In contrast to traditional supply augmentation options, demand management options include specifying and/or replacing many small end uses that individually have a minimal effect on overall water use but that collectively can constitute significant aggregate reductions in demand. This article outlines a systematic procedure to quantify savings potential of single-family residential indoor end-use devices of a given utility and then select the optimal blend of retrofits to achieve a specified goal. Three steps are used to quantify savings potential of all end-use devices. First, a utility's current end-use fixture inventory and associated water use is estimated from parcel-level data for each single-family residence. Second, customers are clustered into relatively homogeneous water use categories based on the age of the dwelling unit and the number of bathrooms. Third, water savings are calculated directly as the difference between current and proposed use after implementation of a management option for each group. This information is used to develop performance functions that estimate total water savings as a function of the number of fixture retrofits for each group.

Water demand management optimization methodology

KENNETH FRIEDMAN,
JAMES P. HEANEY,
MIGUEL MORALES,
AND JOHN PALENCHAR

Water demand management can be a viable alternative to augmenting a supply system to meet future water needs. Demand management should be compared with traditional supply augmentation methods to decide whether it is a viable option. Methods of analysis are well-established for choosing among supply augmentation options such as well field development, reservoir and pipeline construction, and desalination. Demand management is an emerging alternative in which several case studies have illustrated significant demand reduction from various strategies, including technological improvements, behavioral marketing campaigns, and adjustments of water pricing. The major difference between traditional supply augmentation and demand management is that traditional supply options are capital-intensive with long service lives; as a result, capacity expansion is done in discrete, relatively large, increments. Demand management options include many small changes that reduce water use for individual customers by a few gallons per day but that collectively can bring about significant aggregate reductions in demand if applied to a significant portion of the utility's customers.

Advances in database availability, including an associated geographic information system (GIS), make it possible to do a bottom-up evaluation of water demand patterns across the utility and systematically determine the potential savings for all single-family indoor retrofit options within a given utility. An optimal mix of demand management strategies can then be selected by comparing each demand management control with a few large supply augmentation options. Existing water demand management models rely on trial-and-error procedures to estimate the optimal mix of control options with little or no information regarding the actual identification of individual fixture savings potential.

This bottom-up optimization method has been developed as part of Conserve Florida Water Clearinghouse's (www.conservefloridawater.org) activities to develop software that identifies the best mix of single-family residential (SFR) end-use options based on the desired objective. The objective function for optimization can vary depending on the interests of the utility, including maximizing net benefits in comparison to other supply options, minimizing the cost of meeting a target water reduction, or maximizing water savings subject to a budget constraint.

The bottom-up approach is feasible in Florida thanks to the availability of attribute data for each of Florida's 8.8 million property parcels. Because of Florida's Sunshine Legislation (www.myflsunshine.com/sun.nsf/pages/Law), the state may be unique in reporting the attributes of all 8.8 million parcels in its 67 counties. Additional information regarding these parcels is available from the property appraisers' databases for Florida's counties, although the information varies from county to county. This parcel-level information is used, along with US Census block data on persons per dwelling unit and customer level water utility billing data, where available, to find the optimal mix of end-use options.

This methodology uses three core principles for evaluating end-use options: (1) determining existing end-use devices and water use for every customer in a utility, (2) directly determining water savings and associated costs with less water-intensive end-use devices, and (3) determining the optimal mix of end-use demand management options and identifying the highest priority customers to target. These methodologies focus on determining the optimal mix of technological fixture end-use improvements, assuming that behavior and price of water are constant.

WATER DEMAND MANAGEMENT METHODOLOGY

The Water Research Foundation residential (Aquacraft, 2005; Mayer et al, 1999) and commercial/institutional (Dziegielewski et al, 2000) end-use studies provide fundamental information on the nature of urban water use for individual end uses. End-use analysis provides an essential inventory of existing and projected water use devices and their attributes, e.g., 10,000 SFR customers with one bathroom that have 1.28-gpf toilets. The decision variables in end-use optimization are the end-use devices (e.g., replace 5,000 3.5-gpf toilets in one-bath houses with 1.28-gpf toilets).

Other models and reports include the following:

- Maddaus and Maddaus (2004) describe their proprietary Least Cost Planning Demand Management Decision Support System that includes end-use evaluations. This model has been widely applied in the United States as well as in Australia.
- White and colleagues (2004) in their work describe the development of the Sydney Water End Use Model and its application in Australia.
- Maddaus and Maddaus (2006) provide a detailed description of water conservation planning in AWWA's M52 Water Conservation Programs—A Planning Manual.
- Maddaus (2009) presents a detailed description of the end-use decision support system used for regional water supply planning in the East Bay (Calif.) Municipal Utility District.
- Green (2010) presents information regarding the expected costs, savings, and service lives for a variety of demand-management options based on information provided by William Maddaus.

Existing top-down procedures rely on aggregate water system data to estimate end uses. These highly aggregated average values are of little use in estimating the variability of savings that exists across the utility because of differences in water use patterns of existing fixtures. Savings depend on the water use of existing and proposed fixtures. Using a single "average savings" for all fixture replacements provides only a crude estimate of the actual savings rates and provides no information regarding the market share of the option.

