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Predictors of Variations in Residential Water Consumption in Central Texas

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Abstract: Background: The 100th Meridian in Texas aligns with a corridor of large and rapidly growing urban areas with a growing water demand and limited supply. Understanding the variations in residential water consumption may assist with identifying the characteristics associated with disproportionate water consumption that may be responsive to policy changes and enforcement. Methods: Data from the San Antonio Water System, the Bexar County Appraisal District, and the American Community Survey were utilized. The average daily water consumption was estimated for the seasons and a total year for more than 300,000 single-family residences between 2009 and 2015. The presence of a swimming pool, residential parcel hectares, size of the living space, and per capita income were examined as predictors of the variations in residential water consumption using hierarchal modeling. Results: The presence of swimming pools and a residential property's value were the strongest predictors of water consumption. Parcel hectares and household income were positively associated with water consumption. A quartile analysis of select independent variables identified the disproportionate variations of water consumption of units with large yards, swimming pools, and high values. Conclusions: The findings indicate a strong association between variations in residential water consumption and both irrigation and swimming pool water used, which emphasize a need to focus conservation efforts on higher-valued housing and residences with swimming pools and the consideration of tiered pricing.

Keywords: residential water; socioeconomic; swimming pools; irrigation; conservation

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1. Introduction

Climate models for Central Texas indicate a warmer and drier future [1–5]. Central Texas is at the transitional boundary between the more humid Eastern U.S. and the semi-arid Western U.S. This boundary from John Wesley Powell's designated 100th Meridian boundary [6] is a relevant landmark for monitoring shifting climate patterns and the availability of water. This boundary also aligns with a corridor of large and rapidly growing urban areas in Texas. Six of the twenty-five fastest-growing (percent change) cities in the United States between 2018 and 2019 (Leander, Georgetown, New Braunfels, Frisco, Wylie, and McKinney, all in Texas) are along this corridor. Five of the fifteen most significant (numerically) growing cities (San Antonio, Houston, Dallas, Fort Worth, Frisco, and Austin) are also along this boundary, as are four of the top fifteen largest cities in the U.S. (San Antonio, Dallas, Austin, and Fort Worth) [7]. These large and growing cities currently experience stress on their water supplies during drought periods, and with continued increases in population and potentially more significant and prolonged periods of drought, the continued economic prosperity of this area may become threatened. Central Texas is a relevant geographic area that is experiencing changes that are indicative of many of the predicted trends for the U.S. Thus, Central Texas is a valuable proving ground for building a new understanding to address water stress. A better understanding of the predictors of residential water consumption and better modeling will enable more accurate forecasting of the residential water demand [8].

Enhancing the water resilience in Texas during the late 21st century requires (1) a better understanding of the current water consumption in Central Texas for the purposes of targeting conservation efforts and (2) more accurate forecasts of future water consumption as a function of the demographics and population growth. To these ends, we examined the seasonal and annual residential water consumption patterns in San Antonio, Texas, and then examined these as they relate to the socioeconomic characteristics that can plausibly be expected to influence the variations in water consumption. Specifically, we calculated the average daily water consumption overall, during July and August (summer), during January and February (winter), and the differences between the summer and winter months over the study period. We also estimated the proportion and amount of increased summer water use associated with swimming pools, irrigation, housing unit size, and persons per household. Using data from the San Antonio Water System, the Bexar County Appraisal District, and the U.S. Census Bureau, and variations in the average residential water consumption at the parcel and census tract levels of geography, we examined the relationships of the variations in the presence of swimming pools, residential hectares, size of living spaces, and per capita income. In the analyses presented, we do not forecast water consumption, although this is a likely next step using the methods and data shown here.

Population growth along the U.S. Interstate Highway 35 corridor in Central Texas is complexly distributed. Texas is growing and will continue to grow rapidly by natural increase (births minus deaths) and the net in-migration (in minus out-migrants). The state is projected to grow 82%, from 29 to more than 47 million, from 2020 to 2050 [9]. The water planning areas that include Dallas—Fort Worth, Austin, San Antonio, Houston, and the Rio Grande Valley (Figure 1) are anticipated to capture 82% of the state's growth through 2060. The urban core counties have continuing substantial growth, primarily from natural increases. The populations of urban-adjacent, formerly rural areas are growing substantially and rapidly, largely due to the net in-migration. Land use is often less-regulated in unincorporated areas, and opportunities abound to rezone properties. The cost of this development is inexpensive compared to development or redevelopment in or closer to the urban core. Owing to liberal annexation laws, many urbanized areas expand as the demand for residential properties increases with the increasing population.

The socioeconomic characteristics of a population are a significant consideration when examining the coupling of a population and water use in rapidly growing urban centers. A lower socioeconomic status would be expected to correlate with less water use per person, as wealthier residents are more likely to have larger homes, irrigated yards, and swimming pools. The racial and ethnic composition of a population may also correlate with the per capita consumption of water. Research on the relationships between race or ethnicity and variations in water and other natural resource uses is limited [10]. Studies suggest that there are variations in energy consumption by race and ethnicity, which suggests possible variations in the consumption of other natural resources by race and ethnicity [11,12]. There is also evidence that the age structure of a population is related to resource consumption [13]. Thus, consideration of the demographic and socioeconomic characteristics of a population enhances the understanding of natural resource consumption.

Other factors are also relevant when looking at variations in residential water consumption. For example, Chang et. al. found that residential water consumption was best explained by building size, followed by building density and building age [14]. Consistent with the speculation that socioeconomic status is associated with residential water consumption, Wentz and Gober found that household size, the presence of a pool, landscaping practices, and lot size were important in predicting water consumption [15]. Personal and household incomes, education levels, and energy use of appliances all appear to have a significant influence on the daily water use per capita [15–17]. House-Peters et al. found that areas that contain newer and larger homes, higher property values, and more affluent and well-educated residents tended to consume more water [18].

