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Appropriate design and evaluation of water use and conservation metrics and benchmarks

TWO MAJOR RECOMMENDATIONS—ONE PERTAINING TO DATA AND WATER USE RECORDS AND THE OTHER TO THE DEVELOPMENT OF SUPPORTIVE INFORMATION FOR CONSERVATION BENCHMARKS—ARE THE RESULT OF THE RESEARCH PRESENTED IN THIS ARTICLE.

Because of increasing competition and costs for available water supplies, water utilities, and regulators have a growing need for meaningful performance indicators and benchmarks for measuring and comparing water use. Furthermore, utility managers and water researchers alike have a natural tendency to compare measurements of water use to gauge changes over time and differences among water utilities. This article discusses both new and commonly used performance metrics and benchmarks regarding water use efficiency. The purpose is to provide guidance on alternative methods of measuring water use and to show how these methods are most appropriately used to compare and evaluate water efficiency.

The use of metrics and benchmarks is not new to the water utility industry. A widely used metric is the difference between water production and total metered sales, which is now known as nonrevenue water. A related, recently developed benchmark is the infrastructure leakage index (ILI), which is the ratio of annual real losses of water during transmission and distribution to an estimated value of unavoidable leakage (Kunkel et al, 2003). Metrics that measure water use are less common, with the exception of the popular metric of aggregate use—per capita use or gallons per capita per day. Other metrics of disaggregate use of water in different sectors of the water industry are applied in demand forecasting and planning studies, but they are not as routinely used by water utilities.

Historically, the lack of a consistent definition of terms and practices has complicated the water industry's ability to measure, standardize, and compare utility performance. Even when precise definitions exist (e.g., population served), many utilities are challenged when asked to provide accurate numbers and rely instead on best available estimates. Evaluating water use of an individual utility over time is difficult enough, but the lack of standardization of terms and categories of water production and use creates an even greater challenge when comparing performance among utilities. Therefore, it is important that metrics and benchmarks of water use are explicitly defined and carefully evaluated in terms of their appropriate use.

This article summarizes the water use metrics study funded by the AWWA Technical and Education Council and sponsored by the Water Conservation Division (Dziegielewski & Kiefer, 2009), which can be found at www.awwa.org/Resources/Waterwiser.cfm. The purpose of the study was to provide guidance on standardized methods of calculating specific metrics and to describe their advantages and limitations. Using data from seven US water utilities that agreed to participate in the project, the study defined, calculated, and illustrated the appropriate use of several water use metrics.

OVERVIEW OF METRICS, BENCHMARKS, EFFICIENCY, AND CONSERVATION

Before discussing "water conservation metrics" it is necessary to define "water use" and "water use metrics." The term "water use" has multiple meanings, depending on whether it is used in hydrologic, engineering, or regulatory contexts. In the water supply industry, water use usually designates the amount of finished drinking water produced or sold to customers through metered connections. Water sold is often referred to as water consumption—a term that could be confused with the hydrologic concept of consumptive use. This article avoids using the term "consumption"—instead the authors have indicated "water use" to be a generic term to mean water used for any practical purpose. In the context of discussing metrics and benchmarks, this primarily represents the quantity of metered water use at one or more customer connections over any given time interval.

Generally speaking, a metric is a unit of measure (or a parameter being measured) that can be used to assess the rate of water use during a given period of time and at a given level of data aggregation. Another term for a metric is performance indicator. In essence, a metric is a formula that can be applied to water use and related data from a utility for a defined time period to obtain a numerical value. Water use metrics are usually calculated as "usage ratios" that represent a quotient obtained by dividing the volume of water used (or sold) over a specified period of time (e.g., day, month, season, or year) by a scaling factor (e.g., number of accounts, population served, or number of housing units or employees). The numeric value of any particular metric can be compared with a predefined benchmark value to assess a relative level of performance.

A benchmark is a particular (numeric) value of a metric that denotes a specific level of performance, such as a water efficiency target. Sometimes a distinction is made between a benchmark (which indicates a current state of achievement) and a target (which indicates a state of achievement expected or desired at some time in the future). Basically, benchmarks or targets are numeric values with which the calculated metric values are intended to be compared.

Benchmarks can be defined in either absolute or relative terms. Absolute-value benchmarks specify a quantity of water use and usually represent design standards. Relative-value benchmarks are ratios without units in which the value of 1.0 would normally represent a target value (an example is the ILI). Ratio benchmarks can be defined for various end uses of water in which the observed rate of use is divided by an achievable efficient rate of use. Relative-value benchmarks can also be stated as percentage reduction goals, such as a 15% reduction of average annual per capita water use in 10 years. Examples of benchmarks for residential water use can be found in the US Environmental Protection Agency's (USEPA's) WaterSense® publications. Examples of metrics and benchmarks for nonresidential users can be found in Dziegielewski et al (2000).

Determining appropriate values for absolute benchmarks for aggregate-level metrics (such as systemwide or sectorwide measures) presents a special challenge for evaluating water efficiency because the aggregate metrics capture "other-than-efficiency" effects on the calculated unit quantity of water usage. This is a critical point because all metrics tend to be interpreted as indicators of efficiency-in-use, when in reality the calculated values reflect the influence of several other determinants of water use, which are largely unrelated to efficiency-in-use (Figure 1).

Water use metrics and benchmarks are inextricably linked to the concepts of "water use efficiency" and "water conservation." Therefore, it is also helpful to define these concepts in the context of evaluating water use.

> Historically, the lack of a consistent definition of terms and practices has complicated the water industry's ability to measure, standardize, and compare utility performance.

The term "efficiency" derives from engineering practice in which it is typically used to describe technical efficiency or the ratio of output to input. The criterion of technical efficiency is useful in comparing various products and processes. For example, one showerhead would be considered more efficient than another if it could accomplish the same purpose (i.e., of showering) by using less water or other inputs (e.g., lower water pressure). However, the technical efficiency concept is not useful in making decisions about investing money (or resources) in water conservation unless the inputs and outputs are measured in value terms. This expression of efficiency is referred to as economic efficiency.

Water conservation can be defined as a reduction in water use or a reduction in water loss. Baumann et al (1984) developed a practical definition of long-term water conservation as ". . . any beneficial reduction in water use or in water losses." By adding the term "beneficial," the authors proposed a requirement (consistent with the concept of economic efficiency) that the reduction in water use or loss should result in a net increase in social welfare provided where the resources used have a lesser value than those saved. In other words, the beneficial effects of the reduction in water use (or loss) must be considered greater than the adverse effects associated with the commitment of other resources to the conservation effort. This definition provided important guidance (through cost–benefit analysis) for long-term conservation.

This discussion includes an evaluation of water production and water sales metrics and excludes evaluation of water loss metrics. The focus of the discussion is on measurement of technical efficiency and does not approach the question of whether investments in technical efficiency are worthwhile from an economic perspective. Information on water loss metrics can be found elsewhere (Dziegielewski & Kiefer, 2009; AWWA, 2009; AWWA Water Loss Control Committee, 2003).

