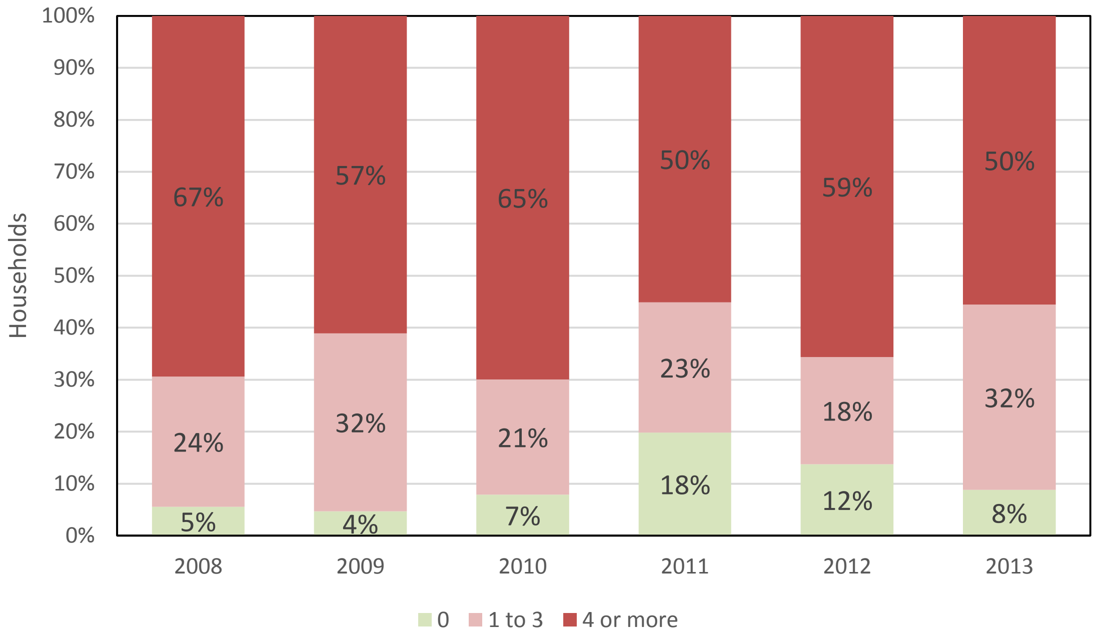

Figure 13. Overwatering frequency by year for the 5,565 households

Frequent overwatering was especially common among the 5,565 households. Figure 13 shows that most exceeded their landscape water budget by 4 months or more each year. The mean number of months over budget decreased significantly ($r^2 = 0.68$; $p < 0.05$) over the period. Furthermore, a significant increase ($r^2 = 0.90$; $p < 0.01$) was observed in the number of lots exceeding their budget by only one month per year. This result coincided with an increase in the number of lots that do not over-irrigate and a decrease in the numbers of lots overwatering by more than 4 times per year since 2008. While these changes were not shown to be significant, they suggest that households may be altering their changing their irrigation regimes.

The 5,565 SFR households applied an average aggregate excess irrigation volume of 218 million gallons per year between 2008-2013 (Table 5). Volume excess irrigation was found to vary significantly from year to year ($p<0.01$). Aggregate excess irrigation volume increased to 212 million gallons following 2012 but decreased slightly in 2013 to about 195.5 million gallons. Our findings revealed that total annual excess irrigation accounted for 45% of total irrigation. This finding is consistent with the EPA WaterSense claim that as much as half of the water used outdoors is wasted (USEPA 2013).

Although excess irrigation widely varied for the households, it was observed to decrease significantly between 2008 and 2013 (Table 6). Mean household excess irrigation volume over the study period was 39,400 gallons per lot and ranged from 9 gallons to 277,816 gallons. The small number of lots that exceed their budget by such a disproportionately large amounts could be easy to target individually for conservation measures. However, even the lot with the single highest observed maximum excess irrigation (482,102 gallons in 2011) co-opted less than 0.3% of the total excess irrigation. A larger number of lots would have to be targeted for more substantial water savings. Excess irrigation volume alone cannot be used to gage irrigation performance since landscape sizes and household overwatering patterns vary. The last objective of this study is to explore the relationship between excess irrigation volume and frequency in further detail.

