Parcel-level modeling of end-use water demands in public supply

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Current methodologies to estimate urban water end uses are largely limited to macro-level analyses that rely heavily on average values. These approaches might offer reasonable estimates in the aggregate, but they fail to differentiate between water users and end-use devices. In order to target customers for water conservation, this article provides a methodology by which to carry out an end-use inventory to arrive at the number, water use efficiency, and frequency of use of water end-use devices at the parcel level for four single-family, five multifamily, and 55 commercial, industrial, and institutional public supply sectors. Such a detailed inventory provides a better understanding of water use and facilitates the evaluation of savings and targeting of individual end-use retrofits associated with water conservation practices based on cost-effectiveness. The seven modeled end uses are male-only toilets, mixed-use toilets, urinals, faucets, showerheads, clothes washers, and prerinse spray valves.

Keywords: *water demand, end-use modeling, residential, commercial, conservation*

Existing urban water use models evaluate water savings at the aggregate level. Jacobs and Haarhoff (2004) devised a residential end-use model that estimated not only demand for potable water but also hot water demand, wastewater flow, and concentration of total dissolved solids in wastewater. This approach requires significant data inputs, relies on average values for a given service area to determine end water uses (no individual fixtures are modeled), and does not target individuals or clusters of the priority users. The Least Cost Planning Demand Decision Support System model—a proprietary end-use model—promotes the use of a combined top-down and bottom-up approach (Maddaus & Maddaus, 2004). For the top-down analysis, this model requires the use of customer water billing data, which might be cost-prohibitive for a utility to obtain. For the bottom-up component, the model outlines a methodology that determines the fixture technology stock, frequency of use, and fixture replacements, but no detailed information on the approach is presented given the proprietary nature of the model.

Several models have been proposed to address the variability in indoor water use and demand management options using probabilistic techniques. Rosenberg (2007) used probability theory to derive a normalized performance function for evaluating conservation options with the focus of quantifying conservation potential. This approach lacked the ability to target customers. Blokker et al (2010, 2011) generated probabilistic high-resolution (per second) demand estimates through simulation of various end-use parameter probability distributions, but did not explicitly use this model to develop optimal demand management strategies.

Gleick et al (2003) documented baseline water use, end-use breakdowns, and sector estimates of potential savings associated with various water conservation best management practices (BMPs). Their methodology relied on survey data regarding the efficiency distribution of water end-use devices within a given sector, providing a means to quantify a BMP's potential impact on water use. Given the focus on quantifying potential savings, average values for the study area were used, which limited the ability to target customers for conservation. For example, all commercial, industrial, and institutional (CII) toilets and urinals were assumed to use 3 and 1.6 gal per flush, respectively.

The limitations of aggregate level models are generally greater within the CII sectors of water use where few sectors have been studied carefully. A US Environmental Protection Agency (USEPA, 2009) white paper summarizes many of the information and research needs for the commercial and institutional sectors. These findings would also apply to the industrial use sector. The paper cites a lack of sector-specific data, such as water usage by facility and end use, and existing benchmarks by which to set targets. Although other studies have provided such data, they have done so for only a limited number of sectors. Gleick et al (2003) included eight CII sectors, Dziegielewski et al (2000) carried out a detailed analysis including submetering and data logging on five CII sectors, and Colorado WaterWise (2007) analyzed four CII sectors. Morales et al (2011) developed CII water use metrics for 55 CII sectors using utility water billing data and heated building area from county property appraisers but did not present methodologies by which to arrive at end water uses, fixture counts, and efficiencies. House-Peters and Chang (2011) presented an extensive literature review on urban water demand models during the past three decades with essentially no mention of CII water use modeling. The article did highlight a trend toward spatial models and the use of micro-scale data.

To overcome the limitations of aggregate demand models and to assess and target the water savings impact of water conservation practices, the authors developed a model that provides parcel-level estimates of water use at the end-use level. The presented methodology allows for a more complete cost–benefit analysis of water conservation practices through an estimation of the end-use inventory of water-using devices, their water use efficiency, and frequency of use. This is done at the parcel level for the 64 sectors shown in Figure 1. The end-use devices modeled are toilets, urinals, faucets, showerheads, clothes washers, and prerinse spray valves. Other end uses were excluded because there are insufficient data to model them, particularly within the CII sectors.

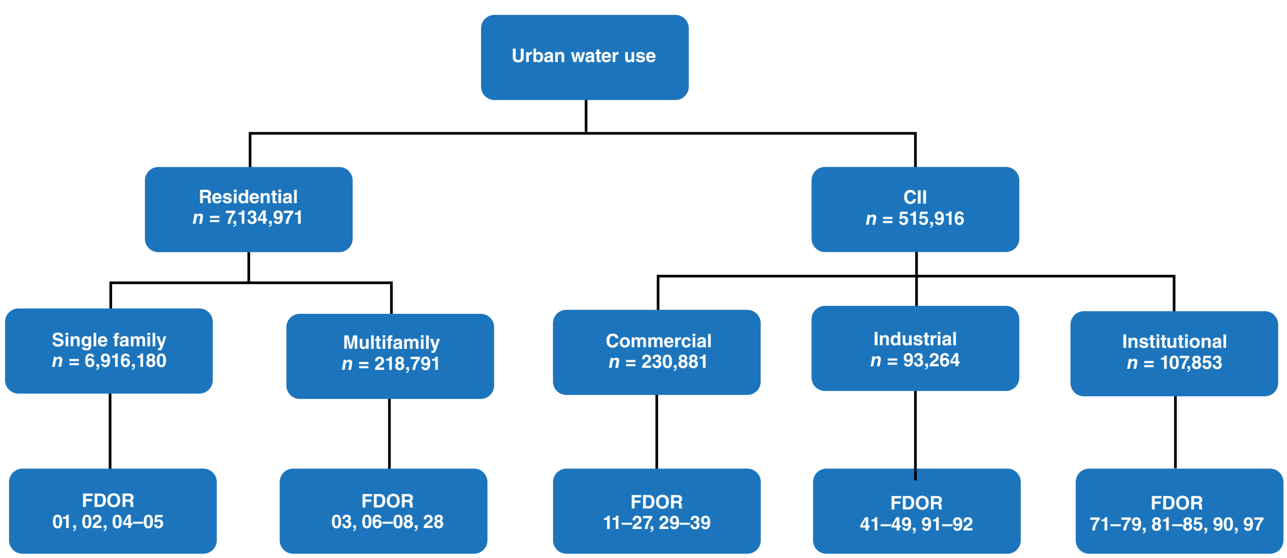
The model relies on a data-driven approach using publicly available databases. The Florida Department of Revenue (FDOR) database serves as the foundation onto which other databases are appended (Figure 2). FDOR maintains a database of legal, physical, and economic property-based information for each of the 8.8 million parcels of land in Florida. This database is publicly available and is audited and updated annually to ensure accuracy given its importance for tax purposes. The following six attributes of interest are provided by the FDOR database:

- parcel identification number
- land use code
- effective year built
- number of residential units
- parcel area
- effective building area

The parcel identification number is a unique identifier to a plot of land and links the various databases in this methodology. The FDOR code is a two-digit classification system that identifies the primary use of the land by its economic activity. The FDOR land-use classification system is standardized across the state and allows for various degrees of disaggregation following the hierarchical structure presented in Figure 1. Effective year built is defined as the last year of major improvements to buildings on a parcel. If there are no major improvements, the field defaults to the actual year built. The effective year built is crucial to the described model methodology by allowing for estimates of the efficiency of water use fixtures at the parcel level. The number of residential units denotes how many individual residences are within a given parcel, which is particularly critical for multifamily parcels. Parcel area is a derived field from the FDOR database, which provides accurate polygon shapefiles delineating all parcels in the state and offering their spatial locations.

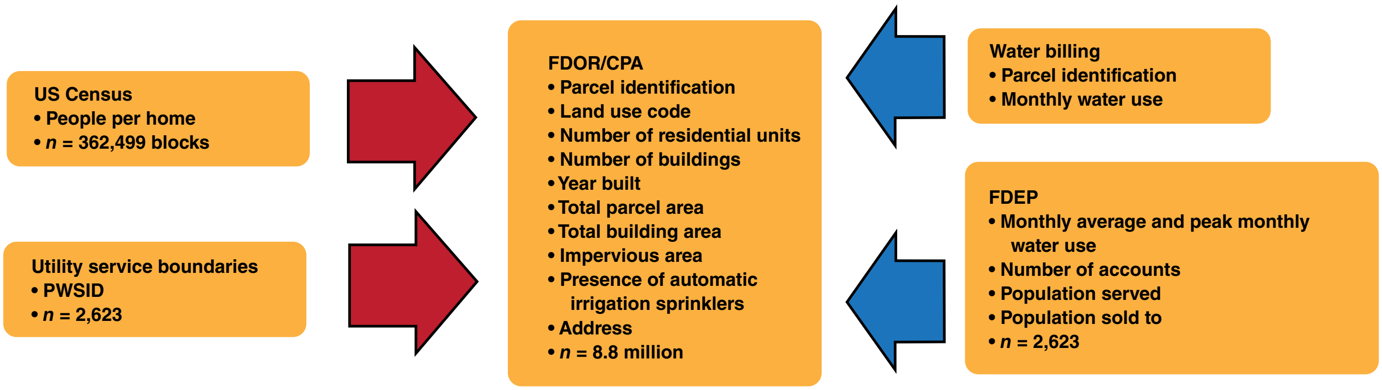
The effective building area is not a true area but rather a calculated field that incorporates economic factors to weight differently the various building area types found within a parcel. The FDOR parcel information is provided annually by the 67 Florida county property appraisers (FCPA). FCPA provides the heated areas (HAs) of buildings in a parcel, defined as all building area under climate control. Unlike the effective building area, provided by FDOR, HA is a physical building area. HA is the commonly used measure of the size of the property for real estate descriptions and is measured accurately because of its importance. With its availability in property appraiser databases

FIGURE 1 Levels of FDOR land use disaggregation into nine residential and 55 CII sectors with associated parcel counts



CII—commercial, industrial, and institutional; FDOR—Florida Department of Revenue, *n*—number of parcels

FIGURE 2 Relational databases for urban water systems in Florida



CPA—county property appraisers, FDEP—Florida Department of Environmental Protection, *n*—number, PWSID—Public Water System Identification

Red arrows denote spatial joins; blue arrows denote attribute joins.

and accurate measurement, heated building area is a good measure of size to develop water use relationships. HA and effective area (EA) have a very strong positive correlation coefficient of $r = 0.996$, allowing for conversion between the two measures with minimal loss of accuracy. The HA/EA ratio, K, for any aggregation of parcels is defined as the total HA divided by the total EA (Eq 1).

$$K = \sum_{i=1}^{n} \mathrm{HA}_i / \sum_{i=1}^{n} \mathrm{EA}_i \qquad (1)$$

in which K = EA to HA conversion coefficient for group of n parcels, HA_i = heated building area of parcel i (m^2), and EA_i = effective area of parcel i (m^2).

Additional databases are appended onto the FDOR/FCPA parcel information through spatial and attribute joins. Spatially, all parcels within a given census block are assigned census data, principally the average people per home. Utility service boundaries are used to determine which parcels are served by a particular utility. Joining parcel-level water billing and utility water production data allows for the calibration of water end-use estimates.

END-USE INVENTORY OF WATER-USING DEVICES

The residential and CII sectors entail differing approaches to arrive at the number of end-use devices within a given parcel. For the residential sector, fixture counts are estimated based on the number of bathrooms in a residence. For CII, coefficients of number of fixtures per heated building area were derived for each sector from building and plumbing codes. These approaches are described in further detail in the following sections.