METRICS OF AGGREGATE USE EXPLAINED

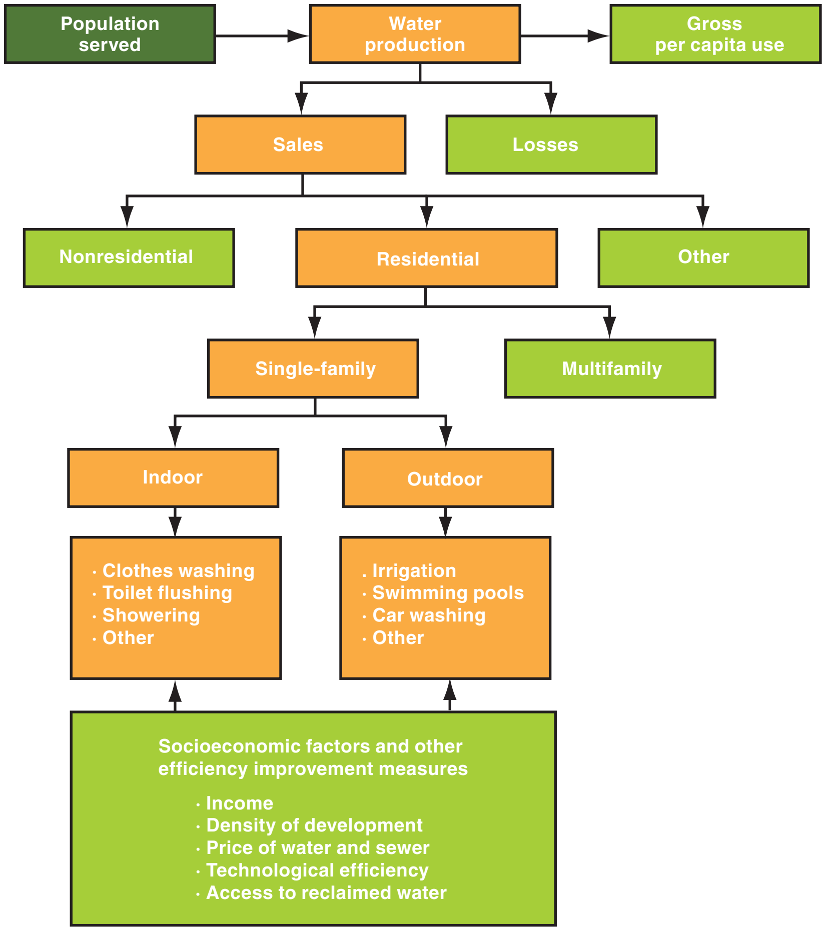
Several different metrics of aggregated (systemwide) water use can be defined. Average rates of use can be obtained by dividing average daily production or total customer sales by a scaling variable. Table 1 describes six metrics for average annual production and total water sales. For water production, the term production quotient (*PQ*) is used. It represents the total volume of water produced divided by a scaling factor such as the number of connections or population served. Additional subscripts are added to the *PQ* acronym to designate the scaling variable being used. For example, the annual average production per customer account per day would be PQ_a, in which a = accounts.

Use of per capita daily production metric. Currently, the most commonly used metric of aggregate use is known as "per capita use" measured in gallons per capita per day (gpcd). This metric is obtained by dividing average daily production (in gallons) by total population served. Water production data are almost always available because they represent an essential operating parameter for treatment, distribution, and water accounting. Production metering provides measured quantities of water being pumped from treatment plants and other sources to the distribution system.

When calculating the per capita daily production (PQ_c) metric (in which c = per capita), the reported annual volumes of water produced should be matched with the population served in the retail service area. This requires that all wholesale water deliveries outside the retail service area be metered and deducted from the production volume. Alternately, if the population served by wholesale customers is known, the PQ_c value can be calculated by dividing total production by the sum of retail and wholesale population served. Also, any water imported into the distribution system should be added to production records.

Population served is perhaps the most common scaling variable used by public water supply utilities. In theory, it represents the number of people who are served (through metered connections) by the water utility. However, this scaling variable is challenging to define in operational terms and to measure precisely. Total population served can be defined more precisely as total year-round resident

FIGURE 1 Influence of external factors on aggregate and disaggregate metrics of water use



population of the retail service area. However, several different populations in water utility service areas can be distinguished. In addition to the year-round (or resident) population, there are household populations, group quarters populations, commuter populations, seasonal populations, and others.

Another issue associated with "population served" is the challenge of measuring population accurately. Relatively accurate estimates of resident population are made every 10 years during the census. Estimates of resident population during noncensus years are obtained by alternative methods and are less accurate. Even during the census years, population counts available for census tracts and city blocks cannot be matched perfectly with the boundaries of areas served by a water utility.

The precise definition and measurement of population served are most challenging when they are used for water allocation (through water use permits) or for other regulatory purposes. Examples of methodologies for calculating population served have been published by the Southwest Florida Water Management District (Gonzales & Yingling, 2008) and the New Mexico Office of the State Engineer (NMOSE, 2009). Standardized measurements of "population served" usually attempt to account for commuters and part-time residents (e.g., hotel guests, students, and seasonal residents). The term "functional population served" is used by some utilities to describe the population served that has been adjusted for hotel populations, commuter populations, and populations in group quarters. However, regardless of its definition, population served cannot be measured accurately during each calendar year and will likely be a crude estimate of actual population, however that is defined.

Metrics based on the number of service connections. Because population served is difficult to measure (even if it is precisely defined), a more accurate measure of system size is needed. One measure of system size that is universally available is the number of water service connections. This measure can be defined precisely by making distinctions between specific characteristics of the various types of connections.

A distinction can be made between retail and wholesale connections, metered and unmetered connections, and connections with different meter sizes. Additional definitions can include active and inactive customer accounts, number of billed accounts, or number of billed accounts with nonzero consumption.

The list in Table 1 also includes metrics based on average water production or sales per account (i.e., the PQ_a and SQ_a metrics). The advantage of these metrics over per capita metrics is that the number of connections (or accounts) is updated frequently and is relatively accurate. The number of billed accounts is also available for each billing period (i.e., monthly, bimonthly, or quarterly).