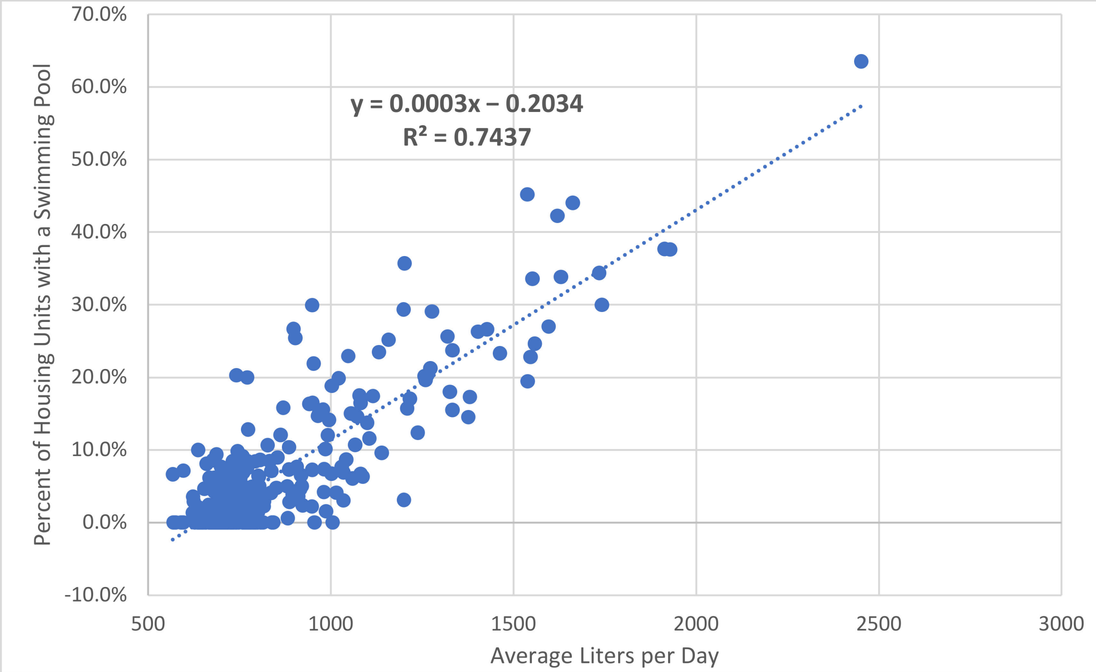

Figure 1. Scatter plot of the percent of housing units with a swimming pool and average liters of water per day, and linear regression of the average liters per day on the percent of housing units with a swimming pool, Census Tracts, Bexar County, Texas.

Grafton et. al. found that volumetric pricing and low-flow toilets were associated with water consumption and that householders expressing environmental concerns were more likely to report water-saving behaviors [19]. Another moderately effective conservation strategy appears to be retrofitting with more efficient water appliances to be more efficient, which, when quantified, can be useful in forecasting water savings [20]. While retrofitting appliances and voluntary behavior changes are promising strategies, mandatory water restrictions combined with pricing strategies appear to be among the most effective strategies to reduce water consumption [21].

Given that we expect that swimming pools are a relevant factor in the variations of residential water consumption, we estimated that, to fill a standard 7.3 × 16.5-m swimming pool (60,105 L) and then account for an evaporation of ~100 mm/month, there are about 33 cubic meters of evaporation per month (4380 L). This comes out to about 560 L evaporated per day from each swimming pool. Additionally, if we account for filling a swimming pool over the summer (60,105 L/90 days), this comes out to about 666 L/day. Add the 4380 L lost through evaporation, and you get about 814 L/day wrapped up in a swimming pool.

The water consumption data used in the analysis presented are from the San Antonio Water System (SAWS) in San Antonio, TX, USA. The SAWS has a history of working to promote the conservation of water through education and various types of rebate programs. Most water for the San Antonio area is sourced from the Edwards Aquifer, and the SAWS effectively communicates the levels of the aquifer and enacts and communicates about water use restrictions when the levels decline below set thresholds. Other than these measures, there is little that is done to reduce residential water consumption. There is currently no tiered pricing, and there is no differential metering for residential and irrigation-related water use.

Differentials in seasonal residential water consumption appear to be associated with several characteristics of housing units and their parcels and with the characteristics of the residents and their associated behaviors. In particular, residential end uses of water seem to vary by summer and winter, resulting in seasonal variations in the total consumption [22,23]. In the San Antonio area, the differential in residential water consumption between hot and dry summer months and cooler and wetter winter months can be substantial. It is logical that, in the summer months, compared to the winter, households will use more water for landscape purposes, and those with swimming pools will use more water due to evaporation. Thus, we expect that housing unit characteristics such as the land parcel size, the size of the housing unit, and the neighborhood (census tract level) social and economic characteristics will be associated with the variations in residential water consumption. We also expect that the presence of residential swimming pools will be associated with residential water consumption. Therefore, we attempted to estimate how much of the differential was associated with irrigation, swimming pools, size of the housing unit, per capita income, and persons per household. The analysis presented employed a method where the volume of residential water consumption can be decomposed by season and by housing and household characteristics. With this information, potentially effective strategies can be developed to target conservation measures to reduce, or slow, the overall volume and increased residential water consumption in areas with growing populations. While we characterize the volumes and variations of residential water consumption in South Texas, we believe that our methods and findings may apply to other regions that have similar climates.

2. Material and Methods

Monthly billing data for residential water consumption (billing) was received from the San Antonio Water System for the months starting in September 2009 through September 2016 for residential water customers through an open records request. The data delivered contained slightly more than 20 million records. The data were collapsed to create a record for each service address and all non-single-family residential addresses were removed, resulting in a bit more than 300,000 records. For each month of service, an estimate of liters per day was calculated by dividing the service days into liters used on the monthly bills. Months with missing values and outliers (extremely high or negative values) were assigned as missing values and were not used in the calculations of the averages. For each address, the average liters per day (ALPD) was calculated, and then, the ALPD was calculated for the summer months (July and August) and winter months (January and February), and the difference between the summer and winter ALPD was calculated.

The data from the Bexar County Appraisal District (BCAD) for all parcels in Bexar County, Texas, were matched to the water consumption data using a unique identifier for each address. The BCAD data elements included the size of the parcel; appraised value; latitude and longitude; and building improvement characteristics (year built, number of bedrooms, square feet of living space, and pool/no pool). The census tract for each housing unit was identified, and census tract-level characteristics from the American Community Survey were assigned to each housing unit from their corresponding census tract. The data on the social and economic characteristics from the American Community Survey (ACS) 5-year Sample for 2012–2016 included: average household size; the median value of owner-occupied housing units; educational attainment of adults; percent of the population who moved current residence in the past year; percent of the population who are foreign-born; percent of the civilian labor force that is unemployed; percent of the population in poverty; percent of owner-occupied housing units; the median value of owner-occupied housing units; the median age of the population; and percent of the population that is Hispanic, non-Hispanic Whites, and non-Hispanic Blacks, among others.

The foci of the analyses presented were to identify quantitative and diagnostic relationships between demographic/economic indicators and residential water consumption, such that future consumption can be modeled by future demographic/socioeconomic variations. That way, we can have some understanding of the range in the infrastructure necessary to support resilience and sustainability in water resources. We examined the housing and economic-related characteristics associated with residential water consumption overall, for seasonal water consumption, and seasonal differences in the average residential water consumption over the study period.

We assume:

- for both irrigation and swimming pools that winter water consumption is a lower-end baseline with minimal irrigation and pool-related consumption compared to the summer months;
- that most of the summer–winter water consumption differential is the result of seasonal differences in irrigation and swimming pools rather than interior household water consumption;
- that the difference in the summer–winter differences (between housing units with and without swimming pools) can be attributed to swimming pool-related water consumption, and thus, by subtracting the summer–winter difference of housing units without swimming pools from those with swimming pools, we estimate the amount of summer consumption attributable to swimming pools.