Single-family and multifamily residential sectors. The number of bathrooms within a residential parcel is not an available field from the FDOR database. However, some FCPAs record this parcel-level information. Therefore, in order to estimate the number of bathrooms for each residential parcel in Florida, a regression equation based on heated building area was developed using a sample of 361,030 parcels in Alachua and Hillsborough counties (Eq 2). The equation results in a minimized mean absolute percent error (MAPE) of 21.3% and an R^2 of 0.474:

$$\mathrm{ResBaths}_i = \| (0.00749 \times \mathrm{HA}_i + 0.780)/0.5 \| \times 0.5 \qquad (2)$$
$$\mathrm{MAPE} = 21.3\%;\ R^2 = 0.474$$

The terms in this equation are defined in the glossary on page E469. The ‖ brackets in Eq 2 denote rounding the result to the nearest integer. Using Eq 2, a HA of 200 m^2 would have 2.5 baths. Having determined the number of bathrooms within a given residence, simple rules can be used to estimate the number of water-using devices because all bathrooms, including half-bathrooms, contain one toilet and one faucet, while full bathrooms additionally contain a shower/bathtub. Thus the number of toilets within a parcel is the number of bathrooms on a parcel rounded up to the nearest integer (Eq 3). Similarly, the number of faucets can be estimated plus an additional kitchen faucet (Eq 4). Showerheads involve rounding down from the number of bathrooms (Eq 5). This rounding approach assumes the presence of only one half-bathroom per residence, which is reasonable for the vast majority of residences. Additionally, clothes washers are estimated by assuming that all single-family parcels and all multifamily residential units larger than 55 sq m contain a clothes washer (Eq 6). Residential dishwashers use only about 3–4 Lpcd, so they are not shown as a separate residential use (USEPA, 2005).

$$\mathrm{ResToilets}_i = \lceil \mathrm{ResBaths}_i \rceil \qquad (3)$$

$$\mathrm{ResFaucets}_i = \lceil \mathrm{ResBaths}_i \rceil + 1 \qquad (4)$$

$$\mathrm{ResShowerheads}_i = \lfloor \mathrm{ResBaths}_i \rfloor \qquad (5)$$

$$\text{ResClothesWashers}_i = (\text{Sector}_i = \text{SF} \rightarrow 1) \wedge \left(\text{Sector}_i = \text{MF} \wedge \frac{\text{HA}_i}{\text{ResUnits}_i} > 55 \rightarrow \text{ResUnits}_i\right) \quad (6)$$

The terms used in these equations are defined in the glossary on page E469.

Commercial, industrial, and institutional sectors. The heterogeneous nature of CII facilities makes it difficult to account for and estimate the number of end-use devices. A methodology by which to estimate the number of single-use toilets (toilets used solely by men), mixed-use toilets (toilets either used solely by women or both women and men), urinals, faucets, showerheads, and prerinse spray valves in each of the 28 commercial, 11 industrial, and 16 institutional FDOR sectors is given in this section. This methodology uses Florida building and plumbing code information on minimum floor area and plumbing fixtures required per occupant for various facility types (Florida Building Commission, 2007). The Florida building and plumbing codes used in this study are derived directly from the International Code Council. As of 2013, the building codes of the International Code Council have been adopted by all US states and territories, whereas the plumbing codes have been adopted by 36 states (including Florida), Washington, D.C., and Puerto Rico (ICC, 2013). Thus these fixture count estimates should be applicable throughout most of the United States, and a similar approach can be replicated using other building and plumbing codes.

The Florida plumbing code provides minimum toilet, faucet, and showerhead fixture requirements for 24 building types. The normalization parameter for the derived coefficients is building occupancy, except for hotels/motels where the coefficients are in terms of the number of rooms. In order to relate these coefficients to FDOR, fixture count coefficients require normalization based on heated building area. The Florida building code provides the conversion from occupancy to square meter for 42 building types. By linking the FDOR land use codes to the appropriate facility-type categories in the Florida building and plumbing codes, fixture count estimates per square meter of heated building area can be developed for the 55 CII FDOR sectors. Because such coefficients provide estimates of fixture counts based on minimum construction code requirements, they can be refined through the use of known parcel-level fixture counts.

The Seminole County Property Appraiser (SCPA) in central Florida reports the total number of fixtures (combined count of all toilets, urinals, bidets, faucets, and showerheads within a parcel) for all CII parcels in their county. A sample size of 1,086 CII parcels in Seminole County was used to calibrate the fixture-count coefficients derived from the plumbing and building codes at the individual FDOR level through an evolutionary solver

TABLE 1 Calibrated number of restroom fixture and functional population coefficients normalized using heated area for the top 10 commercial and three institutional sectors in Florida*

FDOR Land Use Code j	Description	Sample Size, n	Fixture Calibration Factor	MAPE—%	R^2	TC_j—*Toilets per 1,000 m²*	MTC_j—*Mixed-Use Toilets per 1,000 m²*	FC_j—*Faucets per 1,000 m²*	SC_j—*Showerheads per 1,000 m²*	FP_j—*Functional Population per 1,000 m²*
11	Stores, one-story	143	8.0	52	0.18	5.76	2.88	3.84		37.0
16	Community shopping centers	27	8.3	47	0.93	5.92	2.96	3.95		37.0
17†	Offices, one-story	95	2.7	41	0.85	11.8	5.91	7.38		17.7
18†	Offices, multistory	21	2.7	24	0.96	11.8	5.90	7.37		17.7
19†	Medical offices	64	3.5	35	0.38	15.2	7.59	9.48		18.3
21‡	Restaurants	36	1.5	25	0.45	13.5	6.73	5.05		171
22‡	Fast-food restaurants	21	2.6	27	0.28	22.7	11.4	8.53		182
23†	Financial institutions	16	2.4	16	0.53	10.2	5.09	6.36		20.9
27†	Auto sales/repair	67	1.4	35	0.74	6.21	3.10	3.89		5.31
39	Hotels/motels	8	0.5	43	0.58	19.2	9.59	19.2	19.2	36.6
71‡	Churches	84	1.3	48	0.72	8.47	5.64	4.23		5.74
74	Homes for the aged	9	0.9	61	0.86	15.3	7.64	15.3	5.10	7.18
83‡	Public county schools	10	2.1	65	0.64	7.48	3.74	7.48		10.5

