Using process models to estimate residential water use and population served

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A key measure of efficiency in the field of urban water demand is gallons per capita per day of water use. One popular metric, gross gallons per capita per day, can be misleading because it includes nonresidential water uses. As an alternative, this article addresses the calculation of residential water use defined as the product of population and per capita use associated solely with people who are physically present and using water in single-family and multifamily residences at a given time. This approach allows for consistent benchmarking because per capita use multiplied by population yields the actual amount of water delivered to the residential sector. Process models for residential population and indoor and outdoor per capita water use can be used to estimate total residential water use if they incorporate the variability among fixture end uses and irrigable area for every household served by a utility. When this approach was applied to the Sanford, Fla., case study area, the process models predicted single- and multifamily water use with reasonable accuracy.

Keywords: *alternative water supply, per capita water use, population, process model, water demand management, water resources*

A key measure of efficiency in the field of urban water demand is gallons per capita per day of water use. From a process point of view, it is important to define which component(s) of water use and population are represented by the numerator and denominator of the gallons per capita per day calculation in order for water demand trends in a given area to be accurately characterized and evaluated. Many areas are developing standardized terminology and definitions to permit consistent benchmarking of water use across utilities as well as other applications. For example, extensive efforts have been undertaken in California to define the terms of water use and population for consistent benchmarking in response to the target of a 20% reduction in gallons per capita per day use by 2020 (CDWR, 2010).

One popular metric is gross gallons per capita per day, which can be defined as the total volume of treated potable water delivered to the water distribution system divided by the total population served. However, this measure can be misleading because it includes nonresidential water uses, which range from < 5 to > 50% of total use, depending on the blend of customers. This measure also includes water losses calculated by comparing the volume of water delivered from the treatment plant(s) with the volume of water delivered to all customers, as measured by their meters. Water losses constitute 5–25% of the potable water produced. Additionally, accounting for the functional water-using population of the nonresidential sectors is challenging and not well defined. Alternative methods for estimating nonresidential uses on the basis of the heated area of buildings rather than population are presented in Morales et al (2011).

This article addresses the calculation of total residential water use defined as the product of population and per capita water use associated solely with people who are physically present and using water in the single-family residential (SFR) and multifamily residential (MFR) sectors at a given time. This approach allows consistent benchmarking because per capita use multiplied by population yields the actual amount of water delivered to the residential sector. The physically present population includes permanent residents as well as seasonal residents who are present at a given time. Other population sources—e.g., temporary water users such as tourists and people in group quarters—are taken into account separately within the commercial, industrial, and institutional (CII) sectors. In contrast, CII water use estimates rely on a variety of size measures such as number of employees and heated area per building unit (Morales et al, 2013).

Separate models are presented for estimating the residential water-using population, indoor per capita water use, and outdoor per capita water use. The models for indoor and outdoor per capita use incorporate variability among fixture end uses and irrigable area for every household served by a utility. The residential water-using population is based on designated water utility boundaries rather than political boundaries and is modeled with high-quality property appraisal and US Census block data.

Process models for indoor and outdoor per capita water use can be used to predict total water use by determining the product of modeled population and modeled per capita water use for residential users who are physically present and using water at a given time. If data on the total volume of residential water deliveries are available, predicted total residential water use can then be compared with measured total residential water deliveries to validate both the population and per capita process models. This data-driven, bottom-up approach permits more precise estimates of population and water use trends because it directly accounts for variability among heterogeneous users on the basis of well-defined land-use codes and census block delineations. A case study of 13,555 SFR and MFR parcels in Sanford, Fla., where high-quality tax assessor and monthly billing data are available, illustrates these techniques.

The article concludes by describing the validation of model assumptions compared with measured residential water use. These parcel-level methods are being incorporated into a web-based tool designed for a variety of urban water supply applications throughout Florida. Called the Conserve Florida Water EZ Guide 2.0, the tool is available at http://conservefloridawater.org.

LITERATURE REVIEW

Modeling urban water demand has received significant attention in the past few decades, with much of the focus on long-term forecasts for water supply–planning applications (House-Peters & Chang, 2011). Much of this literature uses statistical techniques, such as time series regression, to predict water use per home or connection on the basis of a variety of causal factors including weather, water price, household income, household size, house square footage, and the presence of homeowner associations. (Refer to Donkor et al [2013], Tanverakul and Lee [2012], and House-Peters and Chang [2011] for detailed reviews of this literature.) A small subset of these demand-forecasting models incorporates factors related to water conservation, including conservation rate structures, homes built after 1992, type of water-using fixtures, watering restrictions, the presence of pools, and variations in the size and type of outdoor landscapes (House-Peters & Chang, 2011; Polebitski & Palmer, 2010).

Most of these models can be aggregated to a systemwide scale, with a smaller subset focusing on spatial variations categorized by census tract or block (House-Peters & Chang, 2011). Polebitski and Palmer (2010) evaluated water demand forecasting using the 100 census tracts that make up Seattle, Wash. Chen (1994) argues that census block groups are preferable to census tracts because of their increased spatial disaggregation. Chen's findings suggest that spatial disaggregation is limited primarily by data availability. In addition, these models primarily focus solely on a small subset of single-family homes, thus failing to capture either the variability among single-family and multifamily homes or the differing water use in other sectors. However, recent advances in the availability of spatial data and computational technology make it possible to estimate demand at the customer level.

A necessary first step in evaluating water use is to estimate numbers and trends in the population served by the utility. This is especially important for SFR and MFR water use because household number and size are the primary measures used to determine systemwide water use. Additionally, accurate population estimates are needed to determine per capita use, which is often used as a performance indicator. Traditional top-down methods for estimating the population served by a utility are based on US Census estimates within political boundaries, such as the boundary of the primary city or county (Viessman et al, 2009; McJunkin, 1964). Several demographic techniques—including curve fitting of historical data, comparison with similar cities, and employment forecasts—are then used to forecast population for incorporation into water demand estimates (Smith et al, 2008).

In Florida, the mandated default population is determined by the Bureau of Economic and Business Research (BEBR) at the University of Florida. The purpose of the BEBR analysis is to estimate the number of Florida's permanent residents; BEBR does not estimate seasonal or other temporary residents who may be customers of the utility (Smith & Rayer, 2004; Smith et al, 2002). BEBR uses a combination of data on building permits, electricity customers, and homestead exemptions to estimate the number of households. The number of persons per household is estimated from US Census data, along with site-specific surveys. BEBR prepares permanent population estimates for subcounty areas defined as incorporated cities and unincorporated areas. Estimates of county and state populations are sums of those in the relevant subcounty areas. These estimates are then apportioned to estimate the population served within utility boundaries associated with one or multiple subcounty areas. For water utilities, however, the most direct measure of population served is the number of customers who actually use water at a given time.

Existing methods of estimating water use and population may not be accurate or applicable to most utilities because of conflicting political and utility boundaries as well as inconsistent definitions of land use. Additionally, aggregate statistical approaches are of limited use for estimating process-level water use for each end use in a given area. Process-level or end-use modeling of customer water demand is becoming increasingly important for a variety of applications, including meaningful predictions of per capita water use at the parcel level. In response to these limitations, this article gives a new process-based methodology for estimating SFR and MFR populations and water use patterns. The new method is based on parcel-level, land-use, and water billing databases.