To begin, we examined the relationship between residential water consumption and key explanatory variables with census tract-level scatter plots between the average daily water consumption per housing unit and the percent of housing units with a swimming pool, the log average lot hectares (log was used to spread out clumps of data and bring together spread-out data), average square feet of living space per housing unit, per capita income, and average persons per household. We fit a linear regression of the average liters per day on each of the independent variables and provided both the regression equation and the R^2. This was followed by an examination of the descriptive statistics and bivariate associations: we examined the average liters per day for the total study period, summer months (July and August), winter months (January and February), and the summer–winter months differences by parcel hectares and the presence or absence of a swimming pool by dividing the housing units by parcel sizes into quartiles. Then, we examined the associations between the average daily water consumption; average daily winter water consumption; average daily summer water consumption; and the differences in the average daily water consumption between the summer and winter due to parcel size, housing unit square footage, the presence or absence of a swimming pool, and per capita income. All variables were at the housing unit level of analysis, except for the per capita income, which was at the census tract level. The hierarchical nature of the data led us to use SAS software version 9.4 Proc GLIMMIX in the multivariate analysis. The GLIMMIX procedure fits statistical models to data with correlations or nonconstant variabilities and where the response is not necessarily normally distributed. These models are known as generalized linear mixed models (GLMM). GLMMs, similar to linear mixed models, assume normal (Gaussian) random effects. Conditional on these random effects, the data can have any distribution in the exponential family. Our data were hierarchical, with housing units clustered within the census tracts. With GLIMMIX, we could examine the association of the variations of the individual housing unit characteristics on the housing unit-level-dependent variables and the association of the census tract-level characteristics on the housing unit-dependent variables across the census tracts.

3. Results

In examining variables that are indicators of wealth at the neighborhood level, many of them were highly correlated. For example, the median value of owner-occupied housing was positively associated with the percent with a bachelor's degree and higher; percent with graduate and professional degrees; average number of rooms per housing unit; per capita income; percent born in a different state; and percent employed in management, business, science, and arts occupations, among others. It was negatively associated with percent Hispanic, percent on the Supplemental Nutritional Assistance Program, and percent who speak a language other than English at home. In an exploratory analysis, combining most of these as independent variables in various configurations led to multicollinearity problems in the models. We found that per capita income was strongly associated with most of these variables (both positively and negatively). Therefore, we employed census tract level per capita income as an indicator of the neighborhood socioeconomic status.

Figures 1–5 show the linear association between the average gallons used per day (ALPD) and key independent variables at the census tract level of analysis. The strongest association among the four was between ALPD and the percentage of housing units with a swimming pool (R^2 of 0.74). The average square meters of living space had the second strongest association (R^2 of 0.69). The per capita income had the third strongest association and average hectares per lot the fourth. These scatter plots illustrate the association between these characteristics and residential water consumption. Interestingly, there is a clustering of census tracts at the lower left quadrant of each graph and a smaller number moving toward the upper-right of the graphs. This indicates that a relatively small number of census tracts are large consumers of water and the characteristics of those census tracts are likely significant factors associated with water consumption. Interestingly, for hectares of lot size, there seem to be a fair number of census tracts, with many large lots that are not large consumers of water. These are likely lots that are large but are not landscaped, as is the case for some areas in Bexar County. Finally, persons per household appears to have relatively little association with ALPD but is thought to be a factor that we need to control in looking at other sources of variations in water consumption.

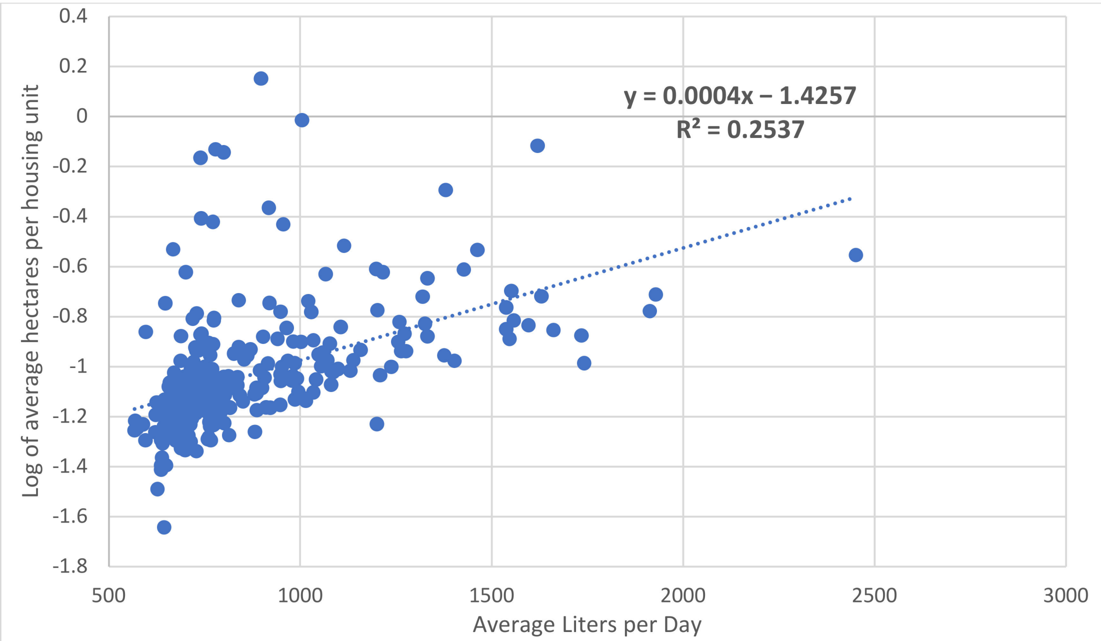

Figure 2. Scatter plot of the log of average hectares per housing unit and average liters of water per day, and linear regression of the average gallons per day on the log of average hectares per housing unit, Census Tracts, Bexar County, Texas.

Table 1 provides descriptive statistics on the average single-family residential water consumption for the summer and winter seasons, the seasonal differences, and the mean ALPD during the study period (2009–2016). Estimates of the average daily, single-family unit residential water consumption over the study period were consistent with estimates of the residential water consumption produced independently by the San Antonio Water System (~26,530 L per month or 856 LPD). The average liters per day (ALPD) for single-family residences in all census tracts over the study period was 905.4 L. In the winter months, the ALPD declined to 758.8 per residence and increased to 1177.6 LPD in the summer months. The difference in LPD between the summer and winter months was 418.8 LPD. The median of all the measures was below the mean, suggesting that a relatively small number of housing units with high consumption skewed the mean toward higher values.