A possible improvement to the PQ_a and SQ_a metrics can be made by converting the total number of connections or accounts (representing different types of customers or connection sizes) into the number of "equivalent connections" or "equivalent accounts," with reference to single-family accounts. This means that the number of accounts in multifamily and all nonresidential sectors is expressed as an equivalent number of single-family accounts. The main reason for creating a number of equivalent accounts for each utility is to develop a scaling variable that is similar to population served. The weights for converting nonsingle-family accounts into equivalent (single-family) accounts reflect the ratio of average annual consumption by customer type or by

TABLE 1 Advantages and disadvantages of metrics of aggregate water use

Metric	Definition	Advantages (↑) and Disadvantages (↓)	
		Numerator: Water Quantity	**Denominator: Scaling Variable**
PQ_c PQ_a PQ_{ea}	Per capita production Production per account Production per "equivalent" account	↑ There is good availability of data on water production. ↑ Water exports can be excluded (and imports included). ↓ Total includes real water system losses. ↓ This metric cannot account for different composition of water use among primary sectors.	↓ Population served is defined differently by water utilities and cannot be measured accurately. ↑ Number of billed accounts is known for each billing period. ↓ Number of equivalent accounts is more precise than population served.
SQ_c SQ_a SQ_{ea}	Retail sales per capita Retail sales per account Retail sales per equivalent account	↑ This metric separates out system losses from total water use. ↓ This metric cannot account for different composition of water use among primary sectors.	↓ Estimates of population served are imprecise. ↑ Number of equivalent accounts depends on sectoral water use characteristics. ↑ Number of billed accounts is known for each billing period. ↓ Number of equivalent accounts depends on sectoral water use characteristics (applies to SQ_{ea} metric only).

meter size (in utilities without customer type designation) to average annual consumption in the single-family sector.

Overview of aggregate metrics in case study utilities. Ten US water utilities were asked to participate in the metrics study, and seven agreed to provide water use data. The utilities were asked to provide production and sector sales and account summaries for the five most recent data years. Table 2 lists the seven utilities, together with a summary of 2008 data for water production, total retail sales, number of customer accounts, and estimated population served.

The seven study sites include four areas in the Southwest and one representative city from the Northwest, East, and Southeast. The participating utilities span a range of system sizes and also differ in prevailing climate and weather patterns. Four of the cities represent arid or semi-arid climates. Two cities (Tampa, Fla., and Philadelphia, Pa.) have humid climates and Seattle, Wash., has a mild oceanic climate with wet winters and dry summers. Table 3 compares the average and 2008 values for precipitation and temperature in the study areas.

The Otay and Irvine Ranch water districts in California receive minimal rainfall during the growing season but tend to have mild temperatures. The Phoenix (Ariz.) Water Services Department and the Rio Rancho (N.M.) Utilities Services Division receive small amounts of rainfall but have very high temperatures. Seattle receives about 7 inches of rainfall during the identified growing season and has the lowest average maximum temperatures among all seven sites. Philadelphia and Tampa have substantially higher rainfall during the growing season than the five western sites. It is apparent that each site has a unique climate.

Table 4 compares the values of aggregate water use metrics for the seven participating utilities. The values of aggregate metrics differ greatly across the seven utilities. The differences are caused by two main factors: climate and the composition of water users. A meaningful comparison of per capita production or average annual sales per billed account should attempt to account for these types of influences on water use both within and among the utilities.

If these data were used for comparison purposes, the six different aggregate metrics would result in different ranking of the utilities in terms of water use. For example, Tampa has the second lowest PQ_c value, but it ranks as the fourth lowest according to the SQ_{ea} (retail sales per equivalent account) metric.

TABLE 2 Water utility participants in the study—*2008 data*

Water Utility	Water Production *mgd*	Estimated Population Served	Retail Sales *mgd*	Number of Customer Accounts	Number of Equivalent Accounts
Otay (Calif.) Water District	37.1	196,416	35.3	48,227	80,718
Irvine (Calif.) Ranch Water District	88.2	330,000	77.6	96,019	201,174
Phoenix (Ariz.) Water Services Department	272.8	1,566,190	258.6	403,412	693,277
City of Rio Rancho, N.M.	11.7	80,000	9.8	29,787	45,276
Seattle (Wash.) Public Utilities	125.5	649,286*	56.4	186,849	277,711
Philadelphia (Pa.) Water Department	250.7	1,660,500	175.8	486,664	889,899
Tampa (Fla.) Water Department	76.0	657,313	68.8	125,260	248,853

*In Seattle, the combined retail and wholesale population served is 1,312,920.

TABLE 3 Annual and growing season (May–September) climatic data for participating utilities

	Annual Precipitation—*inches*		Growing Season Precipitation—*inches*		Growing Season Average Maximum Temperature—*°F*	
Water Utility	Normal	2008	Normal	2008	Normal	2008
Otay (Calif.) Water District	10.8	11.1	0.6	0.3	74.4	73.3
Irvine (Calif.) Ranch Water District	13.8	11.3	0.8	0.4	80.8	83.6
Phoenix (Ariz.) Water Services Department	8.3	9.6	2.9	5.7	99.6	101.6
City of Rio Rancho, N.M.	9.5	6.7	5.3	2.1	86.7	88.4
Seattle (Wash.) Public Utilities	37.1	30.7	6.7	6.7	71.0	70.0
Philadelphia (Pa.) Water Department	42.1	40.3	19.3	17.6	79.8	81.4
Tampa (Fla.) Water Department	44.8	43.8	29.0	25.2	88.8	89.3

It is clear that the values obtained for these alternative aggregate metrics represent the uniqueness of each water utility. This uniqueness can be observed when the equivalent accounts (or customers) are calculated across the utilities. Figure 2 illustrates the differences in the composition of demand at the sector level for six case study utilities. The equivalent account multipliers are based on the ratio of annual use per account to single-family use. In making comparisons of water use by sector, it would be important to understand why an industrial customer is on average equal to 106 single-family customers in Phoenix, but equal only to 20 single-family customers in Irvine Ranch. Also, it is worth determining why a multifamily customer in Tampa is equivalent to 29 single-family customers and equates only to 3 single-family customers in Rio Rancho. It was determined that in Rio Rancho the multifamily sector includes only tri- and fourplexes. Apartments with five and more units are classified as commercial. Apparently, in Tampa all residential customers other than single-family are included in the multifamily sector. These examples are indicative of "definitional noise" that may be encountered in evaluating the water use of utilities that have different customer classification schemes.

Additionally, the values of the metrics shown in Table 4 can vary from year to year. An appropriate use for the aggregate metrics is for comparing trends in annual water use over time at a single utility. The year-to-year percentage change in historical values of the per capita production metric (PQ_c) for six utilities (only 2008 values were available for Rio Rancho) range from –14% in Tampa to +11% in Irvine Ranch. The year-to-year percentage change values of the retail sales per account metric (SQ_a) for five utilities range from a decline of 11% in Phoenix to an increase of 9% in Irvine Ranch. The degree of observed yearly fluctuations is large enough to obscure the interpretation of gains or losses in water use efficiency over time.

In essence, a metric is a formula that can be applied to water use and related data from a utility for a defined time period to obtain a numerical value.

SECTORWIDE ANNUAL USE METRICS EXAMINED

Year-to-year changes in the annual average values of aggregate metrics at a given utility are the result of different weather conditions and changes in the "structure" of total demand. Generally, metrics based on disaggregated demands (i.e., water sales separated into groups of similar users or sectors) provide a better accounting for changes in the composition of demand and are expected to provide a better basis for comparing usage rates than do aggregate metrics.