FAL_j—faucet area limit for FDOR land use code j corresponding to parcel i, FC_j—faucet count coefficient for FDOR land use code j corresponding to parcel i, FCO_j—faucet count coefficient for building areas over FAL_j for FDOR code j of parcel i, FDOR—Florida Department of Revenue, FP_j—functional population coefficient for nonresidential FDOR code j corresponding to parcel i, MAPE—mean absolute percent error, MTC_j—mixed-use toilet count coefficient for FDOR land use code j of parcel i, SC_j—showerhead count coefficient for FDOR land use code j corresponding to parcel i, TAL_j—toilet area limit for FDOR land use code j corresponding to parcel i, TC_j—toilet count coefficient for FDOR land use code j corresponding to parcel i, TCO_j—toilet count coefficient for building areas over TAL_j for FDOR code j of parcel i

*Florida Building Commission, 2007; Nicholas, 2010; Duncan, 2007; Tindale-Oliver, 2007.
†Toilet and faucet coefficients limited to a building's first 465 m² (TAL_j) and 743 m² (FAL_j), respectively. For building areas greater than these limits, the toilet (TCO_j) and faucet (FCO_j) coefficients are half of TC_j and FC_j.
‡Maximum of 67% of single-use toilets for assembly or educational establishments are replaceable by urinals; all other sectors correspond to a 50% single-use toilet-to-urinal maximum replacement rate (MaxUrinalP).

TABLE 2 Fixture water use–efficiency coefficients per age group

Residential Fixture	Service Life—*years*	Current Fixture Efficiencies Pre-1983	1983–1994	Post-1994	Sources
Toilet (L/flush)	Residential: 40 CII: 25	19	13	6.1	5, 7, 8, 11
Urinal (L/flush)	25	9.5	5.7	3.8	7, 8, 11
Residential faucet (L/min)	15	19	11	8.3	4, 5, 9, 10
CII faucet (L/min)	15	19	11	5.7	4, 5, 9, 10
Shower (L/min)	8	25	11	9.5	1, 2, 5, 7, 11
Residential clothes washer (L/load)	11	210	190	160	3, 5, 7, 11
Pre-rinse spray valve (L/min)	5	19	13	6.1	6

CII—commercial, industrial, and institutional

[1]A&N, 2005; [2]Allen et al, 2010; [3]*Appliance Magazine*, 2011; [4]Chandler, 2000; [5]Green, 2010; [6]Koeller & Dietemann, 2010; [7]Koeller & Company, 2005; [8]Peterson, 2007; [9]USEPA, 2011; [10]USEPA, 2005; [11]Vickers, 2001

TABLE 3 Residential and CII single-use and mixed-use frequency of fixture-use coefficients per 24-hour period*

Fixture Type	Single Use	Mixed Use
Residential toilet—*flushes/person/day*	NA	5.10
CII toilet—*flushes/person/day*	1.91	7.65
Urinal—*flushes/person/day*	5.74	
Residential faucet—*minutes/person/day*	8.10	
CII faucet—*minutes/person/day*	1.89	
Shower—*minutes/person/day*	5.60	
Residential clothes washer—*loads/person/day*	0.37	
Prerinse spray valve—*hours/unit/day*	1.44	

CII—commercial, industrial, and institutional, NA—not applicable

*Mayer et al, 1999; USEPA, 2011.

that is available as part of Microsoft Excel and minimizes the mean absolute error between the estimated total number of fixtures (calculated using Eqs 8–13) and the fixture counts provided by SCPA over all the parcels within a given FDOR code. Eqs 8–13 need to be solved sequentially. The complexity in the formulation results from the integer rounding in Eqs 8–13 and the nonconvex relationships that require fewer fixtures per square meter for larger sizes. The decision variable in this optimization is the fixture calibration factor (FCF), which scales the minimum fixture coefficients. This optimization scheme allows the fixture count estimates to more accurately portray actual building practices while maintaining the same mix of end-use devices specified by the Florida Plumbing Code. The calibrated fixture-count coefficients, along with their FCF, are presented in Table 1 for the top water-using CII sectors in Florida as identified by Morales et al (2011). The optimal values of FCF range from a low of 0.5 for hotels/motels (FDOR 39) to a high of 8.3 for community shopping centers (FDOR 16). The sample sizes are relatively small ranging from only eight for hotels/motels to 143 for one-story stores (FDOR 11). The total number of estimated toilets per 1,000 m^2 is shown in column 5 of Table 1. The mixed-use toilets per 1,000 m^2 turn out to be 50% of the total number of toilets except for churches (FDOR 71) where they are 67% of total toilets. The number of faucets per total toilets range from 37 to 100% with an average of 67%. Restaurants have the highest number of people per total toilets of 12.7. The minimum fixture-count coefficients can be derived by dividing the fixture-count coefficients by the FCF for a given FDOR land use code. As a measure of error, the MAPE for each sector is shown in Table 1, which ranges from 16 to 65%. For goodness of fit, the coefficients of determination (R^2) between the estimated and SPCA reported parcel-fixture counts for the top CII sectors are also shown in Table 1. The R^2 values vary widely from 0.18 to 0.96.

Some of the coefficients in Table 1 are limited to facilities smaller than a certain area as described in the footnotes. The hotel/motel coefficient assumes that the average hotel room is 23 m^2, with a gross-to-net ratio of 1.1, where gross area is the total area of a building, and net area is the "usable" area of a building. Thus this coefficient assumes that an average room accounts for 26 m^2 in a hotel/motel. Prerinse spray valves are estimated by assuming either one or two for restaurants (FDOR 21) with a heated building area greater than 510 m^2. This area cutoff is derived from studies (SFWMD, 2010; SBW Consulting, 2004) indicating an average of 1.3 prerinse spray valves per restaurant, which corresponds to the smaller 70% of restaurants ($\leq$ 510 m^2 as determined by the FDOR database) only having one prerinse spray valve. The fixture-per-square-meter coefficients are intended to be applied at the parcel level, allowing for estimates of fixture counts to be rounded to the nearest integer. To estimate the number of urinals, the Florida plumbing code states that a maximum of 67% of single-use toilets for assembly or educational establishments are replaceable by urinals; all other facility types are allowed a 50% maximum replacement, as described in the footnotes to Table 1.