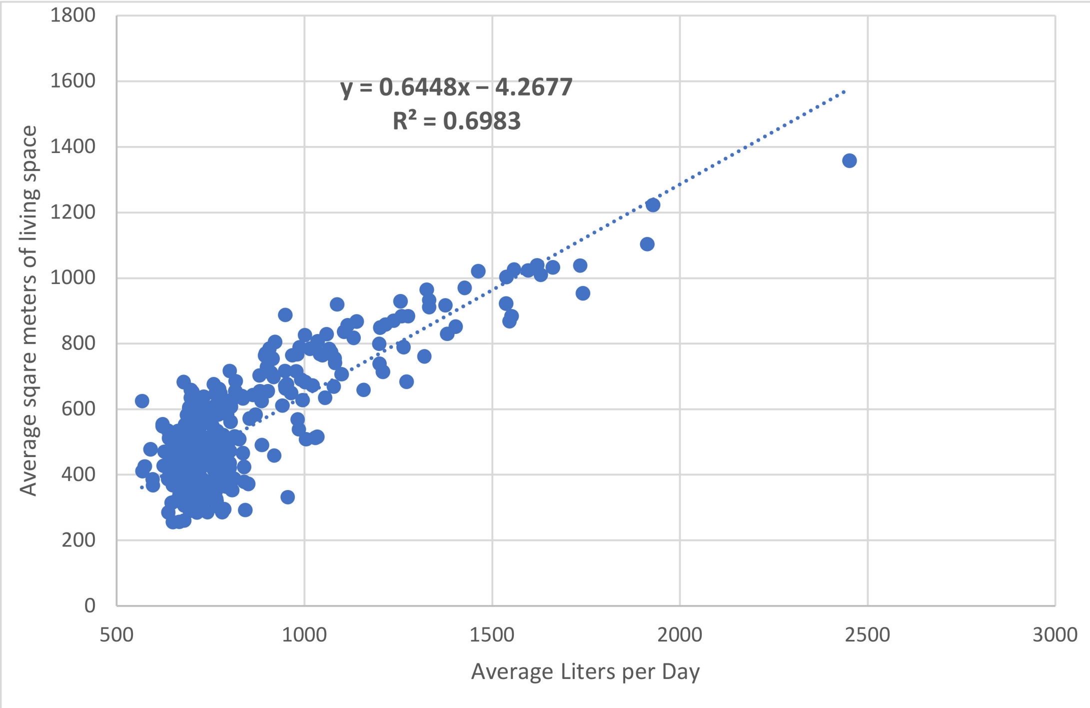

Figure 3. Scatter plot of the average square meters of living space per housing unit and average liters of water per day, and linear regression of the average square meters of living space per housing unit on average liters of water per day, Census Tracts, Bexar County, Texas.

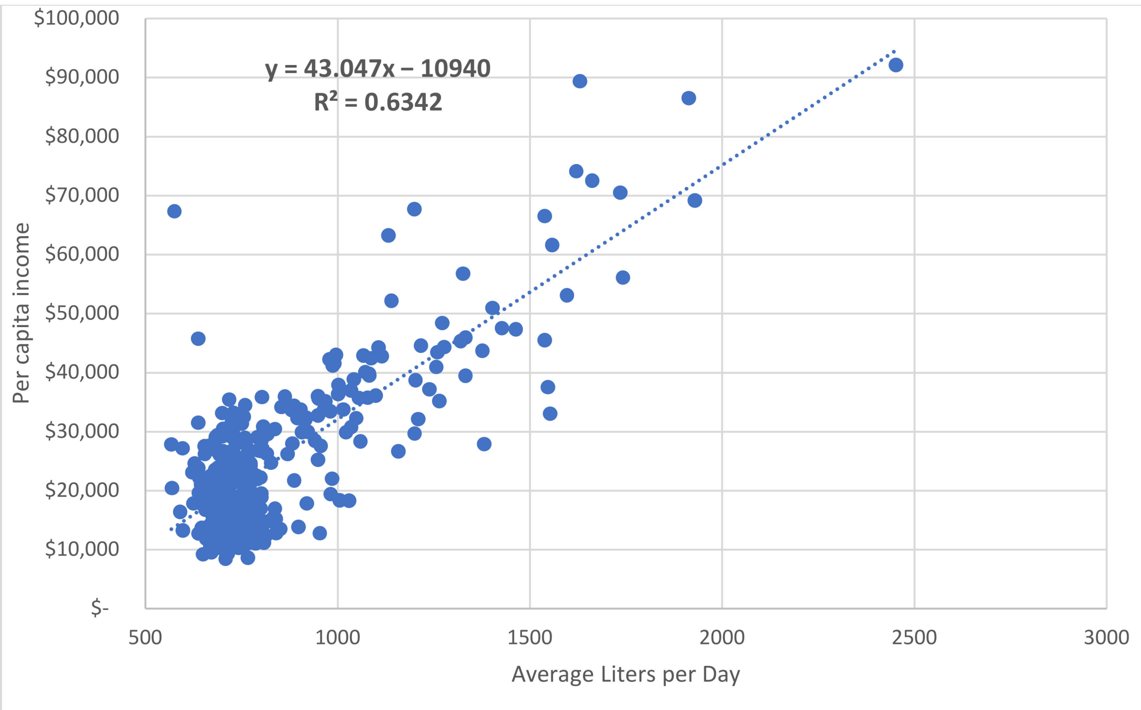

Figure 4. Scatter plot of the per capita income and average gallons of water per day, and linear regression of the average gallons per day on per capita income, Census Tracts, Bexar County, Texas.

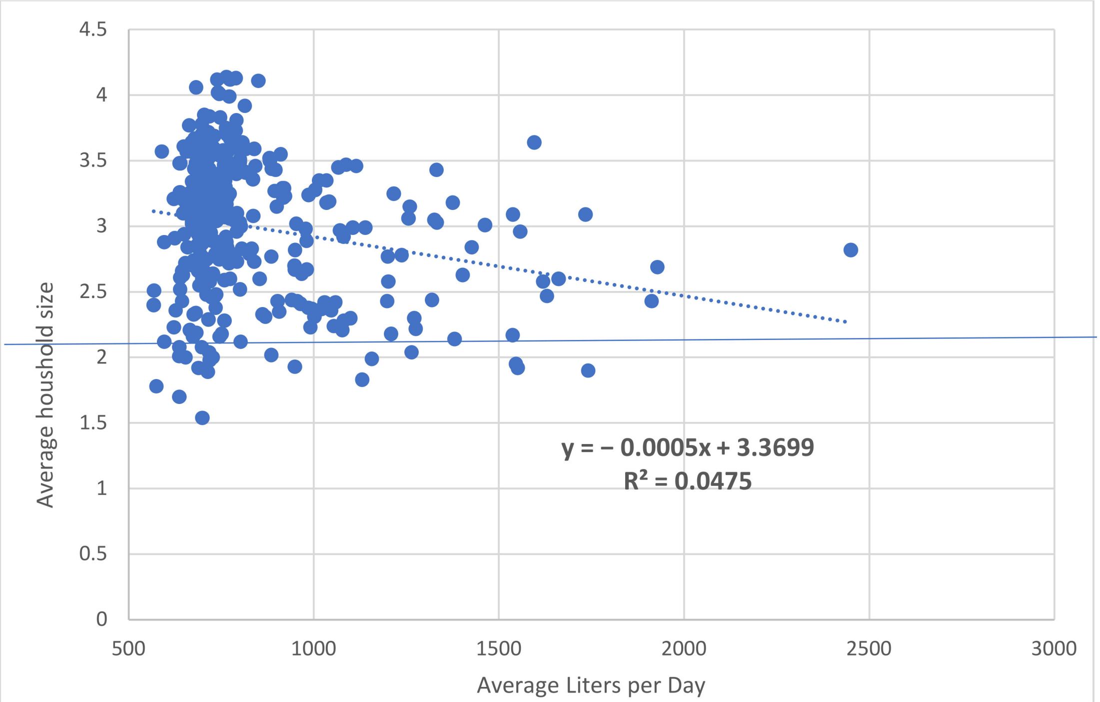

Figure 5. Scatter plot of average persons per household and average gallons of water per day, and linear regression of the average gallons per day on per capita income, Census Tracts, Bexar County, Texas.