The Conserve Florida Water Clearinghouse has developed a bottom-up end-use optimization and decision-support system model for evaluating water demand management options. The basic reporting unit is the individual parcel. The application of this methodology to the SFR sector using Gainesville Regional Utilities will be described as an example. A bottom-up methodology is preferable to reliance on a top-down approach because it provides a basis for evaluating customers individually or in smaller groups. The main limitation to bottom-up analyses has been lack of data at these disaggregated scales.

Polebitski and Palmer (2010) evaluate water demand forecasting using the 100 census tracts of Seattle, Wash. Chen (1994) argues that census block groups are preferable to census tracts because of increased spatial disaggregation. The findings of this study suggest that spatial disaggregation is primarily limited by data availability. Hazen and Sawyer and PMCL (2004) used 1,500 US Census traffic analysis zones as the basic spatial unit in analyzing water use in the Tampa Bay area. They aggregate customer-level water use data to the traffic analysis zone levels for use in their regression models. The average number of people per spatial unit in Florida is shown in Table 1. Census tracts with about 4,000 people provide limited ability to conduct end-use evaluations using relatively homogeneous neighborhood clusters. These exceptional databases provide the basis for accurate end-use evaluations at the parcel level.

The Conserve Florida Water Clearinghouse has developed its water conservation software, called EZ Guide 2 (www.conservefloridawater.org/ez_guide.asp), using the 8.8 million parcels in Florida as the basic reporting unit. The utilities or the water management districts provide the clearinghouse with the utility boundaries as GIS shape files, which are used to determine the parcels to analyze for a given utility. The software uses this information to generate estimates of population, heated area, and irrigable area for each of 60 urban water land-use types based on the Florida Department of Revenue's land use codes. This parcel-level information is then used to do a complete bottom-up evaluation of demand management options.

PARCEL-LEVEL END-USE EVALUATION

The basic structure of the database for parcel-level end-use evaluation can be represented as a single $m \times n$ matrix A, with individual elements, a_{ij}. This single flat-file format provides a convenient computing platform within contemporary spreadsheets such as Excel 2007, which the application EZ Guide 2 uses. The parcels within an individual utility can be determined as the union of Florida parcel geometries and utility boundary geometries using GIS.

The only block-level estimate included in the database is the estimated persons per residence that comes from US Census block data. As shown in Table 1, a census block contains 20–25 parcels, so it should provide a reliable estimate of the number of persons per residence. An average of 2.5 persons per residence has been shown to be stable spatially and temporally over the past few decades (Friedman, 2009; Smith et al, 2002). Because of this stability, US Census persons-per-residence data at the block level of aggregation can be used without adjusting for the 10-year lag time between census years. The Florida Department of Revenue (FDOR) data are updated annually and are generally of high quality because they are carefully audited to ensure accurate property value assessments.

The illustrative application presented in this article is m = 30,903 SFR parcels with 46 attributes served by Gainesville Regional Utilities (GRU) in Gainesville (Table 2). Although only SFR will be analyzed in this article, the same attributes can be obtained and analyzed for other sectors. The 46 attributes for the parcel-level database for GRU that are shown in Table 2 come from four sources: US Census, FDOR, Alachua County Property Appraiser (ACPA), and GRU. GRU represents a best-case utility in which all parcel attribute data are known along with having billing data with separate indoor and outdoor meters for some of the accounts. Not all elements a_{ij} in matrix A are directly known for all utilities. A minimum of 20 specific attribute columns per parcel (attributes 1–20 in Table 2) are required to perform a bottom-up parcel-level analysis. Additional attributes, if available, can improve the accuracy of the method, such as the GRU billing data. Fields 1–11 in Table 2 can be obtained directly for any parcel in Florida from US Census or FDOR data. Fields 12–20 are necessary, but the availability varies by county appraiser. These fields can be estimated if the data are not directly available. Billing data can greatly enhance the analysis methodology by allowing improved calibration of water use estimates but are not necessary to perform this analysis. Significant effort is required to link billing data to the other data sources (Friedman, 2010). County property appraiser and billing data are added and updated on a case-by-case basis as data become available.

The FDOR attributes in the parcel-level database are updated annually. Because of the accuracy and quality of these data, this process is straightforward. US Census block data are updated every 10 years and do not require a significant amount of work unless the census block boundaries have been reconfigured.

It is simple to link the FDOR and county property appraisers' parcel-level databases. However, the content of the county property parcel-level databases varies and the county-level databases must be acquired for each county. A demographic analysis was done for Alachua and Hillsborough counties that include the two benchmark utilities—GRU (Alachua County) and Hillsborough County Water Resources Services (Hillsborough County). The ACPA database has a wealth of parcel-level information for water demand management studies, including the 10 spatial attributes shown in Table 2. The results from the analysis of the Alachua and Hillsborough county databases are used to estimate attributes for other areas that do not include them. For example, most Florida counties provide information about the number of bathrooms at each single-family dwelling; however, that information is absent in some counties. In counties where the information is available, a relationship between the heated area of the home and the number of bathrooms was found to produce a reliable estimate that could be substituted for the missing data in other counties.

