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RESEARCH ARTICLE

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Key Points:

- Total municipal water use in the contiguous U.S. has declined at median annual rate of 9.8 liters per capita per day from 2005 to 2017
- Water use reductions are highest among cities characterized by large population, arid climate and West Census region of the contiguous U.S.
- Five climatic, economic and urban-geologic variables explain the commercial, industrial and institutional to residential water use ratio

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

C. V. Chinnasamy,
ccibiv@colostate.edu

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Characterization of Municipal Water Uses in the Contiguous United States

Cibi Vishnu Chinnasamy¹ , Mazdak Arabi¹, Sybil Sharvelle¹, Travis Warziniack², Canon D. Furth¹, and Andre Dozier¹ 

¹Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO, USA, ²Rocky Mountain Research Station, U.S. Forest Service, Fort Collins, CO, USA

Abstract This study investigates municipal water use patterns across the Contiguous United States (CONUS). The objectives of this study are to explore temporal trends in water use, improve characterization of indoor and outdoor uses, and improve characterization of commercial, industrial, and institutional (CII) water use in cities across the CONUS. A comprehensive survey was conducted to compile monthly water use data from 126 municipalities for the period 2005–2017 with specific information about residential and CII water use categories. Changes in liters per capita per day and the CII to Residential water use ratio were related to climatic, urban-geologic and socio-economic variables. Results indicate an overall decreasing trend in municipal water uses with higher reductions achieved in residential sector. Both residential and CII water use exhibit high seasonality over an average year. The CII to Residential ratio increases with city population and is highest in cities in the Northeast Census region. Cities in South and West Census regions have high municipal water uses and highest reductions in annual per capita-day water use. Cities in arid climate regions have the highest water uses, compared to other cities, due to landscape irrigation. April precipitation, annual vapor pressure deficit, number of employees in the manufacturing (or, other services except public administration) sector, total percentage of houses built before 1950 and total percentage of single-family houses explain much of the variation in CII to Residential water use ratio across the CONUS. This study guides improved characterization of municipal water uses and water demand management strategies.

1. Introduction

Water use in cities is influenced by several physiographic, social, ecological, and other factors. Rapid urbanization along with changes in population and climatic conditions alter water use patterns in cities (Glaeser et al., 2001; Gordon & Richardson, 1997; Grimm et al., 2008; Mills, 2007; Rees & Wackernaegel, 1996; Stone, 1972; Wirth, 1938). More than 82% of North America's population resides in urban areas (United Nations, 2019), with that percentage projected to increase over the coming decades. Growing water uses within cities and diminishing water supplies intensify the competition for water amongst cities, irrigated agriculture, industries, energy production, ecological flows, and recreational uses (Gleick, 2010; Gober & Kirkwood, 2010; Pimentel et al., 1997). The vulnerability of water supply systems to shortage is exacerbated by changing climate (Christensen et al., 2004; Folger, 2017; Gober & Kirkwood, 2010; Yigzaw & Hossain, 2016). Quantifying the end-water uses in the municipal sector is increasingly important for urban planners and policymakers to develop robust and resilient planning and water supply management strategies.

Climate change contributes to the uncertainty in predicting rainfall and snowfall patterns, thereby presenting a water supply planning challenge for the sustainable growth of communities (Pimentel et al., 1997). Climate variability and change necessitate that cities adapt and change the way urban water resources are managed (Breyer et al., 2018; Gleick, 2010; Sharvelle et al., 2017), to address both excess water during intense precipitation events and intense drought years. Climatic forces, therefore, shape the way humans use water to grow food, produce energy, and build societies. This constant feedback cycle between humans and the natural forces is gaining recognition in the form of the “hydro-social cycle” (Linton & Budds, 2014). Thus, climatic factors interact with other forces that drive water use in cities (Turrall et al., 2011). Another well documented aspect of variability in residential water use is the age of the building or the year the building structure was built. DeOreo et al. (2016) and Mayer et al. (1999) have shown that the year in which the

structure was built is highly correlated with the plumbing codes which determine the water use efficiency of the building.

Municipal water supply systems provide water to residential users, both single family houses and multi-complex housing structures, and to commercial, industrial, and institutional (CII) users. In some regions, these systems also trade wholesale water to large energy and manufacturing industries or to neighboring urban centers (Dieter & Maupin, 2017), and are audited as “master meter” use or supply. Traditionally, cities have addressed growing water supply needs and long-term water security by developing new water sources. In the mid-twentieth century, large water supply infrastructure systems, like diversion of rivers, construction of dams and reservoirs, and long-distance piping of water, were developed to support human settlements and rapid urban growth across the U.S. However, by the end of that century diminishing freshwater resources due to climate change, widening socio-economic divide along the rural-urban interface, funding shortfalls, and environmental regulations have constrained the capacity of urban centers to build new water supply infrastructure (Magionni, 2014; Niemczynowicz, 1999; Yigzaw & Hossain, 2016). These factors have led to alternative modes of securing raw water through mechanisms such as inter-basin water transfers, water reclamation and water reuse programs. In the U.S., transfer of water from agriculture to urban users and other inter-basin water transactions are made within the existing physical infrastructure and water laws (Breyer et al., 2018; Merrett et al., 2003; Paterson et al., 2015). These trades often involve high legal and infrastructural transaction costs (Dozier et al., 2017; Paterson et al., 2015).