Table 1. Descriptive statistics of the average single-family average liter per day (ALPD) of water consumption and housing and household characteristics in Bexar County, Texas, 2009–2016 (n = 300,216).

Variable	Mean	Standard Deviation	Minimum	Maximum
Summer ALPD	1177.6	864.1	1.9	9459.8
Winter ALPD	758.8	458.2	1.9	9270.0
Summer–Winter Difference ALPD	418.8	641.6	−6903.1	8927.0
Total ALPD	905.4	594.7	4.2	8953.9
Pool (1 = yes)	0.1	0.3	0.0	1.0
Parcel Hectares	0.097	0.138	0.004	9.068
Sq.M. Living Area	189.8	84.7	1.1	1954.2
Per Capita Income (344 Tracts)	$30,420	$13,630	$8449	$92,139
Average Household Size (344 Tracts)	2.9	0.4	1.5	5.5

We present correlations between the independent variables (sq.m. living space, parcel hectares, # swimming pools, per capita income, and persons per household) and measures of the seasonal average water consumption and the differences between seasons in Table 2. All independent variables were significantly ($p < 0.0001$) correlated with consumption across the seasons. The average number of persons per household had the weakest association with water consumption, and size of parcels (hectares) had a relatively weak bivariate association. The presence of swimming pools and per capita income had moderate associations with water consumption, and the association with area of living space was the strongest.

Table 3 presents the ALPD for the total study period by parcel size quartiles. The smallest parcels consumed the least amount of water (25% of housing units consumed only 19.2% of the water), and the largest consumed the most (25% of housing units consumed 34.8% of the water). Housing units without swimming pools consumed about 84.9% of the single-family residential water over the study period while accounting for 91.6% of all the single-family housing units. Housing units without pools in the bottom, second, and third quartiles of parcel size consumed 19%, 21%, and 22.1% (62.1%) of the total water, respectively, although they represented 24.8%, 24.4%, and 23.3% (72.5%) of all the housing units. Housing units without pools in the upper quartile of lot size consumed 22.8% of the total water while representing only 19.1% of the total housing units. Among those housing units with swimming pools, all consumed a higher percentage of the total water relative to their percentage of the total housing units. Overall, 8.4% of the housing units had a swimming pool, but they consumed 15.1% of the water. Additionally, 5.9% of the total housing in the largest lot parcel quartile consumed 12.0% of the total water. Thus, larger parcel size housing units consumed a disproportionate amount of the total water compared to the smaller parcel size units. This was compounded by the presence of a swimming pool. For perspective, housing units without pools averaged 838 LPD/house, while houses with pools averaged 1626 LPD/house, a 94% increase over those without swimming pools. Finally, we estimated the amount of total residential water consumed by pools by subtracting the ALPD/house in non-pool units from the ALPD/house in pool units. Here, we found that pools accounted for 7.3% of the total single-family residential water consumption.

Table 2. Correlation coefficients * for the characteristics of housing units and households with the total, seasonal, and seasonal difference average liters per day water consumption of 2009–2016.

	Average Liters per Day	Summer Average Liters per Day	Winter Average Liters per Day	Summer–Winter Difference in Average Liters per Day
Sq. M Living Space	0.52	0.56	0.43	0.45
Parcel Hectares	0.27	0.31	0.21	0.26
Swimming Pool (1 = yes)	0.37	0.41	0.29	0.34
Per Capita Income (census tract)	0.40	0.46	0.30	0.40
Averfage Houshold Size (census tract)	−0.10	−0.12	−0.06	−0.12

* All coefficients statistically significant ($p < 0.0001$).

Table 3. Single-family total average daily residential water consumption in Bexar County, Texas, 2009–2016.

Parcel Hectare	Housing Units	Percent of Total Housing Units	Average Liters per Day	Total Row Average Liters Per Day	Row Percent of Total Average Liters per Day
			All Housing Units		
<0.057	75,096	25.0%	697	52,286,309	19.2%
0.057–0.074	75,115	25.0%	785	59,024,596	21.7%
0.074–0.096	74,977	25.0%	879	65,909,082	24.2%
>0.096	75,028	25.0%	1262	94,627,920	34.8%
Total	300,216	100.0%	906	271,847,907	100.0%
			Housing Units with No Swimming Pool		
<0.057	74,371	24.8%	694	51,617,227	19.0%
0.057–0.074	73,185	24.4%	781	57,040,819	21.0%
0.074–0.096	69,967	23.3%	857	60,061,843	22.1%
>0.096	57,460	19.1%	1080	62,059,522	22.8%
Total	274,983	91.6%	838	230,779,410	84.9%
			Housing Units with Swimming Pool		
<0.057	725	0.2%	925	669,083	0.25%
0.057–0.074	1930	0.6%	1027	1,983,781	0.7%
0.0740–0.096	5010	1.7%	1167	5,847,239	2.2%
>0.096	17,568	5.9%	1853	32,568,399	12.0%
Total	25,233	8.4%	1626	41,068,501	15.1%
		Estimated Swimming Pool Units' Contribution to Total Water Consumption Beyond Irrigation and Base Use			
	Pool Units	% of total units	Pool Total ALPD Total Non-Pool ALPD	Total Pool-Associated ALPD	Pool-Associated Total ALPD as Percent of Total ALPD
	25,233	8.4%	788	19,891,709	7.3%

The summer water consumption is presented in Table 4 by parcel size quartiles. Similar to our analysis of the entire study period, smaller parcels consumed proportionately less water than the largest parcel quartile. The largest parcel quartile (25% of the units) consumed 37.8% of the single-family residential water in the summer, while the smallest parcel quartile consumed only 17.3%. When we divided the units into swimming pool and no swimming pool, we found that the large parcel quartile without pools (19.1% of all housing units) consumed 24.3% of the water. Large parcel units with swimming pools consumed more than twice (13.5%) their percentage of the total housing units (5.9%) in the summer. The estimated summer residential water consumed by pools (estimated by subtracting the summer ALPD used by non-pool units from the summer ALPD used by pool units) indicated that pool consumption was about 9.0% of the total summer water consumption (with 8.4% of all units having a pool).