FLORIDA DEMOGRAPHIC DATABASES

The Florida Department of Revenue (FDOR) database provides attributes for every parcel in the state along with the parcel's land-use classification. Parcels are assigned standardized land-use codes, which can be aggregated into defined SFR and MFR sectors (FDOR, 2012). The FDOR database, in conjunction with data from the Florida County Property Appraisers and the US Census, allows parcel-level evaluation of water use and population as well as direct evaluation of best management practices for demand management. These evaluations can be conducted for any utility in Florida, given an accurate geographic information system (GIS) shapefile delineating the parcels within the utility's service area. Customer billing data provided by benchmark utilities such as the Sanford, Fla., utility discussed in this article allow refinement of parameter estimates for utilities without readily available billing data because parameter estimates relating to a specific sector's water use can be calibrated against billed use for that sector.

The dataset from the Sanford utility contains monthly water use data for 13,555 residential parcels and 1,547 nonresidential parcels from October 2005 through May 2011, along with information on the impervious area per parcel (taken from the local Seminole County Property Appraiser's database) and land-use attributes, such as land-use classification and heated building area (taken from the statewide database). This database consists of information on approximately 95% of all parcels that are occupied by residential customers served by the city of Sanford. The remaining 5% were not included because data on customer billing and parcel attributes could not be linked for this subset. (For details regarding the content and processing of these databases, refer to Friedman et al [2013, 2011] and Morales et al [2013, 2011].) This article focuses solely on analysis of the residential sector.

METHODOLOGY FOR ESTIMATING WATER USE AND POPULATION

Monthly water use (Q) at a given time (t) in any sector can be estimated using Eq 1 as the product of a water use coefficient (α_{it}); a measure of the size of the activity (x_{it}), e.g., the number of people per dwelling unit; the occupancy rate for this activity (r_{it}); and the number of activity units in subset i of a given sector (n_{it}), summed over all subsets (m) within the sector.

$$Q_t = \sum_{i=1}^{m} (\alpha_{it} \times x_{it} \times r_{it} \times n_{it}) \tag{1}$$

For the SFR and MFR sectors, in which the measure of size is based on number of people, the population of physically present water-using customers in the residential sector (p), at a given time (t), can be estimated using Eq 2, as the product of people per occupied dwelling unit (x_{it}), the occupancy rate (r_{it}), and the total number of (vacant + occupied) dwelling units on water-using residential parcels (n_{it}) in each subgroup i within the residential sector. The water use coefficient (α_{it}) can be defined as the per capita water use associated with the physically present water-using population. Therefore, the product of the water use coefficient and the physically present water-using population yields total residential water use (Q_t).

$$p_t = \sum_{i=1}^{m} (x_{it} \times r_{it} \times n_{it}) \tag{2}$$

Parcel-level population and per capita water use are estimated as independent variables to determine total residential water use. Customer billing data are used solely as a means to calibrate model assumptions and to validate model accuracy. Defining population and per capita water use as representing only the people physically present and using water on SFR and MFR parcels at a given time allows meaningful comparisons.

RESIDENTIAL WATER-USING POPULATION

Defining the utility service area. A critical first step in determining the water-using residential population served is to accurately determine the parcels within a given utility service area. This can be accomplished by using spatial join tools within specialized GIS software,[1] given GIS layers showing the boundaries of parcels and the boundaries of the utility's service area. A GIS layer containing all Florida parcels is available from FDOR. GIS layers for utility service areas are publically available for portions of Florida, although their accuracy should be checked by utilities that use them. The boundaries of the city of Sanford, Fla., and the service area of the Sanford water utility are compared in Figure 1. These two boundaries are significantly different—approximately 40% of the utility's service area is outside city boundaries. This highlights the need for bottom-up, parcel-driven methods of population and water use analysis within water utilities as opposed to top-down, disaggregation procedures, which rely on political boundary approximations that are difficult, if not impossible, to downscale accurately because of the irregular nature of many utility and city boundaries.

Number of parcels, accounts, and residential dwelling units. The fundamental size unit within the SFR and MFR sectors is the number of dwelling units, defined as the total number of occupied and vacant residences per parcel. FDOR directly reports the number of dwelling units per parcel for all sectors. The number of dwelling units represents a standardized-size unit, which allows accurate population estimates when combined with US Census data on people per dwelling unit.

An alternative measure of size is number of accounts. However, account breakdowns by sector vary depending on how the utility defines sectors. In addition, determining population for MFR accounts is challenging because the number of people per account varies widely, depending on how each account is metered. Few MFR developments meter water use by individual units. For these reasons, the number of dwelling units is preferred rather than the number of accounts.

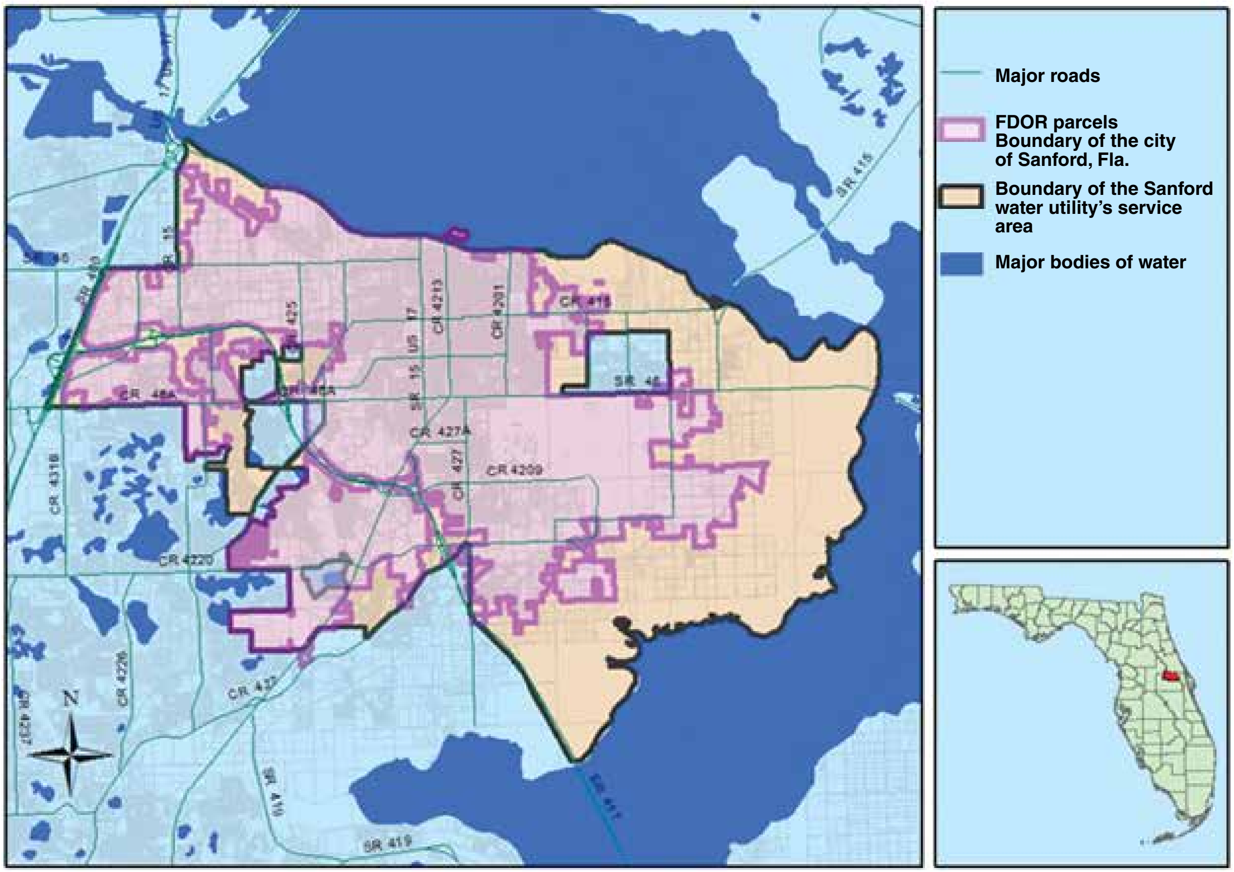
Summary statistics of size attributes for the Sanford case study are shown in Table 1. Although the majority of developed residential parcels are within the SFR sector, 20% of the total heated area comprises MFR structures containing 10 units or more, with an average of 145 residential units per parcel.