Using SFR data for Alachua (n = 50,920) and Hillsborough counties (n = 316,258), the number of bathrooms

TABLE 1 Florida levels of aggregation based on 2009 conditions

Unit	Value	Persons/Unit
Population	18,800,000	1
Parcels	8,800,000	2.14
Census blocks	362,499	51.9
Traffic analysis zones	12,747	1,475
Census tracts*	4,700	4,000
Utilities	2,633	7,140
Counties	67	280,597

*Based on 4,000 persons per US Census tract can be estimated as a function of the heated area of the parcel. The regression equation is

$$B = 0.000732796 \times \text{HA} + 0.766547642 \ (R^2 = 0.545) \quad (1)$$

in which B = number of bathrooms per account, and HA = heated area (sq ft) per account. The results are shown in Table 3 as a table lookup function with the square footage rounded to the nearest 50 sq ft.

The key indicator of size in the FDOR database is the effective area (EA) of the parcel, rather than the heated area that is used to estimate number of bathrooms (attribute 9 in Table 2). The effective area is not a physical area but is the heated area plus the associated impervious area multiplied by a weight that is less than 1. Fortunately, the county property appraisers report the heated area for each parcel. Thus it is possible to estimate heated area as a function of effective area. The result for GRU is shown in Figure 1. The fit is excellent. The HA:EA ratio for a single FDOR code, K_p, is calculated using Eq 2.

$$K_p = \sum_i (\text{HA}_{ip}/\text{EA}_{ip}) \quad (2)$$

For GRU, $K_p = 0.87$. K_p has been shown to be consistent and stable throughout Florida for a given FDOR code (Morales, 2010). Assuming $K_p = 0.87$, Eqs 1 and 2 can be used to estimate the heated area and number of bathrooms for any parcel within the SFR land use FDOR category in Florida.

After the subset of matrix A is known for a given utility, a variety of analyses can be conducted. Because of the structure of the database, level of effort does not depend on the number of parcels selected in the analysis. Thus, the parcel-level methodology described can be conducted for small utilities, large utilities, or large planning regions with the same level of effort. As an example analysis, the clearinghouse statewide database provides the effective

TABLE 2 Parcel-level database of 30,903 SFRs served by GRU and 50,920 SFRs in Alachua County, Fla.

Source	Attribute	Scale	Definition	Period of Record	Type
Census	Census ID	Block	Can be linked with other GIS-compatible databases	2000	Spatial
Census/GIS	GIS geometry	Block	GIS geometry can be linked with FDOR GIS geometry	2000	Spatial
Census	Average household size	Block	Average for the entire block; may include mixed uses	2000	Spatial
FDOR	Parcel ID	Parcel	ACPA database includes FDOR ID	1920–2008	Spatial
FDOR	Use code	Parcel	Indicates which parcels are in the single-family sector	1920–2008	Spatial
FDOR/GIS	Parcel geometry	Parcel	GIS geometry can be linked with other GIS data	1920–2008	Spatial
FDOR	Effective year built	Parcel	Year property built or year of major renovation	1920–2008	Spatial
FDOR	Just value	Parcel	The current (2008) value of a property	1920–2008	Spatial
FDOR	Effective area	Parcel	The effective developed area of the property	1920–2008	Spatial
FDOR/GIS	Parcel area	Parcel	GIS calculated parcel area using FDOR parcel geometry	1920–2008	Spatial
FDOR	Residential units	Parcel	Number of residential units per parcel	1920–2008	Spatial
ACPA	ID number	Parcel	Identification number that is linked to GRU database	1920–2008	Spatial
ACPA	Stories	Parcel	Number of stories per structure	1920–2008	Spatial
ACPA	Associated impervious area*	Parcel	Associated impervious area of a parcel	1920–2008	Spatial
ACPA	Gross area	Parcel	Gross area of the parcel	1920–2008	Spatial
ACPA	Bathrooms	Parcel	Number of bathrooms within a property	1920–2008	Spatial
ACPA	Heated area	Parcel	Heated area of a property	1920–2008	Spatial
ACPA	In-ground irrigation system	Parcel	Yes or no	1920–2008	Spatial
ACPA/GIS	GIS geometry	Parcel	Linked with FDOR and GRU GIS databases	1920–2008	Spatial
ACPA	In-ground pool	Parcel	Yes or no	1920–2008	Spatial
GRU	Customer ID	Parcel	GRU database includes ACPA ID	1920–2008	Spatial
GRU	Dual meter tag	Parcel	Indicates a dual- or single-metered customer	1920–2008	Spatial
GRU	Irrigation meter water use	Parcel	One year of monthly data for irrigation meters	October 2007–September 2008	Temporal
GRU	Regular meter water use	Parcel	One year of monthly data for regular meters	October 2007–September 2008	Temporal

ACPA—Alachua County Property Appraiser, FDOR—Florida Department of Revenue, GIS—geographic information system, GRU—Gainesville Regional Utilities, ID—identification, SFRs—single-family residences

*Sum of areas of garage, driveway, patio, screened-in areas, balconies, sheds/barns and so on.