Unit excess irrigation provided a uniform comparison of water use across widely varying lawn sizes. This quantity fell from 6.1 gal/ft^2 in 2008 to 4.7 gal/ft^2 in 2013. The annual average unit excess irrigation over the period of study of 5.3 gal/ft^2 agreed with findings reported by Salvador et al. (2011). Their approach using the annual relative irrigation supply (ARIS) index was conceptually similar to ours since they defined irrigation requirements based on irrigable area.

Table 6. Average household values for parameters used to assess conformity to water budgets

Year	Irrigation (gal)	Budget (gal)	Excess volume (gal)	Unit excess (gal/ft^2)	Months over budget
2008	78,719	46,753	46,333	6.1	4.1
2009	76,991	59,421	37,953	5.1	3.8
2010	71,147	49,269	39,390	5.4	3.8
2011	107,412	111,448	36,327	5.2	3.2
2012	74,487	58,564	38,833	5.3	3.5
2013	77,603	66,301	34,915	4.7	3.4
r^2	0.01	0.13	0.67	0.61	0.68
p-value	0.860	0.490	0.046	0.068	0.044

4.4 Conformity with Budgets Based on Irrigable Area

Multiple regression analysis (Eq. 6) was used to draw inferences about irrigation performance pertaining to lawn size classification. The R^2 values indicated the degree to which the observed effects could be explained by our irrigation performance variables instead of unaccounted factors or random chance. Analysis of excess volume produced the strongest explanatory result (R^2=0.35). For mean total excess irrigation, homeowners with large lawns were found to apply over-irrigate significantly higher quantities compared to those with the smallest lawn sizes. There did not appear to be significant differences between the excess quantities applied by homeowners with exceptionally small lawns (less than 4,000 ft^2) compared to homeowners with very small lawns (4,000-5,000 ft^2).

Results for relative total overwatering returned weaker explanatory strength (R^2=0.24) by this measure of irrigation performance compared to total overwatering. However, significant differences were observed between each of the ranges of lawn area. Homeowners with lawns smaller than 4,000 ft^2 tended to over-irrigate by 7.66 gal/ft^2, whereas those with larger lawns tended to irrigate by smaller quantities. This result suggested, in contrast to results produced by the overwatering quantity simulation, that homeowners with the largest lawns are the most effective irrigators.

The final simulation for overwatering frequency returned the weakest result (R^2=0.11). Significant differences were only observed between lawn sizes classified as exceptionally small lawns and lawn sizes classified as large and exceptionally large. The coefficient for the intercept, which pertained to the exceptionally small lawns, indicated that the mean annual frequency of over-irrigation among this group was 3.65 times. Large and exceptionally large lots tended to irrigate 0.29 and 0.47 times less frequent, respectively. For very large lots, it may become less likely that all of the area considered irrigable is actually irrigated. This would have the effect of making irrigation performance seem better for larger lawns when they actually may harbor behaviors more similar to smaller lawns.

Households with larger landscapes tend irrigate significantly higher quantities than smaller lots. However, the lower normalized quantity indicates that the excess water they apply tends to be significantly more judiciously applied than smaller lots. This observation may indicate a limitation to the irrigable area assumption. On larger lots, less area may be irrigated relative to the overall pervious area of the lot.

Possible variables specific to each lot might have included household income, irrigation system distribution uniformity, home age, and behavioral factors. Smaller lots over-irrigate less compared to larger lots but the amount of water they use per unit area is more.