Table 4. Single-family summer average daily residential water consumption in Bexar County, Texas, 2009–2016.

Parcel Hectares	Housing Units	Percent of Total Housing Units	Average Liters per Day	Total Row Average Liters per Day	Row Percent of Total Average Liters per Day
All Housing Units					
<0.057	75,096	25.0%	815	61,327,210	17.3%
0.057–0.074	75,115	25.0%	978	73,393,521	20.8%
0.074–0.096	74,977	25.0%	1137	85,182,873	24.1%
>0.096	75,028	25.0%	1781	133,644,409	37.8%
Total	300,216	100.0%	1179	353,548,012	100.0%
Housing Units with No Swimming Pool					
<0.057	74,371	24.8%	811	60,443,526	17.1%
0.057–0.074	73,185	24.4%	966	70,782,544	20.0%
0.074–0.096	69,967	23.3%	1103	77,266,760	21.9%
>0.096	57,460	19.1%	1497	86,049,756	24.3%
Total	274,983	91.6%	1073	294,542,586	83.3%
Housing Units with Swimming Pool					
<0.057	725	0.2%	1220	883,688	0.2%
0.057–0.074	1930	0.6%	1353	2,610,976	0.7%
0.074–0.096	5010	1.7%	1580	7,916,112	2.2%
>0.096	17,568	5.9%	2710	47,594,653	13.5%
Total	25,233	8.4%	2338	59,005,430	16.7%
Estimated Swimming Pool Units' Contribution to Summer Beyond Irrigation and Base Use					
	Pool Units	% of total units	Pool Total ALPD Total Non-Pool ALPD	Total Pool-Associated Summer ALPD	Pool-Associated Summer ALPD as Percent of Total Summer ALPD
	25,233	8.4%	1266	31,977,602	9.0%

The winter water consumption is shown in Table 5. Compared to the total and summer single-family water consumptions, the differentials between parcel quartiles were less stark. The largest parcel quartile consumed 31.3% of the water in the winter months. Houses without pools in the largest parcel quartile (19.1% of the total units) consumed 21.0% of the winter water. Houses with pools in the largest parcel quartile (5.9% of the total units) consumed 10.4% of the total. The estimated amount of winter residential water consumption used by pools (estimated by subtracting the winter ALPD used by non-pool units from the winter ALPD used by pool units) indicated that pool consumption was about 5.4% of the total winter water consumption (with 8.4% of all units having a pool).

We compared the winter and summer consumptions to tease apart the effects of landscape irrigation and swimming pools. To do so, we explicitly assumed that the water demand for these two purposes changed seasonally and that the indoor water use was essentially constant through the year. Thus, the differences between the summer and winter average water consumptions served as a proxy for both the water consumed by landscape irrigation and swimming pools. Table 6 presents the distribution of the differences in summer and winter consumption by parcel size quartiles and the presence and absence of a swimming pool. The largest parcels (25% of units) accounted for 49.5% of the summer–winter differences in water consumption, while the smallest parcel quartile accounted for only 10% of the differences. The largest housing units without swimming pools (19.1% of all units) accounted for 30.5% of the summer–winter differences. Among the units with a swimming pool, the units in the largest parcel quartile (5.9% of all units) accounted for 19.0% of the total summer–winter differences in water consumption. The estimated amounts of the summer–winter differences in residential water consumed by pools (estimated by subtracting the summer–winter difference ALPD used by non-pool units from the summer–winter difference ALPD used by pool units) indicated that pool consumption was only about 15.7% of the total summer–winter differences in water consumption (with 8.4% of all units having a pool).

Table 5. Single-family winter residential average daily water consumption in Bexar County, Texas, 2009–2016.

Parcel Hectares	Housing Units	Percent of Total Housing Units	Average Liters per Day	Total Row Average Liters per Day	Row Percent of Total Average Liters per Day
		All Housing Units			
<0.057	75,096	25.0%	648	48,732,313	21.4%
0.057–0.074	75,115	25.0%	697	52,407,798	23.0%
0.074–0.096	74,977	25.0%	735	55,245,648	24.3%
>0.096	75,028	25.0%	951	71,398,840	31.3%
Total	300,216	100.0%	758	227,784,594	100.0%
		Housing Units with No Swimming Pool			
<0.057	74,371	24.8%	648	48,159,557	21.1%
0.057–0.074	73,185	24.4%	694	50,824,870	22.3%
0.074–0.096	69,967	23.3%	724	50,703,427	22.3%
>0.096	57,460	19.1%	830	47,749,096	21.0%
Total	274,983	91.6%	716	197,436,950	86.7%
		Housing Units with Swimming Pool			
<0.057	725	0.2%	788	572,756	0.3%
0.057–0.074	1930	0.6%	819	1,582,924	0.7%
0.074–0.096	5010	1.7%	906	4,542,220	2.0%
>0.096	17,568	5.9%	1345	23,649,744	10.4%
Total	25,233	8.4%	1201	30,347,644	13.3%
		Estimated Swimming Pool Units' Contribution to Winter Beyond Irrigation and Base Use			
	Pool Units	% of total units	Pool Total ALPD Total Non-Pool ALPD	Total Pool-Associated Winter ALPD	Pool-Associated Winter ALPD as Percent of Total Winter ALPD
	25,233	8.4%	485	12,230,429	5.4%

Table 6. Single-family differences in the summer–winter average daily residential water consumption in Bexar County, Texas, 2009–2016.

Parcel Hectares	Housing Units	Percent of Total Housing Units	Average Liters per Day	Total Row (Hectares) Average Liters per Day	Row Percent of Total Average Liters per Day
		All Housing Units			
<0.057	75,096	25.0%	167	12,594,898	10.0%
0.057–0.074	75,115	25.0%	280	20,985,726	16.7%
0.074–0.096	74,977	25.0%	398	29,937,225	23.8%
>0.096	75,028	25.0%	830	62,245,569	49.5%
Total	300,216	100.0%	421	125,763,418	100.0%
		Housing Units with No Swimming Pool			
<0.057	74,371	24.8%	167	12,283,970	9.8%
0.057–0.074	73,185	24.4%	273	19,957,674	15.9%
0.074–0.096	69,967	23.3%	379	26,563,329	21.1%
>0.096	57,460	19.1%	667	38,300,660	30.5%
Total	274,983	91.6%	352	97,105,633	77.2%
		Housing Units with Swimming Pool			
<0.057	725	0.2%	428	310,932	0.2%
0.057–0.074	1930	0.6%	534	1,028,053	0.8%
0.074–0.096	5010	1.7%	675	3,373,892	2.7%
>0.096	17,568	5.9%	1364	23,944,909	19.0%
Total	25,233	8.4%	1137	28,657,786	22.8%
		Estimated Swimming Pool Units' Contribution to Summer–Winter Beyond Irrigation and Base Use			
	Pool Units	% of total units	Pool Total ALPD Total Non-Pool ALPD	Total Pool-Associated ALPD	Pool-Associated Sum-Win ALPD as Percent of Total Sum–Win ALPD
	25,233	8.4%	781	19,747,173	15.7%