year built (attribute 7 in Table 2) for all customers. The annual number of new accounts and the cumulative total SFR accounts for GRU are shown in Figure 2. There were 30,903 SFR accounts as of 2007. The most rapid annual growth rates occurred between 1968 and 1985. The annual growth rate has remained steady since 1985 at about 600 new customers per year. This annual time series data at the individual customer level provides an excellent basis for evaluating historic growth patterns and projecting future growth patterns. All calculations are done at the account level, and the results are aggregated as needed. The number of bathrooms per house for each five-year period is shown in Figure 3. This information was generated using a data table based on attribute 7 (effective year built) and attribute 16 (number of bathrooms) in the GRU combined database. Before 1970, the majority of new houses had only one bathroom. Since 1970, most houses have at least two bathrooms (Friedman, 2010). The heated area of SFRs has also increased significantly from about 1,500 sq ft in 1970 to 2,300 sq ft in 2007. The number of people per house has remained constant since 1970. Thus, the number of people per toilet has decreased from 1.8 in 1970 to 1.1 in 2007. This major decrease in people per toilet results in a proportionately lower use rate per toilet.

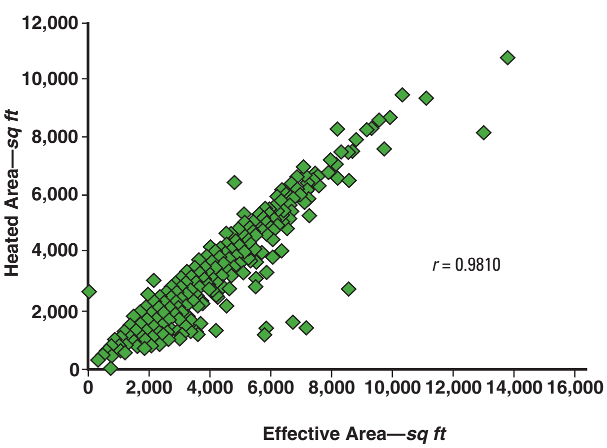
Key comparative statistics for these three periods for SFR served by GRU are shown in Table 4. This table provides valuable insights into the nature of residential water demand in Gainesville. Nearly half of the residences were built before 1983 when little attention was paid to water demand management, although some percentage of these homes likely has newer fixtures because of fixture replacement, as explained in more detail in the next section. About 25% of the residences were built after 1994 and have water-saving indoor fixtures because of improved plumbing codes (Heaney et al, 2010). The average daily gallons per account have increased significantly from 207 for the pre-1983 residences to 292 for the post-1994 residences. Although the newer homes are larger, the average number of people per house has remained stable at about 2.5. The number of bathrooms per house has increased from 1.90 to 2.42 from period 1 to period 3. Thus, the fixture utilization rate has decreased. The average irrigable area has decreased by about 25% from period 1 to period 3. The most dramatic change across these three periods is the major increase in the use of in-ground irrigation systems. The use of in-ground irrigation systems appears to be the major reason why the average daily gallons per account use is 292 for period 3 and 207 for period 1 residences.

TABLE 3 Default lookup table for estimating number of bathrooms per house*

Heated Area Range		
Minimum *sq ft*	Maximum *sq ft*	Bathrooms per House *number*
0	650	1
651	1,350	1.5
1,351	2,000	2
2,001	2,700	2.5
2,701	3,400	3
3,401	4,050	3.5
4,051	4,750	4
4,751	5,450	4.5
5,451	Infinity	5

*Based on regression analysis of a sample of 367,178 single-family residential parcels in Alachua and Hillsborough counties in Florida.

FIGURE 1 Relationship between effective area and heated area for 30,903 single-family residences served by Gainesville (Fla.) Regional Utilities