Using the standardized definition of terms provided in the FDOR database, Eq 2 can be written more explicitly, as shown by Eq 3, to estimate population for a utility's water-using residential parcels. In this approach, every parcel is a subgroup within a residential sector. Total residential population is the summation of the population across the seven SFR and MFR land-use codes, as defined by FDOR.

$$p_t = \sum_{i=1}^{m} (x_{it} \times r_{it} \times n_{it} \times \gamma_{it}),\ \gamma_{it} = \begin{cases} 1, \text{ parcel consists of at least 1 active account} \\ 0, \text{ parcel does not have any active accounts} \end{cases} \tag{3}$$

in which p_t is the water-using population for a residential sector at time t, x_{it} is the number of persons per occupied residential unit on parcel i at time t, r_{it} is the percentage of occupied water-using residential units in parcel i at time t, n_{it} is the number of total residential units on parcel i at time t, γ_{it} is the binary activity on parcel i at time t, and m is the total number of parcels in the sector at time t.

FIGURE 1 Boundary of the city of Sanford, Fla., compared with the utility's service area



FDOR—Florida Department of Revenue

The term for binary parcel activity (γ_{it}), combined with the percentage of occupied residential units in active parcels (r_{it}) and the number of residential units per parcel (n_{it}), determines the number of total residential units in which people are physically present and using water on parcel i at time t. Therefore, multiplying this estimate by the number of people per occupied home (x_{it}) allows the determination of the population associated with people physically present and using water in the SFR and MFR sectors at a given time.

The activity term (γ_{it}), representing which parcels consist of residential units occupied by active utility customers in a given month, can be determined directly if customer-level water use data are available. Otherwise, the utility may be able to provide a listing of its active customers without providing actual water use data. The percentage of occupied water-using residential units in active parcels (r_{it}), as well as the average number of people per residential unit (x_{it}), can be estimated from US Census block data, as described in the following section.

People per residence and occupancy rate. A data-driven method can also be used to estimate average number of people per residence and occupancy rates at the parcel level. The US Census, the countrywide survey conducted at the individual parcel level every 10 years, documents many attributes of the nation's population, including housing data. Data from the 2000 and 2010 censuses are available at the census block level of spatial aggregation (www.census.gov/geo/maps-data/data/tiger.html). Census files from both 2000 and 2010 were combined with current utility boundaries in a GIS program to ascertain the 881 census blocks within the Sanford utility as of 2010. Each developed SFR and MFR parcel was then assigned to the census block that encompassed the centroid of its parcel boundary, which included the 2000 and 2010 average number of people per residence and percent occupancy. The US Census does not distinguish single-family residents from multifamily residents and percent occupancy, and this missing element is critical for separating SFR and MFR populations accurately.

A proposed algorithm to prorate the combination of people per residence and percent occupancy into components is as follows. First, each census block is classified as SFR only, MFR only, or hybrid on the basis of parcel land uses within a given block. Proration of people per residence and percent occupancy into SFR and MFR components is then determined for hybrid blocks on the basis of the relative mix of SFR and MFR units and the assumed ratios of single-family residents to multifamily residents and percent occupancy based on block averages of single-family

TABLE 1 Size attributes for 13,555 Sanford, Fla., SFR and MFR parcels within land-use codes 1–4, 7, 8, and 28 in the FDOR database

FDOR Land-Use Code	Water Use Sector	Description of FDOR Land-Use Code	Total Parcels	Percent of Total Parcels %	Total Heated Area *1,000 sq ft*	Percent of Total Heated Area—%	Heated Area per Parcel *sq ft*	Total Residential Units	Percent of Total Residential Units %	Residential Units per Parcel	Heated Area per Residential Unit *sq ft*
1	SFR	Single family residential	13,118	96.78	19,753	76.99	1,506	13,265	66.41	1.01	1,489
2	SFR	Mobile homes	12	0.09	23	0.09	1,924	12	0.06	1.00	1,924
3	MFR	Multifamily (10 units or more)	37	0.27	5,156	20.10	139,352	5,347	26.77	144.51	964
4	SFR	Condominiums	78	0.58	103	0.40	1,324	78	0.39	1.00	1,324
7	MFR	Miscellaneous residential	5	0.04	9	0.04	1,796	NA	NA	NA	NA
8	MFR	Multifamily (< 10 units)	298	2.20	602	2.35	2,020	708	3.54	2.38	850
28	MFR	Mobile home parks	7	0.05	9	0.03	1,256	564	2.82	80.57	16
		Total or weighted average	13,555	100.00	25,655	100.00	1,893	19,974	100.00	1.47	1,284

FDOR—Florida Department of Revenue, MFR—multifamily residential, NA—not applicable, SFR—single-family residential

residents only and multifamily residents only, as shown in Eqs 4 and 5. The average number of people per residence and percent occupancy for years other than 2000 and 2010 are determined from linear interpolation of the 2000 and 2010 benchmark years. Once baseline, parcel-level water use, and population estimates have been determined, reliable projections based on future build-out of land uses can be made as undeveloped parcels are developed (GIS Associates, 2010).

$$X_b = \lambda_b X_{b,\mathrm{SFR}} + (1 - \lambda_b)\, X_{b,\mathrm{MFR}},\ \frac{X_{b,\mathrm{SFR}}}{X_{b,\mathrm{MFR}}} = k \tag{4}$$

in which X_b is the reported average number of people per residential unit for hybrid census block b, $X_{b,\mathrm{SFR}}$ is the average number of people per SFR unit in census block b, λ_b is the percentage of SFR units in census block b ($0 \leq \lambda_b \leq 1$), $X_{b,\mathrm{MFR}}$ is the average number of people per MFR unit in census block b, and k is the ratio of single-family residents per household to multifamily residents per household.

$$r_b = \lambda_b r_{b,\mathrm{SFR}} + (1 - \lambda_b)\, r_{b,\mathrm{MFR}},\ \frac{r_{b,\mathrm{SFR}}}{r_{b,\mathrm{MFR}}} = m \tag{5}$$

in which r_b is the reported average occupancy rate for hybrid census block b, $r_{b,\mathrm{SFR}}$ is the average occupancy rate for SFR units in census block b, λ_b is the percentage of SFR units in census block b ($0 \leq \lambda_b \leq 1$), $r_{b,\mathrm{MFR}}$ is the average occupancy rate for MFR units in census block b, and m is the ratio of SFR occupancy to MFR occupancy.