Billing data can be used to calculate sector-specific metrics of water use. Table 5 shows three metrics that are derived on the basis of annual water use by sector. All metrics use the number of accounts (for each sector) as the scaling variable. The most commonly used definition of the number of accounts is the number of "billed accounts." In some cases, a water utility may prefer to use a subset of billed accounts, excluding accounts with readings of zero consumption during the billing period.

Table 6 shows the annual average daily water use per account in gallons per day across three sectors within the seven study sites. Similar to the aggregate per capita metrics, per account rates of use show very large differences across the different utilities.

TABLE 4 Water utility calculated aggregate metrics for participating utilities in 2008

Water Utility	Per Capita—*gpd*		Per Account—*gpd*		Per Equivalent Account	
	PQ_c	SQ_c	PQ_a	SQ_a	PQ_{ea}	SQ_{ea}
Otay (Calif.) Water District	189	180	769	732	460	440
Irvine (Calif.) Ranch Water District	267	235	919	808	438	351
Phoenix (Ariz.) Water Services Department	174	165	676	641	393	373
City of Rio Rancho, N.M.	146	123	393	329	258	218
Seattle (Wash.) Public Utilities*	95	87	369	302	249	203
Philadelphia (Pa.) Water Department	151	106	515	361	282	190
Tampa (Fla.) Water Department	116	105	607	519	300	257
Variability—%†	27	37	26	40	24	34

PQ_a—production per account, PQ_c—per capita production, PQ_{ea}—production per equivalent account, SQ_a—retail sales per account, SQ_c—retail sales per capita, SQ_{ea}—retail sales per equivalent account

*The production metrics for Seattle exclude the large quantity of wholesale water (about 52%) from Seattle's production numbers.

†Variability is expressed as a coefficient of variation (standard deviation divided by the mean).

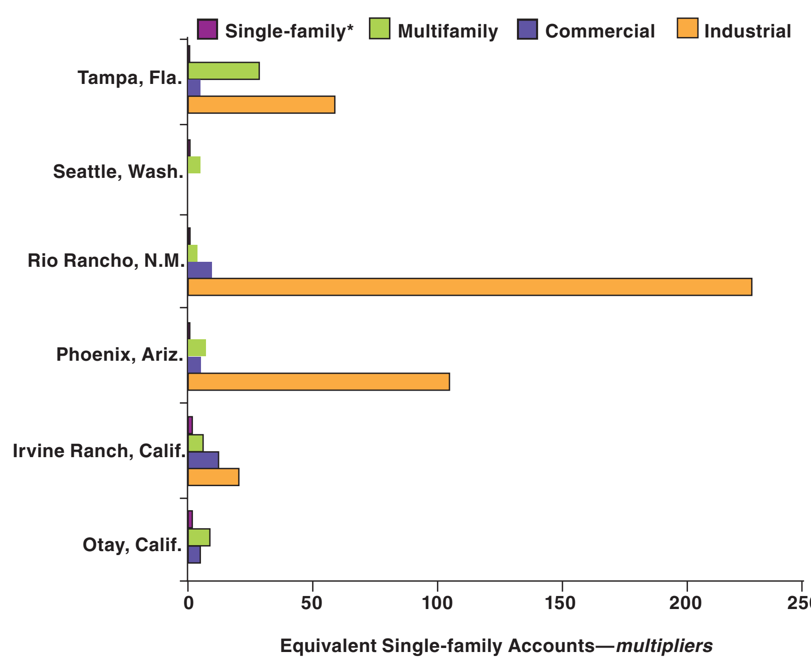
Single-family residential customers represent the most homogeneous sector of urban water use. Usually, a single-family customer represents a land parcel with a free-standing building containing one dwelling unit connected to the city water supply through a single water meter. Possible exceptions to this definition include lots with a secondary building or the presence of a secondary meter for irrigation water, with a few locations still not requiring the use of meters.

Large differences in single-family use per account across different utilities reflect the local climatic conditions and the influence of several other factors (such as housing density or average lot size, average number of people per household, marginal price of water, availability and cost of reclaimed irrigation water, median household income, and other characteristics of the single-family residential sector).

In the multifamily sector, the large differences in annual average water use per account across the utilities are likely the result of different types of multifamily structures and properties and possibly less the result of local weather conditions. Therefore, a more appropriate scaling variable for the multifamily sector may be the number of dwelling units that are represented by the multifamily accounts. In the nonresidential sector, the composition of user types differs among water utilities and is not adequately captured by defining a single broad nonresidential customer class.

The average annual rates of use per account change from year to year. The greatest range in year-to-year changes in use per single-family account are found in Phoenix (–7 to +2%) and in Tampa (–6 to +7%). The average year-to-year percent change (in absolute values) across all data years for all utilities was ±3%. Similarly, year-to-year changes were observed in the multifamily sector with an average absolute change of ±4% across the participating utilities. Much greater year-to-year shifts in water use were observed in the nonresidential sector, ranging from –46 to +37%.

FIGURE 2 Weighting ratios for equivalent single-family accounts by sector



**Equivalent to one account*

METRICS OF SEASONAL AND NONSEASONAL USE

Average daily water use varies throughout the year depending on season and weather conditions. Daily or weekly production data and monthly billing summaries can be used to separate water use into its seasonal and nonseasonal components.

Seasonal uses represent weather-sensitive water demands related to irrigation, cooling, swimming pools, and other purposes affected by weather conditions. In the residential sector, nearly all seasonal use is outdoor use. Nonseasonal use is assumed to be relatively constant throughout the days and months of the year, and in the residential sector it generally represents indoor use.

When calculating the metrics of seasonal and nonseasonal use, an indoor and outdoor designation is often used, although some of the indoor use can be seasonal (e.g., cooling use) and some of the outdoor use could be nonseasonal (e.g., cleaning of concrete surfaces). Although seasonal use does not strictly equate to outdoor use and nonseasonal use is not always indoor use, the seasonal/nonseasonal approximation is used because indoor and outdoor uses are not metered separately.

Minimum-month and seasonal use measurements. The separation of seasonal and nonseasonal components of water use is usually performed using the minimum-month method or a modification. The basic assumption of this method is that the month of lowest water use represents only indoor (or nonseasonal) use. Therefore, seasonal use during the remaining 11 months of the year can be estimated by subtracting the minimum-month use from the total use during each remaining month. As a rule of thumb, in the United States the lowest water use occurs during either of the months of December, January, February, or March.

Once the indoor (or minimum-month) use is estimated, then the average outdoor (or seasonal) use for a calendar year can be calculated. However, as mentioned before, there is a difficulty in making the indoor/outdoor use distinction based on the minimum-month method, especially in areas where there is year-round outdoor and/or cooling use. Table 7 describes eight sector-specific metrics of seasonal and nonseasonal use.