Water demand management strategies are increasingly relied upon to address water supply demand challenges in cities (Gleick, 2010; Odai, 2009; Yigzaw & Hossain, 2016). Municipal water suppliers have already embarked upon planning and implementation of water conservation programs and use of alternate water sources (Hering et al., 2013; Ma et al., 2015; Paterson et al., 2015; Sharvelle et al., 2017). Water conservation programs aimed at the reduction of end-water uses through a combination of voluntary/mandatory restrictions on outdoor water use, tiered water pricing, and improved efficiency in plumbing codes using low flow water fixtures have led to improved water security in cities (Gleick, 2010; Grisham & Fleming, 1989; Kennedy et al., 2012; Maidment & Miaou, 1986; Olmstead & Stavins, 2009; Saurí, 2013). Alternate local water resources, like graywater/blackwater recycling, rainwater/stormwater harvesting, desalination, and aquifer storage and recovery systems, are being recognized as effective solutions to minimizing the dependency on the extraction of limited freshwater resources (Chinnasamy et al., 2018; Gleick, 2010; Sharvelle et al., 2017). For water conservation programs and/or alternate water source systems to be effective, it is imperative that an improved understanding of indoor and outdoor municipal water use patterns across various city clusters is achieved (Maas et al., 2017).

Residential water use for various indoor activities, including clothes and dish washing, bathing, toilet flushing, kitchen and bathroom faucet use, pipe leakage, and other uses for cleaning and sanitation, have been extensively studied using water meters and smart sensors (DeOreo et al., 1996; Paterson et al., 2015; Yang et al., 2017). The residential end-water use study (REU2016) compiled by DeOreo et al. (2016) concludes that on average, indoor residential water use per capita has decreased by 15.4% in North America, compared to the REU1999 study (Mayer et al., 1999). Rockaway et al. (2011) also found declining residential water use in North America due to decreasing household size and improved efficiency in water appliance standards. Although significant strides have been made to understand indoor water conservation programs, water use in the CII sector is poorly characterized due to data paucity (Dziegielewski et al., 2000; Rockaway et al., 2011). Similarly, few studies have investigated outdoor water use patterns across ecohydrologic regions. Understanding patterns of outdoor water use for landscape irrigation and CII water use is vital for improving cost, reliability, and resiliency of municipal water supply systems (Goldstein et al., 2013).

Municipal water use characteristics may be explained by a range of demographic, ecologic, and economic factors. Among these factors, climatic factors have been well-studied by Stoker and Rothfeder (2014), who developed computer models to show that urban water use, primarily outdoor use, is influenced by seasonal changes in the climate, and showed that urban land use pattern also influences the total volume of water used. In recent literature, climatic variables are extensively being used in modeling residential, primarily outdoor, water use (Maas et al., 2017; Mostafavi et al., 2018; Puri & Maas, 2020). In cities with similar population size characteristics, water uses tend to vary considerably (Ahams et al., 2017). Weather influences across multiple cities and specifically in outdoor water use has been documented by Mini et al. (2014),

Gober et al. (2016), and Opalinski et al. (2019). Various factors influence the residential water demand and water demands for economic growth within a city, and these factors have been well studied and documented separately for individual water use categories predominantly for the western part of CONUS (Decker et al., 2000; Folger, 2017; Folke, 2003; Kennedy et al., 2012; Magionni, 2014; Mini et al., 2014; Stoker & Rothfeder, 2014; Wang et al., 2018).

However, an approach to holistically understand municipal water use by analyzing residential and CII water use together across multiple cities for the entire CONUS is non-existent in the literature. CII water use is not well understood (DeOreo et al., 2016), increasing the complexity of characterizing urban water use. Understanding municipal water use under the lens of CII to residential water use (CII/Res) ratio is a new approach suggested in this study, and it is speculated to be influenced by the general characteristics of a city such as climate, socio-economy and urban geography—a pattern of urban development driven by population changes that influences land use and management (McGill, 1964). Currently, these relationships are poorly understood and characterized. Thus, understanding and quantifying the factors that influence residential and CII water uses, within a city or a region, has the potential for use in urban water demand projection models and can facilitate sustainable and resilient water resource management (Puri & Maas, 2020).

This study addresses a critical knowledge gap in characterization of municipal water use patterns across the CONUS using multi-city data. Specifically, the objectives of this study are to: (a) conduct an extensive survey of water use in cities with varying demographic, economic, and ecohydrological characteristics; (b) explore spatial and temporal trends in end-water uses along with improved characterization of outdoor and CII water uses; and (c) explain the variation in CII to residential water use across CONUS using climatic, socio-economic and urban-geographic factors.