The 881 census blocks in the Sanford water utility's service area were divided into the three categories shown in Table 2. Of the 881 census blocks, 726 contained only SFR or MFR parcels, with an average of 15.2 SFR units per census block. The remaining 155 census blocks were hybrids with a blend of SFR and MFR units. The reported average number of people per unit and occupancy rates for hybrid census blocks in 2000 and 2010 were disaggregated into their SFR and MFR components using Eqs 4 and 5. The relative blend of SFR to MFR units for each block in Sanford is known from the FDOR parcel database. Ratios of the average number of single-family residents to multifamily residents and percentage occupancy, based on SFR- and MFR-only blocks (Table 2), were then used to determine the number of single-family and multifamily residents and occupancy rates for each of the 155 hybrid census blocks.

PROCESS-LEVEL MODELING OF RESIDENTIAL WATER USE

Total water use is calculated as the product of modeled population and per capita water use. The discussion thus far has focused on a method for determining population on the basis of property appraisal data combined with census block data on people per residential unit and occupancy rate. The next sections focus on a process-level approach to modeling per capita indoor and outdoor residential water use.

Modeling per capita indoor residential use. Modeling per capita indoor water use requires determining how many of each end-use device exists in each residential unit. Four primary end-use devices were tracked: toilets, showerheads, clothes washers, and faucets. These four devices represent approximately 95% of indoor SFR

TABLE 2 Average number of people per residential unit in Sanford, Fla., and percent occupancy at the census block level of aggregation

Census Block Description	Category	Census Blocks in Sanford	Number of Parcels	Number of Residential Units	Average Number of People per Occupied Residential Unit (2000 Census)	Average Number of People per Occupied Residential Unit (2010 Census)	Average Occupancy (2000 Census) %	Average Occupancy (2010 Census) %
Census blocks with either SFR or MFR parcels	SFR	695	10,465	10,567	2.79	2.85	0.93	0.90
	MFR	31	75	3,720	2.41	2.49	0.89	0.83
	Total residential	726	10,540	14,287	2.69	2.76	0.92	0.88
	SFR/MFR ratio				1.16	1.14	1.04	1.08
Census blocks with both SFR and MFR parcels	SFR*		2,665	2,710	2.75	2.82	0.93	0.90
	MFR*		350	2,977	2.38	2.46	0.90	0.84
	Total residential	155	3,015	5,687	2.50	2.59	0.92	0.87
All census blocks	SFR		13,130	13,277				
	MFR		425	6,697				
	Total residential	881	13,555	19,974	2.64	2.71	0.92	0.88

MFR—multifamily residential, SFR—single-family residential

*The average number of people per occupied SFR and MFR unit and the occupancy rate were estimated using a proration procedure applied within hybrid blocks.

water use, assuming that leaks occurring inside the customer's residence can be prorated to each end use (DeOreo, 2011). Dishwashers are excluded because they constitute a relatively minor percentage of residential water use.

The quantity of each end-use device within a SFR or MFR unit can be estimated on the basis of the number of bathrooms per household, as shown in Table 3. A half bath is assumed to have a toilet and faucet but no showerhead. All residential units are assumed to have one kitchen faucet. One clothes washer is assumed to be installed in 97% of SFR and 63% of MFR units, on the basis of the 2007 American Housing Survey for Tampa, Fla. (US Census Bureau, 2009).

Determining a rated flow for a given fixture within a given home is governed by the required or available technology that existed when the home was built and what is required or available when a homeowner decides to replace existing fixtures. For any given point in time, a fixture can be classified by either the required or lowest available rated flow in one of the five demand-management periods shown in Table 4. Average flow rates and frequencies of use were based on an extensive literature review (DeOreo & Mayer 2012; Aquacraft, 2005; Mayer et al, 1999; Brown and Caldwell, 1984). These studies found frequency and duration to be nearly constant both spatially and temporally. Therefore, only changes in rated flow per device needed to be determined.

As an initial condition, all fixtures were assigned to the demand-management period corresponding to the effective year when the home was built (this information is available for every developed parcel in Florida). All fixtures were initially assigned to the required flow for that period, because this corresponds to the plumbing codes required at the time of construction. Homes were not assigned any fixtures if the year being simulated predated the effective year of construction.

For any time period after the year of construction, household members decide whether to replace their existing fixtures with fixtures having either the lowest available or required rated flow available during the current year's demand-management period.

TABLE 3 Estimated number of fixtures based on number of bathrooms in residential units

Bathrooms per Residential Unit	Toilets per Residential Unit	Clothes Washers per Residential Unit*	Shower-heads per Residential Unit	Faucets per Residential Unit
1	1	1	1	2
1.5	2	1	1	3
2	2	1	2	3
2.5	3	1	2	4
3	3	1	3	4
3.5	4	1	3	5
4	4	1	4	5
4.5	5	1	4	6
5 or more	5	1	5	6

*For percentage of residences estimated to have clothes washers

TABLE 4 Average lowest available and required rated flows for residential fixtures

Demand-Management Period	Toilet		Showerhead*		Clothes Washer		Faucet	
	Lowest Available Flow Rate *gal/flush*	Required Flow Rate *gal/flush*†	Lowest Available Flow Rate *gal/min*	Required Flow Rate *gal/min*†	Lowest Available Flow Rate *gal/load*	Required Flow Rate *gal/load*†	Lowest Available Flow Rate *gal/min*	Required Flow Rate *gal/min*†
Pre-1983	5	5	6.5	6.5	56	56	5	5
1983–1994	3.5	3.5	3	3	51	51	2.8	2.8
1995–2004	1.6	1.6	2.5	2.5	41	41	2.2	2.2
2005–2009	1.28	1.6	2	2.5	27	41	1.5	2.2
2010–present	1.1	1.6	1.5	2.5	14	41	0.5	2.2
Number of uses per person per day	5.1		0.7		0.37		8.1	

*An average shower has a duration of 8 min.
†Required by plumbing code standards during a given period

Two driving forces are assumed to determine a household decision about fixture replacement—fixture service life and economic optimization—although other factors also affect the decision. Use of a model designed to simulate an "economically rational person" provides a consistent way to assign a value representing the propensity to replace a fixture. Results from this model can be compared with historical water use to calibrate the forecast against observed behavior.

The consideration of fixture service life assumes that all households replace an existing fixture at the end of its useful service life with a fixture having the rated flow required by the plumbing code in effect during the replacement year's demand-management period. The consideration of economic optimization involves each household making an annual, independent decision about whether to replace an existing fixture with one having the lowest rated flow available, given the cost-effectiveness of the water saved over the life of the new device versus the initial cost of its purchase and installation. Household members decide to replace a fixture if the net present value of this investment is greater than some minimum net benefit threshold (NB_{min}), which factors in a household's inclination or reluctance to make the investment. Both the economic optimization and service life criteria can be used as calibration parameters.

Although all households are assumed to follow these rules, several clusters of households can be observed on the basis of specific attributes, including year the home was built, number of people per residence, and fixture inventory. Therefore, physical attributes and variations in water use behavior among households affect overall water use within a utility's service area. For example, modeling results for an older community with smaller homes will differ from results for a newer community with larger homes. The relative blend of physical attributes among homes drives the overall household behavior of the community.