Seasonal and nonseasonal use metrics in case study utilities. Because data on household population, occupied housing units, and other scaling variables were not consistently available for most utilities, Table 8 shows the calculated indoor (nonseasonal) and outdoor (seasonal) metrics based on the number of billed accounts for single-family, multifamily, and nonresidential sectors in the case study utilities.

On the basis of the minimum-month method, the calculated annual values of the indoor (nonseasonal) single-family use metric per account (IUM_a^{SF}) show a range from 120 gpd in Seattle to 271 gpd in Otay. This is counter to the idea that indoor single-family use should be similar in all locations (assuming that the average number of people per household is similar in all seven utilities). It is likely that the estimated minimum-month use includes some outdoor use, but it should not be expected that the numbers would be the same if this source of measurement error was removed. The differences in single-family indoor use across utilities are likely a result of differences in end-use composition and socioeconomic characteristics of individual service areas.

Even larger differences can be seen in average daily seasonal use per residential account. These differences reflect climatic and weather conditions and other factors. For example, both Otay and Irvine Ranch water districts have very low average precipitation during the growing season, but the estimated outdoor use in Otay is twice what it is in Irvine Ranch. Factors other than weather possibly contribute to this difference (e.g., average lot size or number of homes with swimming pools). Some differences also result from the use of the minimum-month method of

TABLE 5 Advantages and disadvantages of metrics of average daily (annual) sector-specific water use

Metric	Definition	Advantages (↑) and Disadvantages (↓)	
		Numerator: Water Quantity	Denominator: Scaling Variable
AUM_a^{SF}	Annual single-family use metric per account	↑ Definition of single-family sector is generally consistent. ↓ Sector usage is influenced by seasonal and weather-sensitive end uses.	↑ Number of billed single-family customers is known for each billing period and closely approximates housing units.
AUM_a^{MF}	Annual multifamily use metric per account	↓ Definition of multifamily sector generally varies across utilities.	↓ Number of billed multifamily customers does not represent the number of occupied housing units. ↓ Average number of units served per multifamily account varies across utilities.
AUM_a^{NR}	Annual nonresidential use metric per account	↓ Nonresidential sector includes dissimilar users, and sector definition generally varies across utilities.	↑ Number of nonresidential accounts is available and more accurate than employment and other counting variables.

TABLE 6 Calculated sectorwide metrics of average annual usage for participating utilities—*2008 data*

Water Utility	Single-family—AUM_a^{SF}	Multifamily—AUM_a^{MF}	Nonresidential—AUM_a^{NR}
Otay (Calif.) Water District	437	3,677	3,169
Irvine (Calif.) Ranch Water District	321	1,994	1,949
Phoenix (Ariz.) Water Services Department	373	2,536	2,415
City of Rio Rancho, N.M.	218	679	2,777
Seattle (Wash.) Public Utilities	141	1,243	1,675
Philadelphia (Pa.) Water Department	189	NA	NA
Tampa (Fla.) Water Department	257	7,338	1,707
Variability—%	38	83	27

AUM_a^{MF}—annual multifamily use metric per account, AUM_a^{NR}—annual nonresidential use metric per account, AUM_a^{SF}—annual single-family use metric per account, NA—data not available determining the indoor/outdoor components of annual use.

The wide range of numbers for multifamily metrics in Table 8 would likely be narrowed if the number of housing units was used as a scaling variable. However, estimates of housing units are difficult to obtain and were not available for this study. The nonresidential metrics of seasonal and nonseasonal use reflect the different composition of the nonresidential sector across the utilities. Improved metrics of nonseasonal use (IUM^{NR}) could be obtained by using a standardized composition of the sector (i.e., definition of user types to be included) and by using the number of employees as the scaling variable. For the seasonal use metrics in the multifamily and nonresidential sectors, a better scaling variable would be the sum of the square footage of the irrigated landscape.

NORMALIZING METRICS FOR COMPARABILITY IS IMPORTANT

In order to ensure that water use metrics obtained for a single utility at different time periods or from different utilities are comparable, it would be necessary to "normalize" the calculated value of any given metric by adjusting for differences in climate and weather conditions and other characteristics. However, normalization of these metrics for interutility comparison is difficult because of differences in reference socioeconomic characteristics and is not possible in the case of climatic differences. All aggregate and sector-specific annual and seasonal metrics presented previously can be used only for comparing water production and use over time within a single utility.

Normalization for weather and trends. When comparing metrics for a single utility over time it should be sufficient to adjust the calculated metrics for weather conditions. Year-to-year changes in the number of users are accounted for by the scaling variable, whereas any small changes in other determinants of water use can be neglected over relatively short time intervals.

The weather adjustment can be performed directly on the calculated value of any metric with the use of parameters (in the form of constant elasticities) that capture the sensitivity of water use to weather. The two key variables that are often used in modeling the effects of weather on urban water demand are precipitation and maximum daily air temperature. For example, the weather-normalized value of the

TABLE 7 Advantages and disadvantages of metrics of nonseasonal and seasonal sector-specific water use

		Advantages (↑) and Disadvantages (↓)	
Metric	**Definition**	**Numerator: Water Quantity**	**Denominator: Scaling Variable**
IUM_a^{SF}	Indoor (nonseasonal) single-family use metric per account	↑ Indoor use is considered relatively homogenous. ↓ This metric can include residual outdoor uses in areas with year-round irrigation and other outdoor uses.	↑ Number of billed single-family customers is known precisely for each billing period.
IUM_c^{SF}	Indoor (nonseasonal) single-family use metric per capita	↑ This metric scales indoor use for average number of people residing in households.	↓ Estimates of persons per household may contain errors.
OUM_a^{SF}	Outdoor (seasonal) single-family use metric per account	↑ This metric isolates weather-sensitive uses only.	↓ Classification of irrigation meters can confound estimates.
IUM_a^{MF}	Indoor (nonseasonal) multifamily use metric per account	↑ Indoor use is considered relatively homogenous. ↓ This metric can include residual outdoor uses in areas with year-round irrigation and other outdoor uses.	↓ Number of billed multifamily customers does not represent the number of occupied housing units.
IUM_c^{MF}	Indoor (nonseasonal) multifamily use metric per capita	↑ This metric scales indoor use for average number of people residing in households.	↓ Estimates of persons per household may contain errors.
OUM_a^{MF}	Outdoor (seasonal) multifamily use metric per account	↑ This metric isolates only weather-sensitive uses.	↓ Classification of irrigation meters or multiple meters can confound estimates.
IUM_a^{NR}	Indoor (nonseasonal) nonresidential use metric per account	↑ Indoor use is perhaps less variable than sectorwide use. ↓ This can include residual outdoor uses in areas with year-round irrigation and other outdoor uses.	↑ Number of nonresidential accounts is available and more accurate than employment and other counting variables.
OUM_a^{NR}	Outdoor (seasonal) nonresidential use metric per account	↑ This is a convenient measure of weather-sensitive uses such as irrigation and cooling.	↓ Classification of irrigation meters or multiple meters can confound estimates.

metric of average annual use in the single-family sector can be calculated as

$$AUM_{atn}^{SF} = AUM_{at}^{SF} \times \left(\frac{T_n}{T_t}\right)^{\alpha} \times \left(\frac{R_n}{R_t}\right)^{\beta} \quad (1)$$

in which AUM_{atn}^{SF} = weather-normalized single-family annual use metric in gpd per account in year t, AUM_{at}^{SF} = calculated value of the metric in gal/account in year t, T_t = average maximum daily air temperature during the growing season of year t, T_n = normal value of average maximum daily air temperature during the growing season, R_t = total rainfall during growing season in year t, R_n = normal value of total rainfall during growing season, α, β = constant elasticities of temperature and precipitation, respectively, and *atn* = per account use *a* and normal year weather *tn*.