Finally, Table 7 presents the results from modeling the total, summer, winter, and the summer–winter differences in the average liters per day over the study period, with the independent variables at the housing unit level being the presence or absence of a swimming pool, number of hectares for each housing unit, square feet of living space, and at the census tract level, per capita income. Estimates for all variables in all models were significant at $p < 0.0001$, except for per capita income in the winter model. Average household size was significant at 0.05 for the summer and the summer–winter consumption and not significant for the total or winter consumption. The findings suggested that the strength of the association between all the variables and residential water consumption was strongest for the summer months of consumption and generally the weakest in the winter. Interestingly, per capita income and average household size at the census tract level did not appear to predict winter variations in the residential water consumption. The association of independent variables with the summer–winter differences in consumption suggested that swimming pools increase in summer consumption by about 379 L per day, an additional hectare of land, by about 161 L per day, an additional 10 square meters of living space by about 1.7 L per day, and an additional USD$100 in per capita income about 0.7 L per day. An increase of one person to the average household size would increase the summer–winter differential by about 5 L per day.

Table 7. Hierarchical multivariate analysis of single-family housing unit water consumption with the housing unit and economic characteristics, Bexar County, Texas, 2009–2016.

	Total	**Summer**	**Winter**	**Summer–Winter**
	Estimate	Estimate	Estimate	Estimate
Intercept	181.62	26.08	277.82	−252.88
Swimming Pool (1 = yes)	367.45	602.54	223.74	379.1
Parcel Hectares	106.21	201.44	40.44	160.65
Total SqM Living Space	0.2484	0.3579	0.1889	0.1691
Per Capita Income	0.0032	0.0077	0.00007*	0.0077
Avg. Household Size	27.9 **	35.2 *	30.2 **	5.0 *

* Not significant at $p < 0.05$. ** Significant at $p < 0.05$. All other estimates are significant at $p < 0.0001$.

4. Discussion

The single-family residential water consumption in San Antonio varies substantially by season. The winter consumption is about 30% lower than the summer consumption. This is most likely due to the summer months in San Antonio being very hot and dry (June, July, and August averaging 8.6, 5.8, and 5.8 cm of rainfall, respectively—NOAA (National Weather Service Forecast Office)), and tiered watering restrictions associated with declining aquifer levels are the norm. The San Antonio Water System recently constructed and initiated the operation of a pipeline from the Carrizo-Wilcox Aquifer in Central Texas to San Antonio to expand and diversify the water supply for San Antonio but at a significant cost [24]. The purchase of this water and the associated pipeline, along with other system improvements, have resulted in rate increases [25]. Population growth alone increases demand, and when accompanied by houses built with larger lots with landscape irrigation systems and swimming pools, the associated increasing demand for, and price of, water is substantial. In comparison, housing units where the water demand is based largely on inside household use and minimal landscape irrigation bear a substantial portion of underwriting the costs of ensuring big lawns are green and plush and swimming pools are full. Those households living in housing units with smaller parcels and no swimming pools also may be more likely to have limits on their ability to afford an extensive use of landscape watering in the summer compared to households with higher levels of income.

Periodically, information about the housing units that consume the most water in the city is released by news media through open records requests in San Antonio [26]. Consistently, the extreme consumers of water are located in neighborhoods that have very high market values, and the owners are often recognized as being among the wealthiest in the city.

Strategies to limit increases in the summer water consumption compared to the winter baseline may be effective in reducing the overall water consumption and perhaps effective in reducing water consumption during a time of the year when rainfall may be scarce. The results from the analyses presented suggest that focusing efforts to manage water consumption on households with large square feet of living space, large lots, and swimming pools may be productive toward reducing the summer increases in residential water consumption.

Several strategies could be employed to potentially reduce the overall residential water consumption. The employment of tiered pricing might be one strategy to reduce the extremes in landscape uses of water. For housing units that consume above some defined threshold of volume in a month, the rate they pay for water consumption above the threshold would be substantially higher. This may result in both pressures to reduce excessive consumption on the part of the homeowner but then would also potentially subsidize the cost of ensuring adequate water is available at a fair and reasonable cost to those households who are consuming residential water below the threshold. This, combined with educational efforts that target areas with higher residential water consumption, may help.

Strategies for reducing the water consumption in areas with many swimming pools might also involve the education of homeowners about ways they could reduce swimming pool evaporation and manage the chemical balance to reduce the need to drain and refill swimming pools. Rebate programs for anti-evaporative pool covers may also contribute to reducing swimming pool-related water consumption. Additionally, the enforcement of water restriction rules for pools may help. Currently, at state 1 watering rules and above, the San Antonio Water System requires that all non-public swimming pools must have a minimum of 25 percent of the surface area covered with evaporation screens when not in use. Yet, this rule is rarely, if ever, advertised with a notification of restrictions, and it is unlikely that there has ever been any enforcement of this rule.

The San Antonio Water System (SAWS) has been a leader in water conservation for some time [27]. The SAWS is implementing a comprehensive water conservation plan that incorporates multiple strategies [28]. The residential customer usage in 2018 indicated that about 6% of single-family residences account for 23% of the single-family residence water consumption (each consuming 14,692 liters per month or more) [28]. Many of these high-water consumption residences have larger irrigated lots, and many have swimming pools. SAWS conservation strategies have specific programs to target residential water consumption that include a grass removal incentive program, access to conservation irrigation consultants, and consultations with homebuilders to promote low water consumption landscaping for new constructions. With forecasts that project the SAWS customer base to increase from the current estimate of 1.8 million to 3.3 million people by 2070, there will clearly be challenges in doing even more to conserve water consumption of all kinds in the future.

5. Conclusions

The results of the analyses presented suggest that much of the variations in residential water consumption are the result of landscape irrigation coupled with the presence of swimming pools and associated evaporation loss and that much of the summer–winter differential in residential water consumption can be attributed to these two uses of water. However, the water summer and the summer–winter differences in water consumption are also associated with the size of housing unit living spaces and, to a lesser degree, with the average household size. Three of these factors (parcel size, m living space, and swimming pools) are indicators of socioeconomic status and perhaps an indication that the cost and resulting affordability of water is a factor in the overall residential water consumption and the summer–winter variations. The higher demand for water from larger lot housing units, those units with swimming pools, and those with large areas of living space challenge the supply of water during times of drought and higher temperatures.

The methods employed in the analyses presented allowed the deconstruction of the sources of residential water consumption. By comparing seasons and water consumption differences and isolating housing units with swimming pools, we were able to estimate the volumes of water consumed by irrigation and swimming pool use and the volumes of elevated demand for these two uses of water associated with seasonal changes. The results of the type of analyses presented might prove to be useful in developing strategies to target sources of water use that would promote and advance conservation. Additionally, our results indicated that, by forecasting the housing unit, parcel, and population characteristics of new housing being added to an area, forecasting the residential water demand is likely to be more accurate, and different scenarios could be constructed (i.e., fewer swimming pools, smaller parcels, etc.) to examine the potential strategies for slowing the increase in demand for residential water uses.