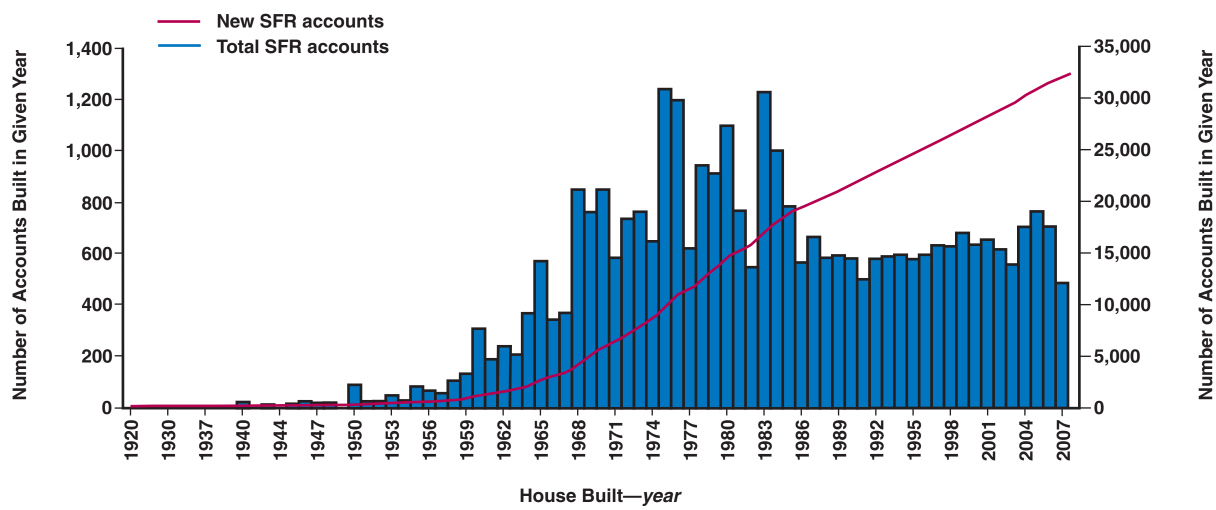
SUBGROUPINGS OF SFR ACCOUNTS

On the basis of the trend analysis in the previous section, SFR accounts can be subgrouped separately depending on whether indoor or outdoor use is being analyzed. SFR accounts are arranged into subgroups based on fixture efficiency (based on three discrete plumbing code periods) and number of bathrooms per residence (based on six discrete values) that reflect distinct indoor use characteristics shown in the previous section. Three fixture efficiency periods reflect significant differences in SFR fixture water use rates, frequency of use, and market penetration. Historical water use is summarized for before 1983, 1983–94, and 1995 to present. The pre-1983 period represents an uncontrolled situation in which few conservation practices had been implemented. The 1983–94 period reflects the beginning of conservation programs and plumbing codes that reduced the allowable water use per event. The period from 1995 to the present reflects the effect of much more proactive demand management practices. Rashid et al (2010) summarize the variety of demand management initiatives that have been taken at the state and federal levels. Most of these activities have occurred during the past 20 years.

SFR accounts are divided based on six discrete number-of-bathrooms-per-account categories. Five values are recommended for the discrete baths-per-account values of 1, 1.5, 2, 2.5, and 3. The final value is for residences with more than three bathrooms. These residences are assumed to have an average of 3.5 bathrooms.

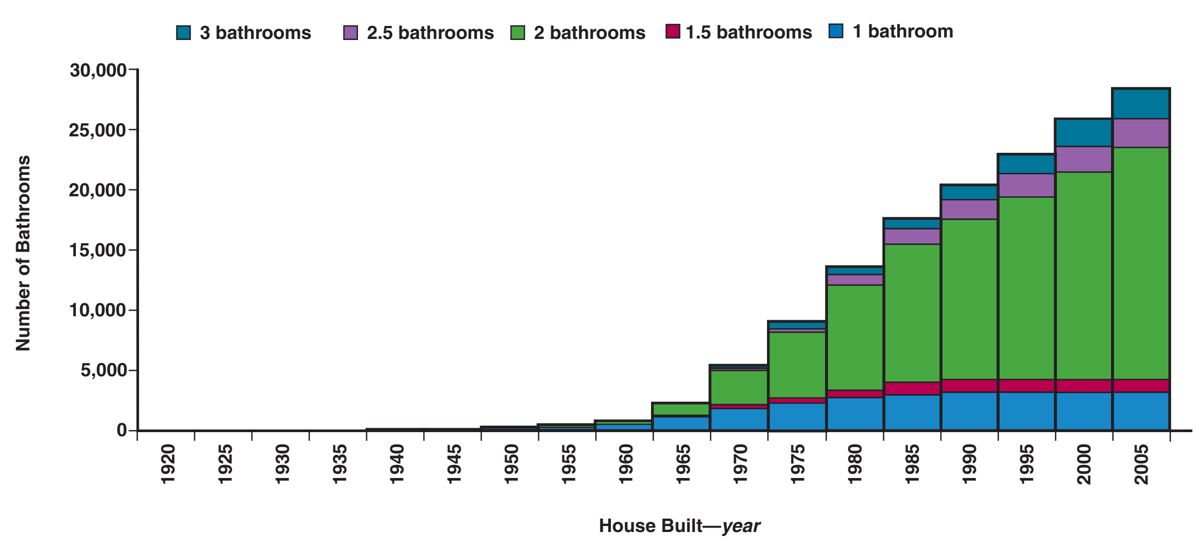
SFR accounts can be categorized into one of 18 subgroups, based on which of the three fixture efficiency periods and which of the six number-of-bathrooms-per-house categories they fall in. For example, accounts with fixtures reflective of those installed before 1983 and having two bathrooms would be grouped together. The total number of bathrooms for accounts within each of these 18 subgroups was determined for GRU based on property appraiser's data and is shown in Table 5. This information is generated from the master data matrix using a pivot table that

FIGURE 2 Annual new SFR and cumulative SFR accounts of customers served by Gainesville (Fla.) Regional Utilities, 1920–2007



SFR—single-family residential

FIGURE 3 Trends in number of bathrooms per single family residence for 30,903 customers served by Gainesville (Fla.) Regional Utilities



sums over the three fixture efficiency periods and the six bathroom values.

GENERATION OF END-USE ESTIMATES

The number of bathrooms is the basic driver that determines the number of toilets and other fixtures per residence. The number of toilets per bathroom is found using Eq 3. (The Excel roundup function rounds up to the next integer.)

$$\text{Toilets} = \text{Roundup (Baths, 0)} \tag{3}$$

This information can be combined to estimate the number of indoor fixtures. This procedure created 12 toilet subgroups, 3 clothes washer subgroups, 9 showerhead subgroups, and 12 faucet subgroups based on fixture efficiency and number of bathrooms per house for indoor end-use analysis. This is a refinement of the initial 18 subgroups; each home is now assigned to one subgroup for each of the four fixtures. Partitioning the total SFR customer base into these categories allows for much more accurate determination of SFR indoor water use and how it varies. Dziegielewski and Opitz (2002) also suggest disaggregating customers into nonconserving, standard, and ultra-conserving classes. In addition, this methodology allows for selecting target groups to retrofit for a conservation plan.