This method can be illustrated using the annual single-family use metric for Phoenix. Recently estimated econometric models of water demand indicated that the responsiveness of single-family demand is +1.065 with respect to the average of maximum daily air temperatures and –0.088 with respect to total precipitation (Kiefer, 2009). The adjustments according to Eq 1 were performed on the AUM_a^{SF} metric (from Table 6) using the two elasticity values and the normal and actual weather parameters for 2008 in the Phoenix area:

$$AUM_{atn}^{SF} = 373 \times \left(\frac{84.5}{86.9}\right)^{+1.065} \times \left(\frac{8.29}{9.58}\right)^{-0.088} = 367 \text{ gpd} \quad (2)$$

The year 2008 was warmer and wetter than normal in Phoenix. The estimated combined effect of these two weather conditions is an increase in water use of 6 gpd per account. There are several ways of statistically specifying the relationship of weather to water use, and different model specifications would modify the exact equation and associated parameters that would be used for weather normalization.

Normalizing water use for changes in socioeconomic conditions in a single utility is also possible using essentially the same normalizing techniques as for weather. All metrics can be normalized for socioeconomic conditions. The elasticities that are used in calculating the adjustments should accurately reflect the responsiveness of water use to changes in the values of determinants of water use. The elasticity values will vary by user sector. Ideally, the elasticities of the determinants should be obtained from water demand studies for the utility during the time period for which the comparisons are to be made. However, if such studies are not available, then it is possible to derive "generalized" values of elasticities based on the available published studies of water demand.

Normalization for cross-utility comparisons. Metrics for comparing efficiency of water use across different utilities would have to ensure that all external factors that influence the quantity of water used but that are outside the control of water users are "corrected for." This means that additional data collection and analysis would be required in order to differentiate between the effects of water efficiency improvements and other factors that can affect average rates of water use.

For example, even when comparing a relatively homogeneous sector of single-family residences, because of local conditions, one community could have smaller single-family parcels and fewer swimming pools than

TABLE 8 Calculated metrics of seasonal and nonseasonal use for participating utilities—*2008 data*

Water Utility	Single-family Sector		Multifamily Sector		Nonresidential Sector	
	IUM_a^{SF}	OUM_a^{SF}	IUM_a^{MF}	OUM_a^{MF}	IUM_a^{NR}	OUM_a^{NR}
Otay (Calif.) Water District	271	156	3,041	567	2,057	1,112
Irvine (Calif.) Ranch Water District	244	78	1,853	141	1,698	683
Phoenix (Ariz.) Water Services Department	248	125	3,184	471	962	457
City of Rio Rancho, N.M.	149	68	563	117	1,691	1,086
Seattle (Wash.) Public Utilities	120	22	822	69	1,139	180
Philadelphia (Pa.) Water Department	163	26	NA	NA	NA	NA
Tampa (Fla.) Water Department	217	39	6,849	493	1,260	136
Variability—%*	29	69	84	72	28	70

IUM_a^{MF}—indoor (nonseasonal) multifamily use metric per account, IUM_c^{MF}—indoor (nonseasonal) multifamily use metric per capita, IUM_a^{NR}—indoor (nonseasonal) nonresidential use metric per account, IUM_a^{SF}—indoor (nonseasonal) single-family use metric per account, IUM_c^{SF}—indoor (nonseasonal) single-family use metric per capita, NA—data not available, OUM_a^{MF}—outdoor (seasonal) multifamily use metric per account, OUM_a^{NR}—outdoor (seasonal) nonresidential use metric per account, OUM_a^{SF}—outdoor (seasonal) single-family use metric per account

*Variability is expressed as coefficient of variation (standard deviation divided by the mean).

another community. Per capita residential use in a more densely developed area would likely be lower than in an area with a lower density of single-family housing. In addition, a more dense urban community could have a greater opportunity to increase indoor water efficiency through the replacement of plumbing fixtures, whereas less-dense suburban communities might have a greater opportunity to increase the efficiency of landscape watering practices.

Because it is possible these situations could be independent of water use efficiency levels, the unadjusted use rates cannot be used to infer water efficiency levels. Without additional information, simple comparisons of average water use rates cannot reveal underlying technological or behavioral practices regarding water efficiency or differentiate among the several market and nonmarket forces that shape residential demand.

Normalization for weather and other confounding factors across different utilities is problematic. Because of fundamental differences in normal weather within particular climatic zones and the relative presence of particular water end uses even within the same climatic zone, there is no easily accessible way to use such normalization procedures for interutility comparisons. Thus the best approach is to derive a benchmark value of a metric for each utility and divide the weather-normalized value of the metric by a theoretical (derived) value of the benchmark (representing an efficient level of water use).

A practical approach to developing metrics for comparing water use efficiency between utilities would be to use metered account-level information for homogeneous groups of customers and the same dimensions of water use (i.e., total annual, seasonal, nonseasonal), then convert the values of the calculated metrics into ratio benchmarks for each utility before making a comparison.

WATER CONSERVATION BENCHMARKS

A concept similar to the ILI can be applied to the indoor and outdoor use of water in different sectors. A ratio benchmark similar to ILI can be defined for each utility by developing an estimate of an efficient level of water use to be achieved. Table 9 describes four conservation metrics that can serve as efficiency benchmarks for indoor and outdoor water use.

All four conservation indexes listed in Table 9 are ratio benchmarks that can be used for interutility comparisons with a 1.0 target (or goal) value. The efficient-use goals can be tailored to reflect the composition of end uses and weather characteristics of any given service area.

Indoor conservation index explained. The indoor conservation index for single-family residential sector in a given utility can be defined as

$$ICI_a^{SF} = \frac{IUM_a^{SF}}{IUM_{aG}^{SF}} \quad (3)$$

in which ICI_a^{SF} = indoor conservation index for single-family sector as a ratio-type benchmark, IUM_a^{SF} = estimated residential single-family indoor use per account per day, and ICI_a^{SF} IUM_{aG}^{SF} = efficiency goal (G) for residential single-family indoor use per account per day.