The following equations provide the detailed mathematical formulations of how the coefficients in Table 1 are applied to estimate parcel-level fixture counts. First the preliminary number of toilets required for a given parcel is estimated because the number of urinals depends on the preliminary number of single-use toilets used solely by men (Eq 7). Subsequently the urinal count is estimated by applying the maximum number of single-use toilets replaceable by urinals (Eq 8). The number of mixed-use toilets (Eq 9) and single-use toilets (Eq 10) follow. Then the actual total number of toilets is the sum of single-use and mixed-use toilets (Eq 11), which differs from the preliminary toilet count estimate if urinals are present within a parcel. The faucet count estimate is given by Eq 12, which ensures that at least two faucets are present if both single-use and mixed-use toilets are present within a given parcel. Estimates of the number of showerheads and prerinse spray valves apply only to certain FDOR codes, and are given by Eqs 13 and 14, respectively. Within the following equations the $\lceil\ \rceil$ brackets denotes rounding up to the next greater integer, and $\lfloor\ \rfloor$ indicates rounding down to the next-smaller integer. The symbols $\wedge$, $\vee$, and $\rightarrow$ are logical conjunctions that link propositions. For example, $A \vee B$ is read "A or B," $A \wedge B$ is read "A and B," and $A \rightarrow B$ is read "if A then B."

The terms used in these equations are defined in the glossary on page E469.

$$\mathrm{PreNToilets}_i = \left\lceil \begin{array}{l} (\mathrm{HA}_i \leq \mathrm{TAL}_j \rightarrow (\mathrm{HA}_i/1{,}000) \times \mathrm{TC}_j) \vee \\ (\mathrm{HA}_i > (\mathrm{TAL}_j \rightarrow (\mathrm{TAL}_j/1{,}000 \times \mathrm{TC}_j + (\mathrm{HA}_i - \mathrm{TAL}_j)/1{,}000 \times \mathrm{TCO}_j) \end{array} \right\rceil \tag{7}$$

$$\mathrm{NUrinals}_i = \left\lfloor \left(\mathrm{PreNToilets}_i - \left\lceil \begin{array}{l} (\mathrm{HA}_i \leq \mathrm{TAL}_j \rightarrow (\mathrm{HA}_i/1{,}000) \times \mathrm{MTC}_j) \vee \\ \left(\begin{array}{l} \mathrm{HA}_i > \mathrm{TAL}_j \rightarrow (\mathrm{TAL}_j/1{,}000) \times \mathrm{MTC}_j + \\ (\mathrm{HA}_i - \mathrm{TAL}_j)/1{,}000 \times \mathrm{MTCO}_j \end{array} \right) \end{array} \right\rceil \right) \times \mathrm{MaxUrinalP} \right\rfloor \tag{8}$$

$$\begin{array}{l} \mathrm{NMixedUseToilets}_i = (\mathrm{NUrinals}_i = 0 \rightarrow \mathrm{PreNToilets}_i) \vee \\ \quad \left(\mathrm{NUrinals}_i > 0 \rightarrow \left\lceil \begin{array}{l} (\mathrm{HA}_i \leq \mathrm{TAL}_j \rightarrow (\mathrm{HA}_i/1{,}000) \times \mathrm{MTC}_j) \vee \\ \left(\begin{array}{l} \mathrm{HA}_i > \mathrm{TAL}_j \rightarrow (\mathrm{TAL}_j/1{,}000) \times \mathrm{MTC}_j + \\ (\mathrm{HA}_i - \mathrm{TAL}_j)/1{,}000 \times \mathrm{MTCO}_j \end{array} \right) \end{array} \right\rceil \right) \end{array} \tag{9}$$

$$\mathrm{NSingleUseToilets}_i = \mathrm{PreNToilets}_i - \mathrm{NUrinals}_i - \mathrm{NMixedUseToilets}_i \tag{10}$$

$$\mathrm{NToilets}_i - \mathrm{NMixedUseToilets}_i + \mathrm{NSingleUseToilets}_i \tag{11}$$

$$\begin{array}{l} \mathrm{NFaucets}_i = \left(\mathrm{NSingleUseToilets}_i = 1 \wedge \left\lceil \begin{array}{l} (\mathrm{HA}_i \leq \mathrm{FAL}_j \rightarrow (\mathrm{HA}_i/1{,}000) \times \mathrm{FC}_j) \vee \\ \left(\begin{array}{l} \mathrm{HA}_i > \mathrm{FAL}_j \rightarrow (\mathrm{FAL}_j/1{,}000) \times \mathrm{FC}_j + \\ (\mathrm{HA}_i - \mathrm{FAL}_j)/1{,}000 \times \mathrm{FCO}_j \end{array} \right) \end{array} \right\rceil = 1 \rightarrow 2 \right) \vee \\ \quad \left(\mathrm{NSingleUseToilets}_i \neq 1 \rightarrow \left\lceil \begin{array}{l} (\mathrm{HA}_i \leq \mathrm{FAL}_j \rightarrow (\mathrm{HA}_i/1{,}000) \times \mathrm{FC}_j) \vee \\ \left(\begin{array}{l} \mathrm{HA}_i > \mathrm{FAL}_j \rightarrow (\mathrm{FAL}_j/1{,}000) \times \mathrm{FC}_j + \\ (\mathrm{HA}_i - \mathrm{FAL}_j)/1{,}000 \times \mathrm{FCO}_j \end{array} \right) \end{array} \right\rceil \right) \end{array} \tag{12}$$

$$\mathrm{NShowerheads}_i = \left\lceil \frac{\mathrm{HA}_i}{1{,}000} \times \mathrm{SC}_j \right\rceil \tag{13}$$

$$\mathrm{NPRSV}_i \leq (\mathrm{HA}_i < 510 \rightarrow 1) \vee (\mathrm{HA}_i \geq 510 \rightarrow 2) \tag{14}$$

$$\mathrm{LFCY}_{if} > \lfloor (\mathrm{YA} - \mathrm{YB}_i)/\mathrm{SL}_f \rfloor \times \mathrm{SL}_f + \mathrm{YB}_i \tag{15}$$

FIXTURE WATER USE EFFICIENCY

Plumbing codes mandate water use efficiencies. Through this regulatory framework, a fixture's efficiency is a function of a building's year built and a fixture's service life. The historical water use efficiencies for toilets, urinals, faucets, showerheads, clothes washers, and prerinse spray valves, required by the Florida plumbing code for both the residential and CII sectors, are shown in Table 2 (Friedman et al, 2011; NCDENR 2009). The 1995–present CII faucet efficiency is taken to be 5.7 L/min given the frequent installation of 8.3 L/min faucets (the residential standard) in commercial establishments despite the maximum flow rate standard for public (nonresidential) faucets being 1.9 L/min (AWE, 2010).