To estimate the mix of each fixture for a particular year, replacement of older fixtures must be accounted for. Knowing the effective year built and an assumed fixture service life for each of the SFR accounts makes calculating the mix of fixtures for any assumed scenario year straightforward. Initially, SFR accounts are classified into fixture subgroups by assuming fixture efficiencies based on the effective year built of the home. Accounts are reclassified if a more efficient device is assumed to exist based on service life assumptions. Previous retrofit programs can be incorporated if specific accounts retrofitted can be identified. As an example, the estimated mix of toilets in 2008 in GRU, based on a service life of 40 years, is shown in Table 6. Estimates of

TABLE 4 Comparative summary statistics for 30,903 single-family residences served by Gainesville (Fla.) Regional Utilities

Statistic	Historical Analysis Period: Before 1983	1983–94	1995–present	Sum or Weighted Average
Count of SFR parcels	15,152	7,896	7,855	30,903
SFR parcels—%	49	26	25	100
Average daily gallons per account (October 2007–September 2008)	207	246	292	238
Coefficient of variation	0.17	0.24	0.26	0.22
Average effective year built	1972	1988	2001	1984
Average heated area—*sq ft*	1,657	1,811	2,171	1,827
Average just value—*$*	154,544	201,087	275,104	197,080
Average persons per house	2.50	2.49	2.63	2.53
Average number of bathrooms	1.90	2.18	2.42	2.10
Average parcel area—*sq ft*	18,097	16,717	15,144	16,994
Average irrigable area—*sq ft*	14,958	12,982	11,109	13,475
Accounts with sprinkler systems—%	9	27	61	27

TABLE 5 Distribution of bathrooms in 30,903 Gainesville (Fla.) Regional Utilities SFR accounts, 2008

Period	Total SFRs	Bathrooms: 1	1.5	2	2.5	3	3.5*
Before 1983	15,152	2,913	828	9,408	965	762	276
1983–94	7,896	374	221	5,278	916	756	351
1995–2008	7,855	20	14	5,023	606	1,300	892
Total	30,903	3,307	1,063	19,709	2,487	2,818	1,519
Percent of total	100.00	10.70	3.44	63.78	8.05	9.12	4.92

SFR—single-family residence

*Residences with more than three bathrooms are assumed to have an average of 3.5 bathrooms.

service life for a variety of end uses are available in NAHB (2007), Maddaus (2009), and Green (2010).

WATER USE PERFORMANCE FUNCTIONS FOR TOILETS

Water use intensity depends on the number of people per SFR. The persons per house is estimated using US Census block-level data that provide average values at an approximate scale of 50–100 residences. The US Census reports the persons per residential dwelling unit. Sometimes this estimate is an average of single- and multifamily population densities for mixed use within a census block. Fortunately, census blocks can be divided into three categories: SFR only, multifamily residential only, and SFR/multifamily residential blends. For the SFR, the persons-per-residence estimate is calculated using Eq 4:

$$\text{Persons/SFR} = \text{Census Block Average for the Nearest Block That is SFR Only} \quad (4)$$

In most cases the nearest block is the block in which the parcel is located. The resulting estimates of persons-per-residence are shown in Table 4. The persons per SFR ratio has remained relatively constant during the three periods; thus, using census-reported persons per SFR is accurate, even though the data are available at 10-year intervals. However, the toilet use rate has decreased significantly because of the increasing number of toilets per SFR that has occurred in recent years.

The next step is to estimate the daily use per existing toilet. These results are shown in Table 7. Additional input information includes the attributes of toilets associated with each period. The gallons per flush and flushes per day are based on the results of the national SFR end-use evaluations and summaries of use estimates in earlier periods (Aquacraft, 2005; Vickers 2001, Mayer et al, 1999). As shown in Table 7, the average daily gallons of water per person has decreased from 25.5 before 1983 to 8.16 after 1994 because of the reduced number of gallons per flush (i.e., from 5.0 to 1.6). The daily water use per toilet is based on the number of persons per toilet. The lower use rate results show the combined effects of technologic improvement in reducing the gallons per flush and the reduced number of people per toilet.

To evaluate whether it is cost-effective to convert some or all of the previously mentioned toilets to 1.28-gpf toilets, assume that the daily flushes per toilet remain at 5.1. The savings from switching the existing toilets to the 1.28-gpf model are shown in Table 8 for each of the 12 categories. The savings vary widely from as high as 48.0 gpd per toilet to a low of 1.10 gpd per toilet. This way of calculating savings is a significant improvement over using a single savings rate for all toilets that provides no information regarding the before and after conditions.