Morales et al (2013) conducted a detailed review of service lives and costs for popular indoor end-use devices in all urban water use sectors. The service lives and costs (including capital and installation costs) of fixtures modeled in the simulation of indoor residential use are shown in Table 5. All costs are in 2011 dollars. With the use of these data, the household-based simulation model for tracking residential fixtures was formulated. This model tracks two variables—installed rated flow (F_t) and remaining service life (RSL_t)—throughout the period of simulation, with a step size of Δt = 1 year. A time step of one year is adequate to simulate long-term trends in fixture-rated flow and indoor water use because seasonal differences in indoor use are minimal. For each home, the simulation starts the year the house was built, as shown as Eq 6. Based on the year the house was built (yrblt), the initial rated flow of a given fixture at the time of installation was assigned to the rated flow required by its plumbing code during that year's demand-management period, as shown in Eq 7. The remaining service life of a new fixture was set equal to its full service life, as shown in Eq 8.

$$t_0 = \mathrm{yrblt}_i \tag{6}$$

$$F_{0,fi} = F_{\mathrm{req},t0,f} \tag{7}$$

$$\mathrm{RSL}_{0,fi} = \mathrm{SL}_f \tag{8}$$

in which yrblt_i is the year the house was built within parcel i, $F_{0,fi}$ is the initial rated flow (gallons per use) at year $t = 0$ (start year) for fixture f in parcel i, $F_{\mathrm{req},t0,f}$ is the rated flow (gallons per use) required by the plumbing codes in effect in year $t = 0$ for fixture f, $\mathrm{RSL}_{0,fi}$ is the remaining service life (in years) at year $t = 0$ for fixture f in parcel i, and SL_f is the service life (in years) for fixture f.

For each year after the house was built, the net benefit of exchanging its existing fixtures for the lowest rated flow technology available during the current demand-management period was calculated using Eqs 9–13. The net benefit weighs the total cost of the new fixture against the total water savings accrued

TABLE 5 Service life and cost* of modeled fixtures with the lowest-available rated flows

Demand-Management Period	Toilet		Showerhead		Clothes Washer		Faucet	
	Service Life *years*	Cost per Lowest-Flow Fixture *$*	Service Life *years*	Cost per Lowest-Flow Fixture *$*	Service Life *years*	Cost per Lowest-Flow Fixture *$*	Service Life *years*	Cost per Lowest-Flow Fixture *$*
Pre-1983	40	NA	8	NA	11	NA	15	NA
1983–1994	40	325	8	43	11	550	15	67
1995–2004	40	325	8	43	11	550	15	67
2005–2009	40	355	8	44	11	650	15	77
2010–present	40	475	8	46	11	850	15	92

Source: Morales et al, 2013

NA—not applicable

*All costs are in 2011 dollars.

by the customer during the fixture's service life. An important feature of this calculation is how weighted-average savings are calculated in Eq 9. The unit water savings achieved by the new fixture is the average volume of water saved between the existing fixture and the lowest-rated flow technology available during the fixture's remaining service life, plus any additional water saved from the difference between potential required flow technology and the lowest-rated flow technology available from the end of the existing fixture's remaining service life to the end of the new fixture's service life. This calculation reflects decreased savings from a mandated reduction of rated flow at the end of the existing fixture's service life.

$$q_{s,t+1,fi} = \left[(F_{t,fi} - F_{\text{low},t+1,f}) \frac{\text{RSL}_{t,fi}}{\text{SL}_f} + (F_{t,fi} - F_{\text{req},t+1,f}) \frac{\text{SL}_f - \text{RSL}_{t,fi}}{\text{SL}_f} \right] \times \frac{\text{util}_f \times x_{it} \times \text{dur}_j}{\text{nfix}_{fi}} \tag{9}$$

$$Q_{s,t+1fi} = \frac{q_{s,t+1,fi} \times \text{SL}_f \times 365 \times \text{nfix}_{fi}}{1{,}000} \tag{10}$$

$$B_{t+1,fi} = b_t \times Q_{s,t+1,fi} \tag{11}$$

$$C_{t+1,fi} = c_{\text{xlow},t+1,f} \times \text{nfix}_{fi} \tag{12}$$

$$\text{NB}_{t+1,fi} = B_{t+1,fi} - C_{t+1,fi} \tag{13}$$

in which $q_{s,t+1,fi}$ is the average daily volume of water saved (gallons per fixture) between an existing fixture and the lowest-rated flow technology available in year $t + 1$ during the existing fixture's remaining service life, plus any additional water saved from the difference between potential required flow technology and the lowest-rated flow technology available from the end of the existing fixture's remaining service life to the end of the new fixture's service life; $F_{t,fi}$ is the installed rated flow (gallons per flush) at year t for fixture type f in parcel i; $F_{\text{low},t+1,f}$ is the lowest-rated flow technology (gallons per use) available in year $t + 1$ for fixture type f; $\text{RSL}_{t,fi}$ is the remaining service life (in years) at year t for fixture type f in parcel i; $F_{\text{req},t+1,f}$ is the required rated-flow technology (gallons per use) based on plumbing codes for fixture type f installed in year $t + 1$; util_f is the utilization rate (use per person per day) for fixture type f; dur_f is the duration of use (in minutes—applicable only to showerheads); nfix_{fi} is the number of a given fixture f in parcel i; $Q_{s,t+1,fi}$ is the total volume of water saved (in 1,000 gallons) from retrofitting all of a given fixture type f in parcel i with the lowest-rated flow technology available in year $t + 1$ for the service life of the new device; $B_{t+1,fi}$ is the total benefit (in dollars) of retrofitting all of a given fixture type f on parcel i with the lowest-rated flow technology available in year $t + 1$; b_t is the value to the homeowner of water saved (in dollars per 1,000 gallons), based on water rates in year t; $C_{t+1,fi}$ is the total cost (in dollars) of retrofitting all of a given fixture type f on parcel i with the lowest-rated flow technology available in year $t + 1$; $c_{\text{xlow},t+1,f}$ is the unit cost (in year t dollars per fixture) of retrofitting one of a given fixture type f on parcel i with the lowest-rated flow technology available in year $t + 1$; and $\text{NB}_{t+1,fi}$ is the net benefit of retrofitting all of a given fixture type f on parcel i with the lowest-rated flow technology available in year $t + 1$.

Once the net benefit has been calculated, the rated flows and remaining service lives of fixtures can be updated on the basis of economic considerations, device attrition, or both as a result of useful service life, as shown by Eqs 14 and 15. Each year, installed rated flow can be updated to one of three conditions: the lowest available rated flow, the rated flow required by the plumbing code, or the existing rated flow (i.e., no change). For a given year, a fixture's condition switches to the lowest-rated flow available if the net benefit (NB) is positive and exceeds the threshold (NB_{min}). If the net benefit of the fixture with the lowest-rated flow is below this threshold but the remaining service life is one year, the fixture with the rated flow required by the plumbing code will be installed the next year because the existing fixture will be replaced as a result of attrition. If neither of these two conditions is the case, then the fixture will not be replaced, and the rated flow will not change. The value of NB_{min} reflects the propensity to retrofit fixtures and can be calibrated to reflect actual household decisions. Remaining service life resets to the full service life if a retrofit occurred or decreases by one year if no replacement occurred.

$$F_{t+1,fi} = \begin{cases} F_{low,t+1,f} & NB_{t+1,fi} > NB_{min} \\ F_{req,t+1,f} & RSL_{t,fi} = 1 \text{ and } NB_{t+1,fi} \leq NB_{min} \\ F_{t,fi} & \text{otherwise} \end{cases} \quad (14)$$

$$RSL_{t+1,fi} = \begin{cases} SL_f & NB_{t+1,fi} > 0 \text{ or } RSL_{t,fi} = 1 \\ RSL_{t,fi} - 1 & \text{otherwise} \end{cases} \quad (15)$$

in which $F_{t+1,fi}$ is the installed rated flow (gpf) at year $t + 1$ for fixture type f on parcel i, NB_{min} = the decision threshold, and $RSL_{t+1,fi}$ is the remaining service life (in years) at year $t + 1$ for fixture type f on parcel i.