The service lives of the various fixture types are also provided in Table 2. Historically, toilets and urinals have lasted for long periods of time. Estimates of their service lives seen in the literature range from 20 years to infinity. For this article, residential toilets are taken to have a service life of 40 years (Heaney et al, 2012). CII toilets and urinals are estimated to have service lives of 25 years based on valve lifecycle analysis (Santa Clara Valley Water District, 2008; Scheuer et al, 2003). A Lagrangian approach to estimating service life is used because it is important to retain the identity of the fixtures over time. The last fixture change-out year for each fixture type within each parcel is calculated using Eq 15, and is used to arrive at the efficiency of each fixture within a given parcel using Table 2. The alternative approach of estimating fixture replacement using replacement rates (e.g., 5% of the urinals are replaced each year) causes the identity of an individual fixture to be lost.

FREQUENCY OF USE

The proposed method for estimating how often fixtures are used within the residential and CII sectors is given in this section. This determination is made possible given that fixture frequency of use is driven by people. By estimating how many, and for how long, people are in a building, one can estimate frequency of use. For the residential sectors, the number of people within a given residence is derived from the US Census, which provides the average people per home within a given census block. This estimate is more complicated for CII facilities, which have arrival and departure rates that vary widely depending on the mix and type of customers and employees. To overcome these challenges, functional population coefficients are proposed.

Functional population is a building's population normalized to 24 hours per day and seven days per week (Nelson & Nicholas 1992). For example, if 24 people visit a store for an hour each day, this corresponds to a functional population of one. Functional population coefficients are available for many facility types from impact fee studies specific to Florida (Nicholas, 2010; Duncan, 2007; Tindale-Oliver, 2007). These coefficients are derived from transportation modeling statistics on employment, visitor trips, and length of stay, and can be mapped to FDOR (Table 1). Functional population coefficients are normalized by heated building area and thus apply directly to FDOR parcel-level data. Similar transportation statistics are available throughout the United States, allowing for geographic-specific estimates of frequency of use (ITE, 2012).

In addition to estimates of the number of people in a building, measures of how often and for how long people use water fixtures are required to arrive at estimates of water use. Mayer et al (1999) gathered such data for 1,188 single-family residences in 12 cities and the results are shown in Table 3. For the CII sectors, because functional population is a standardized measure across all land uses, this allows for the application of generic human frequency-of-restroom-use estimates. The average person in a single-family residence flushes a toilet 5.1 times per day (Mayer et al, 1999). Assuming this statistic is based on a 16-h period, its 24-h equivalent would be 7.65 flushes per person per day. Following this procedure, single-use (fixtures used solely by men) and mixed-use (fixtures used either solely by women or both women and men) frequency-of-use coefficients per end-use fixture are also shown in Table 3. The single-use coefficients assume that, when applicable, urinal use occurs three times as frequently as toilet use. Faucet use is estimated by assuming 15 seconds of faucet use following every toilet or urinal event. Toilet and urinal coefficients are expressed in flushes per person per day, whereas faucet and shower use is in minutes per person per day. Prerinse spray valves were assumed to be used an average of 1.44 h/day (USEPA, 2011).

WATER END-USE ESTIMATES AT THE PARCEL LEVEL

The methodology described in the previous sections allows for the estimation of water use per end-use device at the parcel level. Knowing how much water a given device currently uses, it is possible to derive the water saved through retrofitting such a device. The calculation to estimate water use per end-use device is shown in Eqs 16 and 17 for the residential and CII sectors, respectively.

$$\mathrm{CFWU}_{if} = \mathrm{PPH}_i \times \mathrm{FOU}_f \times \mathrm{FE}_{if}/\mathrm{NF}_{if} \tag{16}$$

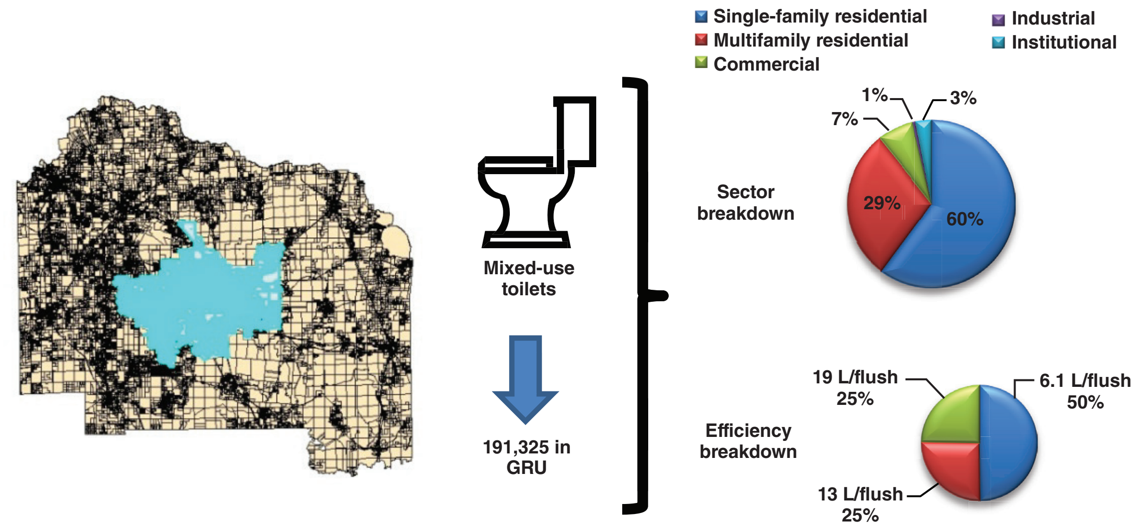
$$\mathrm{CFWU}_{if} = (\mathrm{HA}_i \times \mathrm{FP}_j) \times \mathrm{FOU}_f \times \mathrm{FE}_{if}/\mathrm{NF}_{if} \tag{17}$$

The terms used in these equations are defined in the glossary on page E469. Estimates of water use are carried out at the parcel end-use level, but the results can be aggregated to any level as needed. For example, Figure 3 shows the distribution of mixed-use toilets across the major sectors of water use for an entire utility—in this case Gainesville Regional Utilities (GRU). Such an approach extends to all of the end uses covered in this article. The GRU end-use inventory of all modeled devices is shown in Table 4 across the major water use sectors. This table highlights the differing water usage rates across the sectors. Commercial mixed-use toilets in GRU use an average of 3.1 times more water than single-family toilets. With cost information included, these toilets are likely more cost-effective to retrofit, but there are also fewer of them (Figure 3).