The information from Tables 6 and 8 can be combined to generate a performance function for replacing existing toilets with 1.28-gpf toilets (Figure 4). The performance

TABLE 6 Number of toilets in the SFR category of GRU's 30,903 customers in 2008 based on a toilet service life of 40 years

Year Built Group	Total	Toilets/SFR 1	Toilets/SFR 2	Toilets/SFR 3	Toilets/SFR 4	Average Toilets/SFR
Before 1983	23,088	1,306	16,358	4,488	936	2.22
1983–94	18,128	553	11,130	5,037	1,408	2.40
1995–2008	25,626	1,448	14,056	6,390	3,732	2.48
Total	66,842	3,307	41,544	15,915	6,076	2.37
Percent of total	100.00	4.95	62.15	23.81	9.09	

GRU—Gainesville (Fla.) Regional Utilities, SFR—single-family residence

TABLE 7 Gallons used per day per toilet

Period	Toilets per House 1	Toilets per House 2	Toilets per House 3	Toilets per House 4	Toilet Attributes: Gallons per Flush	Toilet Attributes: Daily Flushes per Person	Daily Gallons per Person
Before 1983	63.7	31.8	21.2	15.9	5	5.1	25.5
1983–94	44.5	22.2	14.8	11.1	3.5	5.1	17.85
1995–2008	21.5	10.7	7.17	5.37	1.6	5.1	8.16

function is generated by ranking the retrofit options from highest to lowest savings rates. By definition, this function exhibits diminishing marginal productivity because the savings rate decreases as the number of toilets retrofitted increases. The slope in the resulting piecewise linear function shown in Figure 4 is the water savings rates from Table 8.

OPTIMAL TOILET REPLACEMENT POLICY

Given the performance function for toilet retrofits (Figure 4), the unit cost of a toilet retrofit per day of service life, and the associated unit utility savings, it is possible to find the optimal number of toilets to change to 1.28-gpf models. This problem can be formulated as a linear program to maximize net benefits as follows:

Maximize $Z = p \times y - c \times x$

Subject to:

$$y = \sum_i a_j x_j \qquad (5)$$

$$s_j \leq (x_j)_{max}$$

$$x_j \geq 0$$

in which Z = total benefits – total costs in dollars/day; p = value of water saved in dollars/gallon; y = quantity of water saved in gallons per day; c = unit cost of a 1.28-gpf toilet in dollars/day; a_j = savings rate for the j^{th} chord in the piecewise linear function in gallons/toilet/day; x_j = number of toilets in the j^{th} category with an upper bound of $(x_j)_{max}$.

A linear program has been set up within EZ Guide 2 to automatically find the optimal blend of demand-management options. The value of water saved and unit cost parameters are determined case by case for individual utilities. The value of water saved can include several benefits for the utility, including avoided production cost, avoided expansion, or avoided need for alternative sources. Groves et al (2008) describe categories of savings that can be included depending on the accounting stance of the utility. The unit cost is based on the present value of the initial replacement cost, factoring in installation costs, rebate programs, and the estimated operating costs over the service life of the end-use device. This formulation extends the linear program detailed previously to simultaneously find the optimal blend across all demand management options. Lund (1987) used linear programming to find the mix of conservation options that could reduce or eliminate the need for expanding the supply system. Lee et al (2005) use production function theory to find the optimal blend of land use adjustments and stormwater best management practices to satisfy low impact–development stormwater goals. Rosenberg (2007) uses probability theory to derive a normalized performance function for evaluating conservation options. Griffin (2006) presents a general overview of production economics and how water systems can be optimized. Baumol (1977) describes how production economics problems can be solved using linear programming. It is also possible to solve this optimization problem by fitting an equation to the production function and finding the value of x such that

$$dy/dx = c/p \qquad (6)$$

in which dy/dx is the slope of the production function.

In this case the maximum net benefits are $1,438 per day that will save 762,000 gpd of water by converting 41,216 older toilets from residences with fewer toilets per residence. EZ Guide 2 also allows other formulations of the decision problem, including maximizing the amount of water saved for a given budget or minimizing the cost of meeting a performance goal, e.g., gross gallons per capita per day ≤ 100 (Heaney et al, 2010). Economic optimization is not the only consideration in selecting the preferred alternative. Maddaus and Maddaus (2006) show how to set up a scoring matrix that incorporates noneconomic factors.

Is 1.28 gpf the best toilet retrofit option? In the example presented previously, only a 1.28-gpf toilet was considered as the retrofit option. However, depending on the water-savings rates and the relative savings and control costs, other gallons-per-flush options may be better. The linear program in EZ Guide 2 finds the best blend of 1.6-, 1.28-, 1.1-, and 0.8-gpf toilets. The 0.8- and 1.1-gpf

TABLE 8 Daily water savings if all customers use 1.28-gpf toilets

	Toilets per Single-family Residence			
Period	**1**	**2**	**3**	**4**
Before 1983	47.4	23.7	15.8	11.8
1983–94	28.2	14.1	9.41	7.05
1995–2008	4.30	2.15	1.43	1.07

TABLE 9 Net benefits and water saved by retrofitting toilets to a single flush rate or the optimal blend of flush rates

Option	Net Benefits *$/day*	Daily Gallons Saved—× 1,000
1.6 gpf only	1,484	683
1.28 gpf only	1,438	762
1.1 gpf only	1,295	795
0.8 gpf only	1,459	1,052
All options*	1,564	997

*Optimum is blend of 1.6 and 0.8 gpf.

toilets are more expensive but save more water, whereas the 1.6-gpf toilet is less expensive but saves less water. The linear program was run with the unit cost of the four toilet options being $100 (1.6 gpf), $150 (1.28 gpf), $200 (1.1 gpf), and $300 (0.8 gpf). The results are shown in Table 9. If a single gallons-per-flush value is used, the net benefits are greatest if 1.6-gpf toilets are used. The 1.28-gpf option has lower net benefits. The net benefits are maximized by using a blend of 0.8- and 1.6-gpf toilets. These preliminary linear programming solutions and the associated sensitivity analysis provide valuable insights into the best blends among end-use options.