As an example, consider a house built in 1985 with two people using one toilet with five flushes per person per day and a toilet service life of 40 years. In 2010, assume the current installed rated flow is 3.5 gpf, the remaining service life is 15 years (40 – [2010–1985]), and the required rated flow to be installed at the end of remaining service life (2025) is 1.6 gpf. Now assume that in 2010, a new 0.8-gpf toilet comes to market. If the value of the potential water savings is \$2/1,000 gal and the initial cost of a 0.8-gpf toilet is \$475, the net benefit of this investment from the perspective of an individual customer can be computed by Eqs 9–13. The incremental operating cost of the toilet is assumed to be zero.

$$q_{2010} = \left[(3.5 \text{ gpf} - 0.8 \text{ gpf}) \frac{15}{40} + (1.6 \text{ gpf} - 0.8 \text{ gpf}) \frac{40 - 15}{40} \right] \times \frac{5 \text{ flush/person/d} \times 2 \text{ people}}{1 \text{ toilet}} = 15.13 \text{ gal/toilet/d}$$

$$Q_{s,t+1} = \frac{15.13 \text{ gal/toilet/d} \times 40 \text{ y} \times 365 \text{ d/y} \times 1 \text{ toilet}}{1{,}000} = 220.90 \text{ kgal}$$

$$B_{t+1} = \$2/\text{kgal} \times 220.90 \text{ kgal} = \$441.80,\ C_{t+1} = 475/\text{toilet} \times 1 \text{ toilet} = \$475$$

$$NB_{t+1} = \$441.80.78 - \$475 = -33.20$$

A negative net benefit and a remaining service life of > 1 year indicate that no change would be made—i.e., the homeowner would keep the 3.5-gpf toilet. In 2011, the existing toilet's remaining service life would become 14 years. Equivalently, the preceding calculation can be generalized for determining the break-even (or prespecified NB_{min}) number of years of remaining service life. If the remaining service life is greater than or equal to this threshold, the customer would replace the fixture. The utility can also use this analysis to estimate the potential effect of financial incentives—e.g., a \$50 incentive would result in a net benefit in this example.

Simulating trends in aggregate, per capita indoor water use. Simulated trends in aggregate per capita indoor water use for a given fixture were calculated as the weighted-average flow rate across all parcels within a given sector at time t multiplied by the average rate of use (Eq 16). DeOreo (2011) showed that leakage, which can constitute a significant component of water use, can be prorated to fixtures on the basis of the relative household use of each fixture. In the simulation model, a default value of 10% of total indoor use is assumed to be leakage.

$$q_{in,t} = \sum_{f=1}^{4} \bar{F}_{f,t} \times \text{util}_f \times \text{dur}_f + \text{leak}_{f,t} \quad (16)$$

in which $q_{in,t}$ is the sectoral, weighted-average, per capita indoor use at year t (gpcd); $\bar{F}_{f,t}$ is the average use intensity (gallons/use) for fixture f in year t; and $\text{leak}_{f,t}$ is the prorated household leakage (in gallons per person per day) attributable to fixture f in year t.

Modeling per capita outdoor residential use. Because of significant seasonal and spatial variability resulting from a wide range of factors influencing irrigation—including climate, price signals, individual practices, restrictions, and technology—outdoor water use can be much more challenging to predict than indoor use. Friedman et al (2013) conducted a detailed analysis of parcel-level irrigation patterns and trends and showed that significant variability exists among household irrigation patterns as a function of application rate and irrigable area. Furthermore, the percentage of households that irrigate with potable water varies widely among utilities, with only a portion irrigating at or above theoretical requirements. Despite this variability, Romero and Dukes (2011a) found the correlation between actual average application rates and average net irrigation requirements to be statistically significant with at least 95% confidence for seven of the 11 utilities studied. The ratio of estimated to calculated irrigation needs for the 11 utilities varied within the range of 0.46–1.02, with a weighted average of 0.78. A similar value of 0.72 was determined for Gainesville Regional Utilities irrigators (Friedman et al, 2013). These results suggest that the mean application rate of residential irrigation water can be reasonably predicted on the basis of irrigation requirements, which can be predicted by process-level modeling. A critical element of this methodology is that water used for irrigation must be evaluated for all residential customers served by a utility as opposed to a cross-sectional sample focusing on irrigators using large amounts of water.

On the basis of these results, a process-level model of average irrigation water use as a function of net irrigation requirements was adopted as an appropriate modeling framework. The model formulation is shown as Eq 17.

$$q_{out,t} = \frac{\left(\overline{AR}_{req,t} \times \dfrac{\sum_{i=1}^{m} (IA_{i,t} \times \gamma_{i,t})}{\sum_{i=1}^{m}} \times \sum_{i=1}^{m} (\gamma_{i,t}) \times \dfrac{\overline{AR}_{act,t}}{\overline{AR}_{req,t}} \times \text{Pirrig}_t \right)}{p_t} \quad (17)$$

in which $q_{\text{out},t}$ is the sectoral, average, per capita outdoor water use at time t; $\overline{AR}_{\text{req},t}$ is the average net irrigation requirement at time t; $IA_{i,t}$ is the irrigable area for parcel i at time t; $\gamma_{i,t}$ is the binary activity of parcel i at time t; $\overline{AR}_{\text{act},t}/\overline{AR}_{\text{req},t}$ is the ratio of actual average net irrigation to the irrigation requirement; Pirrig_t is the percentage of active water-using parcels on which irrigation water is taken from the potable supply at time t, and m is the total number of parcels in the sector.

The irrigable area of every residential parcel is known from property appraisal data on parcel area and impervious area (for details, refer to Friedman et al, 2013). Romero and Dukes (2011b) reported average net irrigation requirements for 10 Florida locations and one Alabama location over a 30-year period from 1980 to 2009. These requirements, based on a simulation of daily soil–water balance presented by these investigators, were used to estimate average irrigation requirements.

MODEL CALIBRATION AND VALIDATION

Proprietary spreadsheet software[2] was used to apply process models for both indoor and outdoor per capita water use to the 13,118 parcels in the FDOR database's land-use code 1 classification (consisting of SFR parcels) and the 335 parcels in the database's land-use codes 3 and 8 (consisting of MFR parcels with ≥ 10 units and < 10 units, respectively) for Sanford, Fla. The simulation period October 2005–May 2011 was used to match available billing records, allowing model calibration and validation. Population was modeled with a monthly time step to account for variability in the number of active accounts each month. Indoor use was modeled with an annual time step, and outdoor use was modeled as an annual average to permit evaluation of long-term trends in gallons per capita per day use in the Sanford utility's service area.

The model for indoor use assumed a value of water (b) of \$2/1,000 gal and a retrofit-decision threshold ($\text{NB}_{\min}$) of \$100. The model for outdoor use assumed a constant ratio of average net irrigation to irrigation requirement of 0.75 (Friedman et al, 2013). Net irrigation requirements for Orlando, Fla., were used because the data for this city most closely represented the city of Sanford. According to Romero and Dukes (2011b), the average net irrigation requirement in Orlando was 1.98 in./month. The initial estimate of the percentage of irrigators was set at 25% to reflect the extensive use of reuse water for irrigation in Sanford. The percentage of irrigators was the primary parameter used for model calibration because direct data about which customers irrigate with potable water are difficult to obtain.