The total modeled water use for GRU in Table 4 equates to 47.7 ML/d using an analysis year of 2012. The Florida Department of Environmental Protection (FDEP) collects the average monthly and peak daily water production data for each utility in the state. For 2011, GRU reported an average daily water production of 93.1 ML/d. This suggests that the model accounts for 51% of all water produced. This is reasonable because water losses, as well as other important end uses such as residential irrigation, are not included in this end-use model.

For the CII sectors, with the limited availability of end-use data and the plethora of end uses, only sanitary end uses are modeled. Because end uses and rates vary significantly across the FDOR CII sectors, it is reasonable that the modeled water use percentage of the total varies as well. The modeled parcel estimates of sanitary water are compared with billing data from seven utilities in Florida in Table 5. The billing data sample for the top 13 CII sectors is 3,631 parcels, and with the use of all available parcels, the CII percent of total modeled varies from 6 to 82% across the major sectors. Through the parcel-level estimation of sanitary water use, however, it became apparent that a large number of suspect outliers were present in the billing data. In particular, one-story stores (FDOR 11) and community shopping centers (FDOR 16) had a large number of parcels in which the model greatly overestimated the actual billed water use. The principal reason for this conflict is believed to be that such land use parcels often encompass multiple businesses and meters, and thus the overestimation of water use is due to the billing data not representing all meters on a parcel. Other outlier effects can include misclassification of land uses; for example, a large warehouse that is classified as a one-story store will have a much lower billed water use than modeled. Also, there might be inaccurate building areas in the FDOR data, both under- and over-reporting, resulting in erroneous model inputs. However, there are also parcels that have no erroneous data but are at either end of their sector's water use bounds. Thus it is difficult to determine which parcels linked to billing data are erroneous or simply extreme values.

FIGURE 3 Sector and efficiency breakdown of all 191,325 mixed-use toilets in GRU for an analysis year of 2012



GRU—Gainesville Regional Utilities

In an effort to reduce the outlier effect, a simple rule was implemented to filter out suspect outliers. The rule states that any given parcel must have a modeled sanitary usage between 5 and 100% of billing, a reasonable range for sanitary uses across the CII sectors. This filter decreased that billing data sample size by 30% to 2,550. The filtered percent modeled effect varies across the sectors, with the greatest decreases being in one-story stores (FDOR 11) and community shopping centers (FDOR 16), whereas auto sales/repair (FDOR 27) saw a significant increase from 6 to 13%. Other sectors such as one-story offices (FDOR 17), fast-food restaurants (FDOR 22), homes for the aged (FDOR 74), and public county schools (FDOR 83) remained essentially unchanged. Overall the filtered estimates across the CII sectors of total water use that is accounted for in the model correspond better with the sanitary end-use values in the literature as shown in Table 5. With the proximity to the values in the literature, the CII water end-use estimation methodology described in this article appears to provide reasonable estimates throughout the CII sectors.

SUMMARY AND CONCLUSIONS

The parcel-level methodology to estimate water uses described in this article provides a process-level understanding of customer water use. This facilitates the evaluation of savings

TABLE 4 Modeled 2012 fixture count and end-use water use for Gainesville Regional Utilities

Values	Single-Family Residential	Multifamily Residential	Commercial	Industrial	Institutional	Total
Single-use toilet count			3,260	204	1,855	5,319
Mixed-use toilet count	115,017	56,144	13,295	1,062	5,807	191,325
Urinal count			3,021	171	2,531	5,723
Faucet count	163,936	92,990	14,471	1,437	8,720	281,554
Showerhead count	87,446	38,784	3,927		1,070	131,227
Prerinse spray valve count			128			128
Clothes washer count	48,405	24,996				73,401
Total	414,804	212,914	38,102	2,874	19,983	688,677
Single-use toilet—*L/d*			395,235	11,379	173,720	580,334
Mixed-use toilet—*L/d*	6,660,134	3,469,135	2,418,760	112,393	727,927	13,388,349
Urinal—*L/d*			651,075	19,851	303,374	974,300
Faucet—*L/d*	7,306,023	4,501,201	738,742	31,843	293,634	12,871,443
Showerhead—*L/d*	5,739,859	3,536,296	346,717		148,539	9,771,411
Prerinse spray valve—*L/d*			66,983			66,983
Clothes washer—*L/d*	6,219,550	3,831,830				10,051,380
Total—*L/d*	25,925,566	15,338,462	4,617,512	175,466	1,647,194	47,704,200

TABLE 5 Percentage of total water use modeled as sanitary for each of the top 10 commercial and 3 institutional sectors through use of parcel billing data from 7 utilities in Florida*