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References

1. Mihunov, V.V.; Lam, N.S.; Zou, L.; Rohli, R.V.; Bushra, N.; Reams, M.A.; Argote, J.E. Community Resilience to Drought Hazard in the South-Central United States. *Ann. Am. Assoc. Geogr.* **2018**, *108*, 739–755. [CrossRef]
2. Schwantes, A.M.; Swenson, J.J.; González-Roglich, M.; Johnson, D.M.; Domec, J.; Jackson, R.B. Measuring canopy loss and climatic thresholds from an extreme drought along a fivefold precipitation gradient across Texas. *Glob. Change Biol.* **2017**, *23*, 5120–5135. [CrossRef] [PubMed]
3. Venkataraman, K.; Tummuri, S.; Medina, A.; Perry, J. 21st century drought outlook for major climate divisions of Texas-based on CMIP5 multimodel ensemble: Implications for water resource management. *J. Hydrol.* **2016**, *534*, 300–316. [CrossRef]
4. Wuebbles, D.; Meehl, G.; Hayhoe, K.; Karl, T.R.; Kunkel, K.; Santer, B.; Wehner, M.; Colle, B.; Fischer, E.M.; Fu, R.; et al. CMIP5 Climate Model Analyses: Climate Extremes in the United States. *Bull. Am. Meteorol. Soc.* **2014**, *95*, 571–583. [CrossRef]
5. Nielsen-Gammon, J.W.; Banner, J.L.; Cook, B.I.; Tremaine, D.M.; Wong, C.I.; Mace, R.E.; Gao, H.; Yang, Z.; Gonzalez, M.F.; Hoffpauir, R.; et al. Unprecedented Drought Challenges for Texas Water Resources in a Changing Climate: What Do Researchers and Stakeholders Need to Know? *Earth's Future* **2020**, *8*, 1552. [CrossRef]
6. Revelle, R. The Scientist and the Politician. *Science* **1975**, *187*, 1100–1105. [CrossRef]
7. U. S. Census Bureau. City and Town Population Totals: 2010–2019. Available online: https://www.census.gov/data/tables/time-series/demo/popest/2010s-total-cities-and-towns.html (accessed on 25 August 2021).
8. House-Peters, L.; Chang, H. Urban water demand modeling: Review of concepts, methods, and organizing principles. *Water Resour. Res.* **2011**, *47*, W05401. [CrossRef]
9. Texas Demographic Center. Population Projections for Texas. Available online: https://demographics.texas.gov/ (accessed on 23 August 2021).
10. De Oliver, M. Attitudes and Inaction: A Case Study of the Manifest Demographics of Urban Water Conservation. *Environ. Behav.* **1999**, *31*, 372–394. [CrossRef]
11. Lazarus, A.; Sharp, J.S. Explaining Residential Energy Consumption: A Focus on Location and Race Differences in Natural Gas Use. *J. Rural Soc. Sci.* **2011**, *26*, 107.
12. Valenzuela, C.; Valencia, A.; White, S.; Jordan, J.; Cano, S.; Keating, J.; Nagorski, J.; Potter, L.B. An analysis of monthly household energy consumption among single-family residences in Texas, 2010. *Energy Policy* **2014**, *69*, 263–272. [CrossRef]
13. Solveig, E.; Ragnar, N. Consumption and Population Age Structure. *J. Popul. Econ.* **2008**, *21*, 505–520. [CrossRef]
14. Chang, H.; Parandvash, G.H.; Shandas, V. Spatial Variations of Single-Family Residential Water Consumption in Portland, Oregon. *Urban Geogr.* **2010**, *31*, 953–972. [CrossRef]
15. Wentz, E.A.; Gober, P. Determinants of Small-Area Water Consumption for the City of Phoenix, Arizona. *Water Resour. Manag.* **2007**, *21*, 1849–1863. [CrossRef]
16. Harlan, S.L.; Yabiku, S.T.; Larsen, L.; Brazel, A.J. Household Water Consumption in an Arid City: Affluence, Affordance, and Attitudes. *Soc. Nat. Resour.* **2009**, *22*, 691–709. [CrossRef]
17. Xue, P.; Hong, T.; Dong, B.; Mak, C. A preliminary investigation of water usage behavior in single-family homes. *Build. Simul.* **2017**, *10*, 949–962. [CrossRef]
18. House-Peters, L.; Pratt, B.; Chang, H. Effects of Urban Spatial Structure, Sociodemographics, and Climate on Residential Water Consumption in Hillsboro, Oregon1. *JAWRA J. Am. Water Resour. Assoc.* **2010**, *46*, 461–472. [CrossRef]
19. Grafton, R.Q.; Ward, M.B.; To, H.; Kompas, T. Determinants of residential water consumption: Evidence and analysis from a 10-country household survey. *Water Resour. Res.* **2011**, *47*, 1–14. [CrossRef]

20. Bennett, C.; Stewart, R.A.; Beal, C.D. ANN-based residential water end-use demand forecasting model. *Expert Syst. Appl.* **2013**, *40*, 1014–1023. [CrossRef]
21. Mini, C.; Hogue, T.S.; Pincetl, S. The effectiveness of water conservation measures on summer residential water use in Los Angeles, California. *Resour. Conserv. Recycl.* **2015**, *94*, 136–145. [CrossRef]
22. Gato-Trinidad, S.; Jayasuriya, N.; Roberts, P. Understanding urban residential end uses of water. *Water Sci. Technol.* **2011**, *64*, 36–42. [CrossRef]
23. Rathnayaka, K.; Hector, M.; Shiroma, M.; Biju, G.; Bandara, N.; Meenakshi, A.; Peter, R. Seasonal Demand Dynamics of Residential Water End-Uses. *Water* **2015**, *7*, 202–216. [CrossRef]
24. Huddleston, S. Like it or not, Vista Ridge pipeline now delivering water to San Antonio. In *San Antonio Express-News*; Hearst Corporation: New York, NY, USA, 2020.
25. Cline, S. San Antonio water customers facing continued rate increases in 2020. In *San Antonio Express-News*; Hearst Corporation: New York, NY, USA, 2019.
26. Chavey, S.M. Ranked: San Antonio's top 20 residential water users so far in 2018. In *San Antonio Express-News*; Hearst Corporation: New York, NY, USA, 2018.
27. Petersen, C. Like a cactus: San Antonio water system has made conserving water in the desert look easy with its innovative conservation efforts and expansion. *US Bus. Rev.* **2009**, *9*, 34.
28. San Antonio Water System. 2019 SAWS Five-Year Conservation Plan. Available online: https://www.saws.org/conservation/conservation-conservation-plan/ (accessed on 18 November 2021).