Table 7. Multiple regression analysis results for conformity with water budget based on landscape size, with coefficient values indicating difference with respect to extremely small lawn sizes (less than 4000 ft^2)

		Irrigation performance parameter coefficient		
Variable	Lawn area range (ft^2)	Number of times over	Relative excess irrigation (gal/ft^2)	Volume excess (gal)
XSL (constant)	<4,000	3.65* (52.58)	7.13* (38.01)	23,432* (17.15)
VSL	4,000-5,000	-0.10 (-1.18)	-1.68* (-7.01)	1,121 (0.64)
SL	5,000-7,000	0.10 (1.24)	-2.09* (-9.85)	6,882* (4.45)
MED	7,000-10,000	0.06 (0.78)	-2.51* (-11.66)	14,316* (9.13)
LG	10,000-14,000	-0.29* (-3.15)	-3.56* (-14.22)	17,949* (9.84)
VLG	14,000-18,000	-0.05 (-0.43)	-3.51* (-11.78)	33,788* (15.55)
XLG	≥18,0000	-0.47* (-4.27)	-4.45* (-14.88)	37,797* (17.36)
Multiple R^2		0.107	0.242	0.325

Note. Significance indicated by $^*p < 0.01$; two-tailed tests; *t*-statistics in parentheses.

Table 8. Trends in mean unit excess irrigation by size of irrigable area (gal/ft^2/year)

Lawn area range (ft^2)	2008	2009	2010	2011	2012	2013	r^2	p
<4,000	8.3	7.4	8.5	9.0	8.6	7.2	0.01	0.87
4,000-5,000	6.7	6.2	6.2	6.2	6.2	5.9	0.69	0.04
5,000-7,000	6.3	5.4	5.6	5.3	5.4	4.9	0.74	0.03
7,000-10,000	6.0	4.7	5.1	4.8	5.0	4.6	0.50	0.12
10,000-14,000	4.8	3.9	3.9	3.4	4.0	3.6	0.49	0.12
14,000-18,000	5.0	3.9	3.9	3.3	3.8	3.5	0.57	0.08
≥18,0000	3.9	2.9	2.9	2.7	2.9	2.4	0.69	0.04

Table 9. Trends in mean excess irrigation volume by size of irrigable area (gal/year)

Lawn area range (ft^2)	2008	2009	2010	2011	2012	2013	r^2	p
<4,000	27,587	24,418	27,466	29,022	28,500	24,010	0.01	0.85
4,000-5,000	30,175	28,145	27,762	27,839	28,039	26,598	0.70	0.04
5,000-7,000	37,885	32,555	33,573	32,130	32,482	29,345	0.73	0.03
7,000-10,000	49,435	38,864	42,135	39,335	40,954	37,186	0.51	0.11
10,000-14,000	55,661	45,720	45,165	39,431	46,561	41,511	0.50	0.12
14,000-18,000	79,492	61,671	61,784	51,690	60,171	54,878	0.58	0.08
≥18,0000	90,272	67,087	67,529	60,499	64,328	55,851	0.70	0.04

4.5 Limitations of Study

The limitations of this study are discussed in this section. Several key assumptions were made while developing landscape water budgets and estimating excess irrigation. The assumption of a monoculture lawn did not include the possibility of other landscape plants and their respective water needs. Since turf grasses have among the highest water needs of plants commonly found on urban landscapes, this assumption had the effect of elevating the water budget. This study did not determine if the landscape area included shrubs and trees nor did it ascertain if homeowners differentially watered these areas.

A second assumption of the study was that sprinklers efficiently applied water to the landscape. Since sprinkler droplet dynamics are accounted for by the crop coefficient, future studies of irrigation performance should incorporate percentage water loss. Factors known contribute to such losses are the size of the droplets, water temperature, wind velocity, relative humidity, net radiation, and time of flight (Lorenzini 2004; Playán et al. 2005). For instance, droplet evaporation decreases as droplet diameters increase. Accounting for such evaporative losses would increase the water budget, but the impact cannot be assessed without further study. One possible way of determining the impact of evaporative losses would be to conduct a sensitivity analysis for the variables in the water budget equation. Incorporating an error term into the water budget could help toward establish confidence intervals for the irrigation performance measures.