<table>
<tr><th colspan="2"></th><th colspan="2">All Data</th><th colspan="2">Filtered Data</th><th colspan="5"></th></tr>
<tr><th>FDOR Land Use Code j</th><th>Description</th><th>Sample Size</th><th>% Sanitary</th><th>Sample Size</th><th>% Sanitary</th><th>EBMUD, 2008—%</th><th>Dziegielewski et al, 2000—%</th><th>Seneviratne, 2007—%</th><th>Gleick et al, 2003—%</th><th>SWFWM, 1997—%</th></tr>
<tr><td>11</td><td>Stores, one-story</td><td>618</td><td>82</td><td>294</td><td>33</td><td rowspan="2">26</td><td rowspan="2"></td><td rowspan="2">48</td><td>24</td><td rowspan="2"></td></tr>
<tr><td>16</td><td>Community shopping centers</td><td>306</td><td>70</td><td>177</td><td>41</td><td></td></tr>
<tr><td>17</td><td>Offices, one-story</td><td>600</td><td>23</td><td>437</td><td>23</td><td rowspan="3">34</td><td rowspan="3">37
(17–77)</td><td rowspan="3">37</td><td rowspan="3">26</td><td rowspan="3">24</td></tr>
<tr><td>18</td><td>Offices, multistory</td><td>132</td><td>44</td><td>89</td><td>35</td></tr>
<tr><td>19</td><td>Medical offices</td><td>429</td><td>24</td><td>349</td><td>20</td></tr>
<tr><td>21</td><td>Restaurants</td><td>245</td><td>44</td><td>156</td><td>35</td><td rowspan="2">33</td><td>44
(23–58)</td><td rowspan="4"></td><td rowspan="2">35</td><td>35</td></tr>
<tr><td>22</td><td>Fast-food restaurants</td><td>141</td><td>37</td><td>124</td><td>35</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>23</td><td>Financial institutions</td><td>161</td><td>11</td><td>102</td><td>15</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>27</td><td>Auto sales/repair</td><td>286</td><td>6</td><td>226</td><td>13</td></tr>
<tr><td>39</td><td>Hotels/motels</td><td>98</td><td>49</td><td>84</td><td>43</td><td>35</td><td>49
(42–55)</td><td>63
(54–72)</td><td>54</td><td>62</td></tr>
<tr><td>71</td><td>Churches</td><td>484</td><td>18</td><td>402</td><td>22</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="3"></td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>74</td><td>Homes for the aged</td><td>51</td><td>15</td><td>44</td><td>16</td></tr>
<tr><td>83</td><td>Public county schools</td><td>80</td><td>24</td><td>66</td><td>24</td><td>44</td><td>12
(5–19)</td><td>21</td><td>31</td></tr>
</table>

*The table shows estimates using all 3,631 parcels, as well as filtered samples where parcels with a modeled percentage of the total billed outside of 5–100% were removed as a means to eliminate erroneous data.

associated with water conservation practices and the targeting of customers for these practices based on cost effectiveness. The methodology described in this article is applicable nationwide given that similar county property appraiser databases are available throughout the United States. The default fixture count, functional population, and frequency-of-use coefficients should provide reasonable assumptions for the rest of the country although site-specific data should be used when possible (Mayer et al, 1999). The inclusion of CII customers in the methodology is significant, given the limited understanding of how water is used by such customers.

Future work should include other water end uses such as irrigation by residential customers and cooling towers, clothes washing, and other process uses by CII customers. Furthermore, water end-use data for other CII sectors should be included to better calibrate the model. An uncertainty analysis should also follow to provide a more comprehensive measure of the accuracy of the approach.

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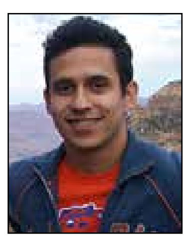

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PEER REVIEW

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Glossary

$CFWU_{if}$ = current fixture water use of fixture type *f* in parcel *i* (litres/fixture/day)

FAL_j = faucet area limit for Florida Department of Revenue (FDOR) land use code *j* corresponding to parcel *i* (m^2)

FC_j = faucet count coefficient for FDOR land use code *j* corresponding to parcel *i* (faucets/1,000 m^2)

FCO_j = faucet count coefficient for building areas over FAL_j for FDOR code *j* of parcel *i* (faucets/1,000 m^2)

FE_{if} = fixture efficiency as determined by Eq 15 and Table 2 (litres/flush or minute)

FOU_f = frequency of use for fixture *f* as shown in Table 3 (flushes or minutes/person/day)

FP_j = functional population coefficient for nonresidential FDOR code *j* corresponding to parcel *i* (functional population/m^2)

$LFCY_{if}$ = last change-out year of fixture *f* in parcel *i*

MAPE = mean absolute percent error

MTC_j = mixed-use toilet count coefficient for FDOR land use code *j* of parcel *i* (toilets/1,000 m^2)

$MTCO_j$ = mixed-use toilet count coefficient applicable to building areas over TAL_j for FDOR land use code *j* corresponding to parcel *i* (toilets/1,000 m^2)

$NFaucets_i$ = faucet count estimate for parcel *i*

NF_{if} = number of fixtures *f* on parcel *i* as determined by Eqs 3–6 for residential parcels and Eqs 7–14 for CII parcels

$NMixedUseToilets_i$ = count estimate of toilets used either solely by women or both women and men for parcel *i*

$NPRSV_i$ = prerinse spray valve count estimate for parcel *i*

$NShowerheads_i$ = showerhead estimate for parcel *i*

$NSingleUseToilets_i$ = count estimate of toilets used solely by men for parcel *i*

$NToilets_i$ = total toilet count estimate for parcel *i*

$NUrinals_i$ = urinal count estimate for parcel *i*

PPH_j = people per dwelling unit for parcel *i*

$PreNToilets_i$ = preliminary toilet count estimate for parcel *i*

$ResBaths_i$ = number of bathrooms on residential parcel *i* rounded to the nearest 0.5 baths

$ResClothesWashers_i$ = integer number of clothes washers on residential parcel *i*

$ResFaucets_i$ = integer number of faucets on residential parcel *i*

$ResShowerheads_i$ = integer number of showerheads on residential parcel *i*

$ResToilets_i$ = integer number of toilets on residential parcel *i*

$ResUnits_i$ = integer number of residential units on parcel *i*

SC_j = showerhead count coefficient for FDOR land use code *j* corresponding to parcel *i* (showerheads/1,000 m^2)

$Sector_i$ = parcel descriptor based on FDOR land use code denoting single-family (SF) or multifamily (MF) land use or parcel *i*

SL_f = service life in years of fixture *f*

TAL_j = toilet area limit for FDOR land use code *j* corresponding to parcel *i* (m^2)

TC_j = toilet count coefficient for FDOR land use code *j* corresponding to parcel *i* (toilets/1,000 m^2)

TCO_j = toilet count coefficient for building areas over TAL_j for FDOR code *j* of parcel *i* (toilets/1,000 m^2)

YA = year of water conservation analysis

YB_i = effective year built of parcel *i*

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