The value of IUR_{aG}^{SF} can be obtained by disaggregating indoor water demand into its specific components or end uses and estimating an efficient quantity of water for each end use. A rational representation of the average quantity of water in each end-use can be made using a structural end-use equation of the following form (Dziegielewski, 1996):

$$EU^i{}_G = [(\sum_j M_j S_j) \times U + K \times F] \times A \quad (4)$$

in which $EU^i{}_G$ = quantity of water in end use i representing an efficiency goal G, Mj = efficiency classes of the end use (set of mechanical or design parameters), Sj = fraction of end uses within efficiency classes j = 1, 2 . . . k, U =

TABLE 9 Water conservation benchmarks for indoor and outdoor residential water use

Metric	Definition	Advantages (↑) and Disadvantages (↓): Numerator: Water Quantity	Advantages (↑) and Disadvantages (↓): Denominator: Scaling Variable
ICI^{SF}	Indoor single-family conservation index	↑ Indoor use consists of nearly identical end uses across residential customers.	↑ This metric can be appropriately defined for each utility.
ICI^{MF}	Indoor multifamily conservation index	↓ Indoor use measure may include outdoor uses using minimum-month methods.	↓ This metric requires a baseline study on existing end uses.
OCI^{SF}	Outdoor single-family conservation index	↓ Outdoor use is rarely metered and has to be estimated.	↓ Outdoor benchmark values require multiple assumptions to reflect service-area characteristics.
OCI^{MF}	Outdoor multifamily conservation index		

usage rate per event (or intensity of use) in end use i, K = average flow rate of leaks, F = fraction of end uses with leaks (incidence of leaks), and A = proportion of users with end use i in a given sector of users.

An application of Eq 4 would require the knowledge of all end-use parameters for all indoor end uses. An example application for toilet end use is shown in Table 10.

The efficiency classes for toilets are defined using the typical values for the design parameter M_i of 5.0, 3.5, 1.6, and 1.28 gpf. For the purposes of illustration, the corresponding fractions of end uses within each class under current conditions are assumed to be 0.20, 0.50, 0.30, and 0.0. With a typical value of 5 flushes per person per day and an average household size of 2.8 persons, the usage rate for the toilets would be 14 fpd per single-family home. An average leakage rate of 20 gpd can be assumed, with the incidence of leaks of 0.15 to represent unavoidable toilet leaks. The presence parameter for toilets is 1.0. Using Eq 4, the average quantity of the current end use of water for toilet flushing would be 48.2 gpd per account.

An efficiency goal for toilet flushing in this example is defined by assuming that all nonconserving and standard toilets are replaced with the 1.28 gpf model that is recommended by WaterSense (i.e., S4 = 1.0). Then, at the same intensity of use (i.e., same number of flushes per day) and the same rate and intensity of leaks, the toilet end use that represents an efficiency goal would be 20.9 gpd per single-family account. Other end uses and their efficiency goals can be estimated using similar parameters and assumptions. Once all significant indoor end uses are estimated, the total value of the indoor efficiency goal can be calculated as

$$IUM_{aG} = \sum_{1}^{n} EU^{i}_{aG} \qquad (5)$$

in which EU^{i}_{aG} is the efficiency goal for end use i, and $i = 1 \ldots n$.

Table 11 shows the calculation of efficiency goals for indoor use based on the results of the AWWA residential end use study of a sample of single-family homes (DeOreo et al, 1999). The table compares the average rates of use at the time of the study and the estimated use with the most efficient fixtures and appliances existing at that time. The actual average indoor use in the AWWA study was 69.3 gpd per person. The efficiency goal of 43.5 gpd per person represents a condition requiring the installation of water efficient fixtures and appliances and requires no change in water use behavior.

Using the average and the goal values of indoor use in Table 11, the calculated value of the indoor conservation index (ICI) metric for single-family indoor use based on average values in the AWWA end-use study would be calculated as

$$ICI_a^{SF} = \frac{IUM_c^{SF}}{IUM_{cG}^{SF}} = \frac{69.3}{43.5} = 1.59 \quad (6)$$

Each water utility would likely develop its own efficiency goal by selecting realistic assumptions about achieving the adoption of the efficient fixtures and appliances. Also, the intensity (U) and relative presence (A) of end uses may vary among different utilities. The numerator value in Eq 6 can be estimated using the minimum-month method or by another method, such as data logging and analysis similar to the AWWA residential end-use study.

Outdoor conservation index explained. A sectorwide efficiency benchmark for outdoor use can be calculated by first determining total irrigated area in the sector and then assuming an agronometrically-based theoretical value of irrigation demand. An example of the theoretical formula for efficient irrigation use is given by Bennett and Hazinski (1993). The authors calculated the theoretical irrigation water requirement based on reference evapotranspiration, crop coefficient, microclimate factor, canopy density, assumed irrigation efficiency fraction (typically 0.80), irrigated area, and the assumption landscaping plants perform well when only 80% of reference evapotranspiration (ET_0) is supplied.

More recently, USEPA developed a method for WaterSense Water Budget Approach (USEPA, 2009). USEPA subsequently released a revised draft of the tool in a spreadsheet format that

TABLE 10 Example calculations of water use for toilet flushing

Parameter	Parameter Description	Current	Goal
M_1	Inefficient class 1 rate—*gpf*	5.00	5.00
S_1	Inefficient class 1 fraction	0.20	0.00
M_2	Standard class 2 rate—*gpf*	3.50	3.50
S_2	Standard class 2 fraction	0.50	0.00
M_3	Efficient class 3 rate—*gpf*	1.60	1.60
S_3	Efficient class 3 fraction	0.30	0.00
M_4	Efficient class 4 rate—*gpf*	1.28	1.28
S_4	Efficient class 4 fraction	0.00	1.00
U	Intensity of use—*fpd*	14.00	14.00
K	Leakage rate—*gpf*	20.00	20.00
F	Incidence of leaks	0.15	0.15
A	Presence of end use	1.00	1.00
EU	End use quantity—*gpd*	48.2	20.9

facilitates the water budget calculation for urban landscapes. This calculation can determine how much water the designed landscape requires based on climate, plant type, and irrigation system design.

According to USEPA, the landscape water requirement (LWR) can be calculated for each hydrozone, and the sum of these values is the LWR for the site. The LWR is based on ET_0, the landscape coefficient (K_L), the area of the hydrozone, the lower quarter distribution uniformity (DULQ) of the associated system, and a portion of local rainfall designated as allowable rainfall (R_a):

$$LWR_H = RTM \times [ET_0 \times K_L) - R_a] \times A \times C_u \quad (7)$$

in which LWR_H = landscape water requirement for the hydrozone (gallon/month); RTM = run time multiplier, equal to 1/lower quarter distribution uniformity (dimensionless; this factor is used to increase zone run time to account for lack of distribution uniformity within the root zone); ET_0 = local reference evapotranspiration (inches/month) that represents the rate of evapotranspiration from an extensive surface of cool-season grass cover of uniform height of 12 cm (4.7 inches), actively growing, completely shading the ground, and not short of water; K_L = landscape coefficient for the highest water-using plant in that hydrozone (dimensionless; this coefficient is used to modify reference ET, which includes species factor K_s, density factor K_d, and microclimate factor K_{mc} in which $K_L = K_s \times K_d \times K_{mc}$; for the purpose of this tool WaterSense is assuming K_d and K_{mc} are both ÷1 to reduce the complexity of the calculations); R_a = allowable rainfall, designated by WaterSense as 25% of the site's peak monthly rainfall; A = area of the hydrozone (in square feet) that represents the grouping of plants with similar water and environmental requirements for irrigation with one of more common station/zone valves; and C_u = conversion factor (0.6233 for results in gal/month).