Model calibration and validation involved comparing predicted annual trends in total indoor and outdoor water use with measured annual trends in total residential use for the period of record. A commonly used approach for model calibration and validation is to split the data into training and validation datasets. The training dataset is used to calibrate the model, and the validation dataset is used to evaluate the model's predictive performance (Shmueli et al, 2010). Errors in both model calibration and validation were evaluated with the criterion of mean absolute error (MAE), defined by Eqs 18 and 19. The term "mean absolute error of prediction" (MAEP) is used to distinguish predictive model error using the validation dataset from error associated with calibration using the training dataset.

The model was calibrated using a training dataset that included data from October 2005 through May 2010, with the exception of May 2008 because reported data for water use in the MFR sector during this month was an unusually low outlier. The final 12 months of available data (June 2010–May 2011) were used as the validation dataset. Model calibration and validation were performed separately for both the SFR and MFR sectors by solving a simple optimization problem to minimize the MAE between measured and predicted total water use for the training period; the optimization problem was solved by estimating parameters for the percentage of irrigators using potable water. All other parameters were unchanged. Figures 2–5 show aggregate modeled versus measured per capita and total water use trends for the SFR and MFR sectors in Sanford. Table 6 summarizes the best parameter estimates for model error and the percentage of utility customers using potable water for irrigation in the SFR and MFR sectors in Sanford. Parameter estimation resulted in a small percentage of SRF irrigators who were using potable water, reflecting an extensive network of reuse water in Sanford.

$$\text{MAE} = \left| \frac{1}{\omega} \sum_{t=1}^{\omega} \left[Q_t - p_t \left(q_{\text{in},t} + q_{\text{out},t} \right) \right] \right| \tag{18}$$

in which MAE is the mean absolute error; ω is the number of months represented in the training dataset; Q_t is total, sectoral water use during time period t; p_t is the sectoral population at time t; $q_{\text{in},t}$ is the sectoral, weighted-average per capita indoor use at year t; and $q_{\text{out},t}$ is average sectoral per capita outdoor water use at time t.

$$\text{MAEP} = \left| \frac{1}{v} \sum_{t=1}^{v} \left[Q_t - p_t \left(q_{\text{in},t} + q_{\text{out},t} \right) \right] \right| \tag{19}$$

in which MAEP is the mean absolute error of prediction, and v is the number of months represented in the validation dataset.

The process models for SFR and MFR population and per capita use provided a reasonable prediction of measured total residential water use. Results showed that SFR water use in Sanford declined during the study, a decline caused by a reduction in indoor gallons per capita per day use associated with only a slight decline in population. Results for the SFR sector suggest, perhaps, that the Sanford utility's service area included a slightly larger number of irrigators before 2007 because modeled use was slightly less than the observed annual trend for this period. Water use and population in the MFR sector have declined at similar rates, indicating relatively stable gallons per capita per day use during the study.

SUMMARY AND CONCLUSIONS

Existing methods of forecasting water use and population may not be accurate or applicable to most utilities as a result of inconsistent definitions or unavailable data. With these limitations, this article presents a new process-based method for estimating SFR and MFR population and water use patterns based on parcel-level

FIGURE 2 Measured total water use, population served, and modeled total water use for 13,118 single-family residential parcels in Sanford, Fla.

FIGURE 3 Measured total water use, population served, and modeled total water use for 335 multifamily residential parcels in Sanford, Fla.