Another assumption and possible limitation of this study is that indoor water use for the summer months was derived from winter water usage. The assumption was that water use during the winter months when grass was dormant represented indoor use. Unless there is a separate meter for the irrigation system indoor water use must be estimated from the wintertime average. Outdoor water use did not account for recreational activities or swimming pool upkeep. While swimming pools lose water at faster rates than lawns due to open surface evaporation, the area of lawn they displace may actually lead them to save water compared to households with all-turf landscapes. This is also an area that warrants future study.

5. SUMMARY AND CONCLUSION

The current study offered several refined approaches useful for future application in landscape irrigation research while proposing a new methodology for assessing irrigation performance. Lot data acquired in GIS format from the City of College Station and the Brazos Central Appraisal District permitted the development of estimates of landscape area. Approaches taken by past studies relied on living area or building area and assumptions about the remaining impervious area. In the current study, any impervious area other than buildings and driveways (including decks, walkways, and courtyards) was assumed to be small in comparison. Using actual information about impervious area specific to each lot permitted closer approximation of actual pervious area. Another alteration to this study methodology that may contribute to the development of more accurate water budgets could be the use of monthly-varying crop coefficients. The availability of precise impervious area data at the lot level made it possible to explore the relationship between pervious area and lot size.

Water use data obtained in a raw format from city records is typically assumed to lag the contributing behaviors by a month. Correcting for this misalignment can be difficult but crucial for comparing consumption based on meteorological variables on a monthly time step. The procedure for adjusting College Station’s water use dataset computed quantities proportional to the date readings were taken and may be applicable to other cities. Estimation of indoor water use can be difficult to assess since different methods apply better depending on the location of the study. For instance, the minimum month and per capita methods may be more appropriate for the Gulf Coast region (Romero and Dukes 2013), whereas average winter consumption may be more appropriate for regions with well-defined winters (DeOreo and Mayer 2012). Increased use of smart metering in the future could facilitate the process of computing indoor consumption. The proposed model may be useful for assessing the effect of the water consumption data adjustment on irrigation performance results.

Longstanding evidence has indicated that there is a strong positive relationship between landscape area and household water use (Chavez III and Cotter 1973; Guhathakurta and Gober 2007; Stoker and Rothfeder 2014). However, no study prior to this one has assessed irrigation performance with respect to estimated landscape area. Salvador et al. (2011) used hierarchical conglomerates technique to analyze irrigation performance between SFR lots. While this approach was based on ARIS, a factor which normalizes for irrigable area, it was not possible to discern possible patterns of irrigation performance with respect to property characteristics. Results from our multiple regression model permitted us to draw inferences regarding property characteristics. Though patterns of irrigation performance were explored only across classifications of lawn area, this procedure could applied to demographic variables, home age, or additional property characteristics.

The analysis of irrigation performance revealed several important relationships. Most of the 5,565 lots in this study were found to irrigate excessively and repeatedly over the six years of the study. Assessing the rate of over-irrigation in citywide data can reveal the extent of the problem, which can be useful for determining how widely irrigation restrictions could impact customers. However, the intensity of over-irrigation cannot be assessed without deeper analysis of patterns pertaining to individual lots.

Analysis of irrigation performance offers one approach to assessing irrigation efficiency, which can be useful for determining where certain behaviors might be problematic. Estimated irrigation requirements appeared to increase due to much larger computed values for monthly moisture deficit. White et al. (2004) demonstrated that a lower monthly water budget would increase conservation potential. The opposite would hold true if the water budget was to increase. Homes that irrigated more during the drought, while not considered inefficient if they remained below the budget, still contributed unprecedented high demands in August 2011. This suggests one of the limitations of using excess irrigation to assess irrigation performance.