A water utility could use Eq 6 to determine landscape water requirements for hydrozones and then entire parcels for residential and nonresidential customers to determine average water requirement per customer in a given service area. The outdoor conservation index (OCI) for the single-family sector can then be calculated as

$$OCI_a^{SF} = \frac{OUM_a^{SF} \times (365/153}{LWR_{gs}^{SF}/153} \quad (8)$$

in which OCI_a^{SF} = outdoor conservation index for single-family sector as a ratio-type benchmark, OUM_a^{SF} = weather-normalized residential single-family outdoor use per account per day, LWR_{gs}^{SF} = efficiency goal (G) for residential single-family outdoor use per account per day represented by average irrigation water requirement during the growing season (gs), and 153 = number of calendar days during the May–September growing season.

Similar calculations can be performed for landscapes in multifamily and nonresidential sectors. Unfortunately, the detailed data and assumptions required to provide an example could not be derived for this study.

SUMMARY

This examination of the potential for developing water use and conservation metrics for public water supply utilities reveals several limitations as well as some practical and emerging possibilities for constructing metrics to monitor progress in achieving more efficient water use. The analysis of different metrics and their comparisons for the seven case study utilities result in several relevant findings regarding these metrics. The following is a summary of key findings.

- Available water production and sales records can be used to calculate both systemwide and sector-specific metrics of water use. However, the only accurate and regularly updated measure of system size is the number of connections or customer accounts. Other measures of system size such as population served, number of housing units, or the number of employees are not precisely defined and at best are updated on an annual basis. For this reason the commonly used metric representing annual production per capita is not a reliable measure of water use and as a result should not be used as a

TABLE 11 Examples of average and efficient levels of indoor residential end uses

Purpose of Use	Average Frequency of Use—*events/person/day*	Average Use ($M_i \times S_i$) *gallon/event*	Average Use (EU^i) *gpcd*	Efficiency Assumption ($M_3 \times 1.0$) *gallon/event*	Efficient-use Goal (EU^i_G) *gpcd*
Toilet flushing	5.05	3.7	18.5	1.28	6.5
Clothes washing	0.37	40.6	15.0	25.8	9.5
Showering	0.70	16.6	11.6	14.4	10.1
Bathing	0.05	23.8	1.2	18.6	0.9
Faucet use	17.60	0.6	10.9	0.5	9.3
Dishwashing	0.10	10.0	1.0	8.0	0.8
Leaks	0.46	20.7	9.5	20.7	4.8
Other domestic	NA	NA	1.6	NA	1.6
Total indoor use	NA	NA	69.3	NA	43.5

NA—data not available

benchmark.

• Useful sector-specific metrics can be defined and calculated precisely. However, water utilities may use different systems for classifying customer accounts. This makes it difficult to consolidate the existing customer types into user sectors such as residential, commercial, industrial, institutional, and others. Even if such sector groupings are made, their customer characteristics and composition may vary across different utilities.

• Both systemwide and sector-wide metrics can be used to track water use per account over time. However, the year-to-year changes in the values of each metric have to be carefully interpreted. These changes may have different causes; often changes that are related to weather conditions and composition of water users can mask changes that might be expected from water conservation efforts.

• No metrics of water use (measured in absolute terms) should be used for judging relative water use efficiencies across different utilities. Different utilities will likely display uniqueness in terms of the climate, the composition of demands in their respective service areas, and how they define their customer classes. From the standpoint of technical efficiency, only ratio metrics such as the ILI metric with a benchmark value of 1.0 can be used for interutility comparisons. However, derivation of any benchmark value should consider economic criteria to judge whether the benefits of investing in technical efficiency exceed the costs of doing so—i.e., whether the technical benchmark is also economically efficient.

• Ratio-type benchmarks can be formulated for different components of water use within sectors. These benchmarks can be compared across different utilities; however, the absolute benchmarks and metrics of use on which such ratios are based should be unique to each utility and would show the degree to which any given utility is approaching its own benchmark value. For example, the proposed ICI would be based on a technical efficiency goal of indoor use that would take into account specific conditions of each utility, including customer characteristics and the costs of expediting greater water use efficiency.

• A promising way for developing metrics, absolute benchmarks, and efficiency goals is to disaggregate sector demands into specific end uses. End-use-specific benchmark values can be formulated on the basis of technological standards and assumptions regarding the intensity or frequency of use. Measurement of water use at the end-use level would naturally improve the indoor and outdoor metrics discussed in this article. Unfortunately, highly disaggregated end-use data are not available or routinely collected for most water utilities.

The results of this study lend support to two major recommendations: one pertains to the data and water use records and another to the development of supportive information for the conservation benchmarks.

First, significant improvements in the ability of water utilities to reduce "definitional noise" in monitoring and comparing rates of water use would be achieved if the water supply industry adopted a standard set of customer types and customer classification procedures. This ability would be enhanced further if water utilities collected and maintained additional characteristics for each customer. These would depend on customer type and could include such measurements as irrigated area, number of dwelling units, number of employees and visitors, and the presence of specific end uses such as swimming pools or evaporative coolers.

Second, the suggested

Notations

Acronyms for metrics:

PQ = water production quotient

SQ = water sales quotient

UM = usage metric

CI = conservation index

Dimensions of water use (added in front of the acronyms for metrics):

A = annual average water production, sales, or usage

I = indoor (nonseasonal) water use

O = outdoor (seasonal) water use

Sectors of water users (added as a superscript after the acronyms for metrics):

SF = single-family sector

MF = multifamily sector

NR = nonresidential sector

Scaling variables (added as a subscript after the acronyms for metrics):

c = per capita based on population served or number of residents

a = per account based on the number of billed accounts

G = goal or benchmark value

conservation indexes for indoor and outdoor use (i.e., ratio benchmarks ICI and OCI) should be further investigated through a pilot study in a sampling of water utilities. The indoor component of the study could include end-use measurement similar to the 1999 end-use study conducted by AWWA for both single-family and multifamily sectors, in particular to improve upon the limitations of the minimum-month method for estimating indoor use, as well as to establish baseline conditions and conservation benchmarks. The outdoor component of the study could include measurement of irrigated areas and watering requirements through advanced remote-sensing techniques and onsite measurements of actual water use for irrigation and outdoor purposes in a sample of residential and nonresidential parcels.

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