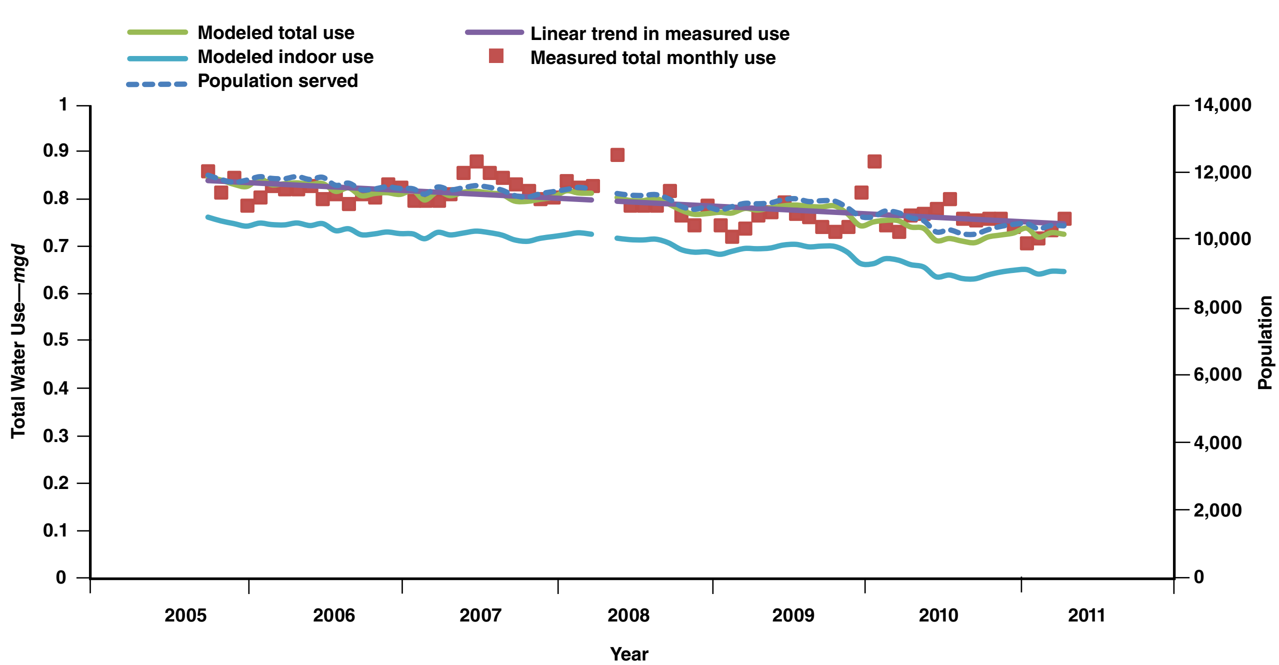
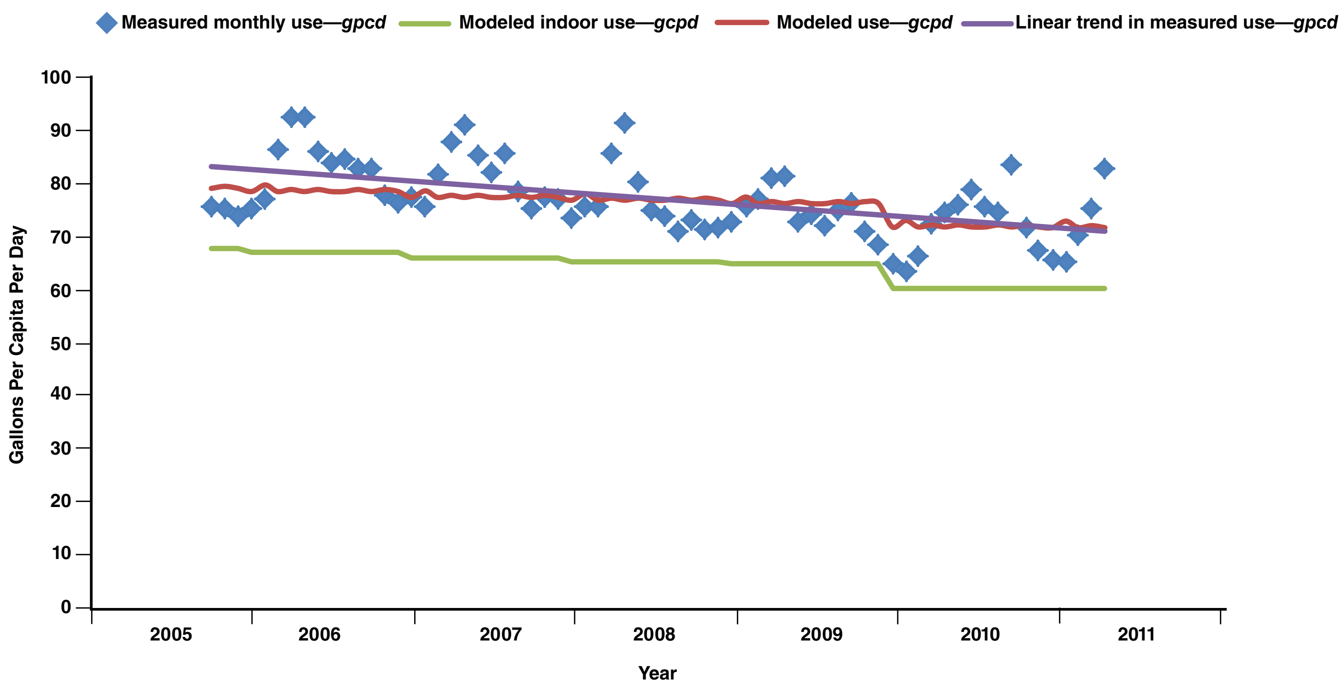
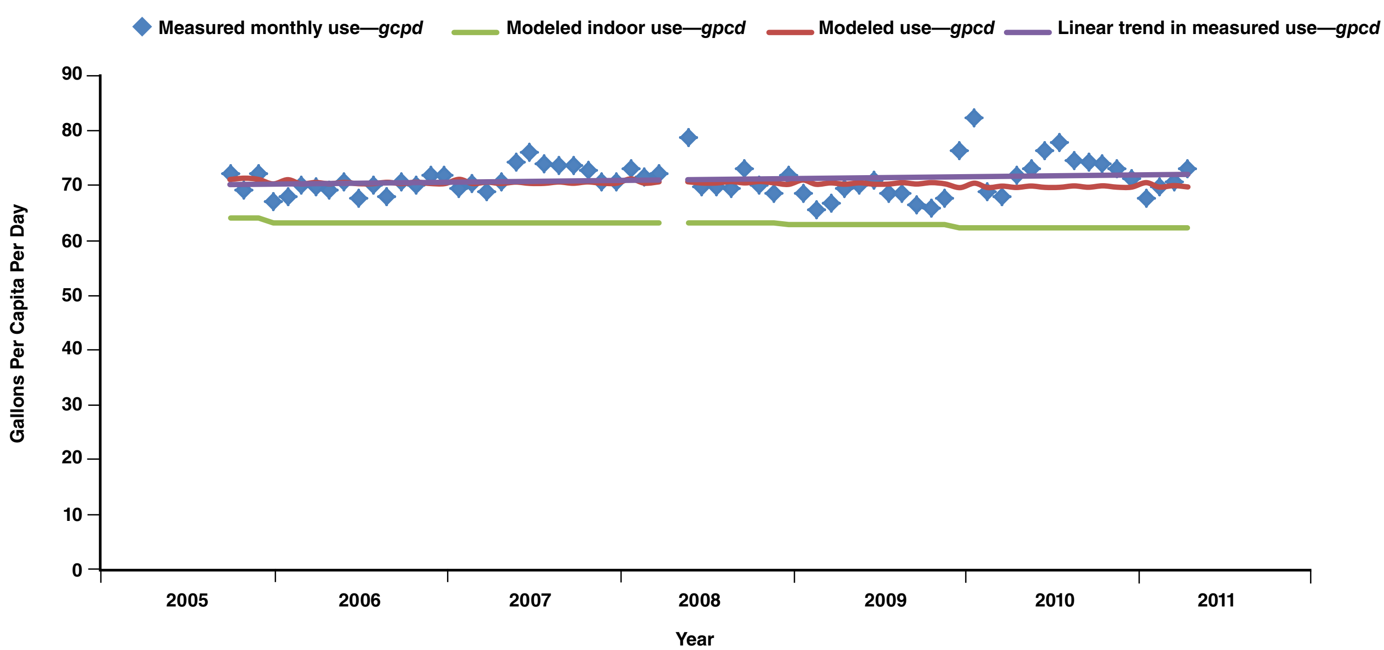


FIGURE 4 Measured versus modeled per capita water use for 13,118 single-family residential parcels in Sanford, Fla.



gpcd—gallons per capita per day

FIGURE 5 Measured versus modeled per capita water use for 335 multifamily residential parcels in Sanford, Fla.



gcpd—gallons per capita per day

TABLE 6 Summary of best parameter estimates of model error and percentage of utility customers using potable water for irrigation in the SFR and MFR sectors in Sanford, Fla.

Estimate	SFR Sector	MFR Sector
MAE—*mgd*	0.0566	0.0083
MAEP—*mgd*	0.0217	0.0325
Percentage of customers using potable water for irrigation—%	13	45

MAE—mean absolute error, MAEP—mean absolute error of prediction, MFR—multifamily residential, SFR—single-family residential

land-use databases. The FDOR database provides attributes for every parcel in the state along with the parcel's land-use classification, and the parcels can be grouped into defined sectors, including SFR and MFR sectors. This database, in conjunction with data from the Florida County Property Appraisers and the US Census, allows parcel-level evaluation of water use and population served applicable to any utility in Florida.

The methods presented in this article permit consistent analysis of water use and utility population served with standardized definitions and input parameters. Of particular importance is the ability to treat the SFR and MFR sectors independently, which properly accounts for the many differences between them. A unique method for prorating the combined number of persons per residence and the percentage of occupancy into SFR and MFR components accounts for the differing housing characteristics of these two sectors. Given the increasing availability of property appraisal databases and advances in database and GIS technology, data-driven approaches can be used elsewhere as the required inputs become more prevalent. In addition, the methods for determining population and per capita water use can be easily applied elsewhere because customer billing data are not a required input for the model. Default parameter estimates based on the Sanford, Fla., case study can be used if local information is unavailable.

Process models for residential population and indoor and outdoor per capita water use can be used to estimate total residential water use, incorporating variability among fixture end uses and irrigable area for every household in a utility's service area. Total residential water use can be predicted as the product of modeled population and modeled per capita water use for residential users who are physically present and using water at a given time. This approach allows consistent benchmarking because per capita use multiplied by population yields the actual volume of water delivered to the residential sector.

Parameter estimation for the Sanford case study resulted in a small percentage of SFR irrigators who were using potable water, reflecting the city's extensive network of reuse water for irrigation. Process models for both the SFR and MFR sectors provided reasonable predictions of measured total water use.

Future work includes further investigating possible sources of error, including the relationship between actual irrigation and required irrigation needs, as well as the effect of price on irrigation demand. Investigating seasonal occupancy trends, particularly in the MFR sector, could explain much of the remaining error in the results for this sector. In addition, future work includes combining the residential model with analogous nonresidential water use and water loss models to evaluate estimates of total potable water supplied, estimates that could be validated by comparison with a utility's measured monthly production records.

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FOOTNOTES

[1]ArcGIS, Esri, Redlands, Calif.
[2]Microsoft Excel, Microsoft, Redmond, Wash.

PEER REVIEW

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