Urban irrigation performance is a product of many factors, some essentially fixed in time (i.e. lawn area) and others that can exhibit wide inter-annual variability (i.e. monthly irrigation and irrigation requirements). Other variables may influence the observed behaviors in irrigation performance, but such analysis was beyond the scope of this study. While it is conceivable that larger properties could irrigate more efficiently than smaller properties, additional factors such as water price and affordability may mediate the relationship (Harlan et al. 2009). By conducting our analysis based the average of annual totals, our results were incapable of explaining inter-annual variability. Further work could be conducted to develop a model that incorporates time as a variable. This would permit irrigation performance to be analyzed using a monthly time or weekly time step. Another alternative could be to develop a mixed-effects model to account for additional factors, such as evapotranspiration, precipitation, and home age, and income.

Trudgill et al. (2010) demonstrated that lawns exhibit a degree of physical resilience during summer drought with temperature increases representative warming related to climate change. The cosmetic value of lawns is not likely to disappear soon, but altered management practices could be fostered through more widespread water conservation guidelines.

Population growth and climate change projections throughout the United States have necessitated reduction of wasteful water use. Wasteful urban irrigation can be widely observed but is not well understood. Developing a landscape water budget can be an especially useful strategy for identifying problematic and exceptionally wasteful overwatering. Accurate water budgets can also be used to help inform customers about the water needs of their property's landscape. Helping customers irrigate more efficiently, by virtue of reducing landscape overwatering, may have potential to significantly reduce domestic water demand. It is hoped that this study can benefit impact municipal and regional water management.

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APPENDIX

Table A1. Population and water withdrawal trends in the United States from 1950 to 2005.

Year	Population Total	 Urban	Water Withdrawal Total	 Public Supply	Increase in public supply
	millions		10^9 gal/day	10^9 gal /day	%
1950	150.7	96.4	681	53	
1955	164	109.5	908	64	0.21
1960	179.3	125.3	1,022	79	0.24
1965	193.8	139.4	1,173	91	0.14
1970	205.9	151.5	1,401	102	0.13
1975	216.4	159.4	1,590	110	0.07
1980	229.6	169.2	1,628	125	0.14
1985	242.4	180.7	1,503	138	0.10
1990	252.3	189.7	1,529	147	0.07
1995	267.1	205.4	1,510	152	0.04
2000	285.3	225.4	1,563	164	0.07
2005	300.7	240.7	1,552	167	0.02

Table A2. Residential water use in College Station between 2008 and 2009.

Calendar Year	2008	2009	2010	2011	2012	2013
	10^6 gallons					
January	159	162	151	166	163	168
February	162	178	152	165	162	164
March	158	194	158	186	170	169
April	193	203	199	271	203	213
May	224	205	237	316	261	238
June	314	293	260	317	292	255
July	384	416	261	351	275	345
August	335	329	357	439	370	377
September	275	308	305	415	327	377
October	256	191	272	319	254	250
November	209	168	245	257	217	202
December	186	167	203	197	201	185
TOTAL	2,853	2,814	2,801	3,399	2,893	2,943

Table A3. Counts of lots by category range used to derive coefficients for determining pervious area

		Lot Area (ft^2)									
		4,000-6,000	6,000-8,000	8,000-10,000	10,000-12,000	12,000-14,000	14,000-18,000	18,000-24,000	24,000-30,000	30,000-60,000	60,000-90,000
Living Area *(Heating and Cooling)* **(ft^2)**	500-1,000	69	54	18	18	9	4	4	1	2	
	1,000-1,500	310	820	540	328	138	78	27	6	6	2
	1,500-2,000	41	936	1079	736	393	315	101	28	33	7
	2,000-2,500	7	176	572	697	400	324	171	41	70	13
	2,500-3,000	1	13	63	299	281	255	130	44	65	13
	3,000-3,500		2	5	62	116	157	126	63	55	11
	3,500-4,000			1	9	26	62	90	46	37	15
	4,000-5,000					4	19	43	53	39	7
	5,000-9,000					1	5	11	19	26	3