Location of priority retrofits. The databases described in Table 2 include GIS spatial information that allows the results to be presented in terms of the locations of the more promising parcels to retrofit. Illustrative results for toilets and irrigation systems in SFR areas in Gainesville are shown in Figure 5. The spatial clustering indicates the priority areas. In this case, the priority toilet retrofit areas are in the older sections of the city with smaller houses, fewer bathrooms, and older fixtures. The priority irrigation areas are the newer homes that have in-ground sprinkling systems.

CONCLUSIONS

Acceptance of water demand management as a viable alternative to traditional supply-augmenting options has been limited because of concern that the estimated savings might not materialize. The recent availability of accurate measurements of indoor end-use patterns and accurate parcel-level information about customer attributes and historical water use patterns is making it possible to develop reliable estimates of the savings from demand management. In addition, Florida's Sunshine Legislation has made it possible to obtain accurate information on parcel attributes for each of the state's 8.8 million parcels. Also, parcel-level water use data are available for selected utilities that have linked the parcel-attribute and customer-billing databases. The Conserve Florida Water Clearinghouse has used this unusual, if not unique, information to develop a bottom-up water demand management decision support system for utilities within the state.

The information presented in this article shows how this parcel information can be used to develop performance functions for each end use and combine it with savings and cost data to develop a linear program that can find the optimal demand management program that describes the optimal blend of the intensity of the option (e.g., 1.28- versus 0.8-gpf toilets) as well as across options (e.g., toilets versus clothes washers). This entire procedure is programmed into EZ Guide 2, which provides Florida water utilities with a unique analysis tool driven by a uniform statewide database. Interested utilities can obtain these data sets preloaded into the software. Output from this evaluation provides new insights into the opportunities and challenges of demand management.

The approaches outlined in this article provide a solid basis for planning and allocating resources toward targeted conservation technology changes. Followup steps include implementing and evaluating actual water savings. These results can then be used to improve the next iteration of the model run. Utilities outside of Florida should find this information and approach of value because EZ Guide 2 includes default equations or lookup tables to estimate important parameters if detailed data are unavailable.

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FIGURE 4 Total savings performance function for changing to 1.28 gpf toilets

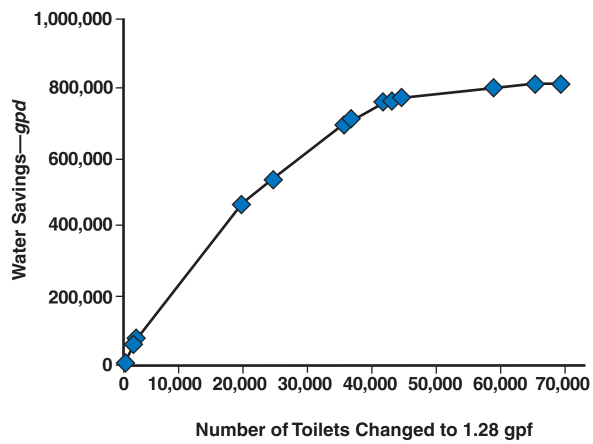
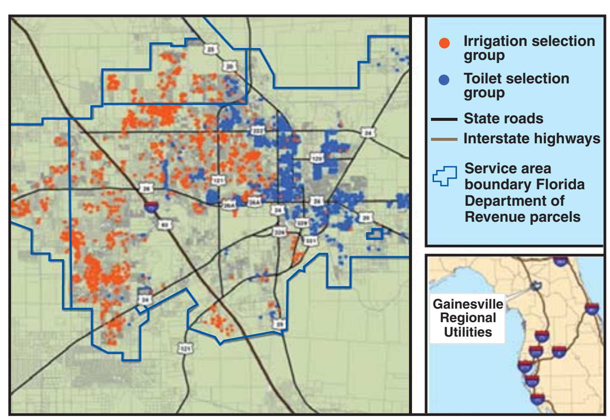


FIGURE 5 Priority parcels for toilet and irrigation single-family residential retrofits, Gainesville, Fla.



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ABOUT THE AUTHORS

Kenneth R. Friedman *(to whom correspondence should be addressed) is a doctoral student for the Conserve Florida Water Clearinghouse (CFWC) in the Department of Environmental Engineering Sciences at the University of Florida, 424 Black Hall, University of Florida, Gainesville, FL 32611; kick5@ufl.edu. He has bachelor's and master's degrees in environmental engineering from the University of Florida. James P. Heaney is the principal investigator for the CFWC and a professor of water resources and environmental engineering at the University of Florida. Miguel Morales is a doctoral student with the CFWC. John Palenchar is an environmental engineer with the Florida Department of Environmental Protection.*

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