2. Materials and Methods

The methods applied in this study explore trends and patterns of residential and CII water use at monthly, seasonal, and annual timeframes. A survey of monthly municipal water uses from 126 cities for the period 2005–2017 was conducted in various ecohydrological regions across the CONUS. Municipal water use patterns are characterized under three clusters: (a) U.S. Census regions, (b) Koppen climate regions, and (c) population size clusters. Finally, a multivariate analysis is carried out to define water use patterns by climatic, urban-geologic and socio-economic factors.

2.1. Survey of Municipal Water Use Across CONUS

A sample of 250 Census designated cities and towns, distributed across the CONUS, were randomly identified based on climate, population and socio-economic patterns. The primary municipal water supplier in each of those cities was contacted to collect monthly municipal water use data for the period 2005–2017. A standardized spreadsheet form (Figure S1) was designed to record monthly information, from the cities and municipalities, about total water supplied under the four categories—residential, CII, master meter, and total, along with the information on annual population served. The survey also included geographic information associated with the water utility's service area. The data collection process involved email correspondences and open data access. Approximately 5% of the municipal water supply data was obtained through open data access websites maintained by the state or municipality. The state of California has made available all its municipal water and sewerage data through open data access portals (California State Water Resources Control Board, 2019). For the remaining cities, data was collected via email correspondence with the city's water supply utility.

Often, due to the sensitivity and proprietary status of the municipal water use data, municipal water supply companies have the authority to legally reject any type of request related to the water use characteristics of their clients. The response rate of the survey was 126 out of 250 utilities. More than half of the municipalities that provided water use data did not provide either a service area map or specify the served population. For these municipalities, the U.S. Census Incorporated Area boundaries and population were used. Out of the 126 participating utilities, 103 respondents provided both monthly residential and CII water supply data. The compiled municipal water use data set encompasses cities from a range of climate regions, population size, and socio-economic clusters that are spatially distributed across the CONUS. Thus, this data set

Table 1
Groups of 81 Exploratory Factors Used in This Study

Category	Groups of variables
Climate	Monthly max temperate, monthly max vapor pressure deficit, monthly average precipitation
Urban-geologic	Latitude, longitude, service area coverage, NLCD developed land cover area (open, low, medium, high, percent imperviousness), percentage of housing units built in different time periods, percentage of single-family houses and multi-density housing complexes, median rooms in a housing structure
Socio-economic	Population, population density, number of employees and number of establishments in different economic sectors, average family income, gross domestic product per capita

contains representative information to adequately characterize the variability, trends, and patterns of U.S. municipal water use. The supporting information (SI) provides tables—Tables S1 and S2, with a summary of the cities that responded to this survey and the corresponding water provider in those cities.

It should be noted that the definition of CII water use categories have constantly changed over the past 60 years (Donnelly & Cooley, 2015; Dziegielewska et al., 2000). This ambiguity is also reflected in classifications of CII sectors in the United States Geological Survey's (USGS) bi-decadal, estimated water use reports over the years. Dziegielewska et al. (2000) also state that defining CII water use is complex because of the heterogeneous nature of customers with highly varying non-domestic water uses. Typically, “commercial water use” refers to private facilities providing a service or distributing a product, such as, hotels, restaurants, golf courses, laundries, retail, or office buildings. “Industrial water users” include, metal and textile fabricators, technology related businesses, beverages industries, fruit, vegetable and meat processing and dairy processing. “Institutional water use” is classified as water supplied to public facilities such as schools, colleges, universities, courtrooms, hospitals, and government buildings. Studies often cluster commercial, industrial, and institutional water uses together into CII water use for the ease of analysis (Dziegielewska et al., 2000; Gleick et al., 2004), and the same approach has been followed in characterizing CII water uses in this study.

In most municipal water supply system audits, open space irrigation and water supply for city-owned parks are classified as total CII water use. There are also water suppliers like, Denver Water, who maintain separate accounts for such water use (Denver Water, 2019). In this study, water use for open space irrigation and city parks were summed into the CII water use category to prevent noise in characterizing residential water uses, and an assumption was made that well-maintained open spaces and city parks are an indication of the city's economic prosperity. Another point to note is, only 29 out of 126 cities provided master meter data. Due to this small number, master meter use was not considered for characterization purposes, and hence, Total water use in this study represents only the sum of residential and CII water use within a city.

2.2. City-Level Climatic, Urban-Geologic and Socio-Economic Data Collection, and Clustering of Study Cities

A total of 81 climatic, socio-economic, and urban-geologic variables were collected for this study at city-level (Table 1) for exploratory purposes. Climate variables, in terms of monthly 30-years precipitation, temperature and vapor pressure deficit normals covering the period 1981–2010, were extracted from the PRISM Climate data set (PRISM Climate Group, 2019). Land use/land cover information was obtained from the USGS National Land Cover Data set (Homer et al., 2015). Demographic and housing information for each city were obtained from the U.S. Census datasets (U.S. Census Bureau, 2019) and American Community Survey. Finally, detailed economic factors such as employment information were compiled from the U.S. Bureau of Economic Analysis.

Three clusters were used to understand and summarize municipal water use patterns across the 126 study cities in the CONUS:

1. U.S. Census regions: Midwest, Northeast, South and West.
2. Level-1 Koppen climate regions: Arid, Continental, Temperate, Tropical, and Highlands.

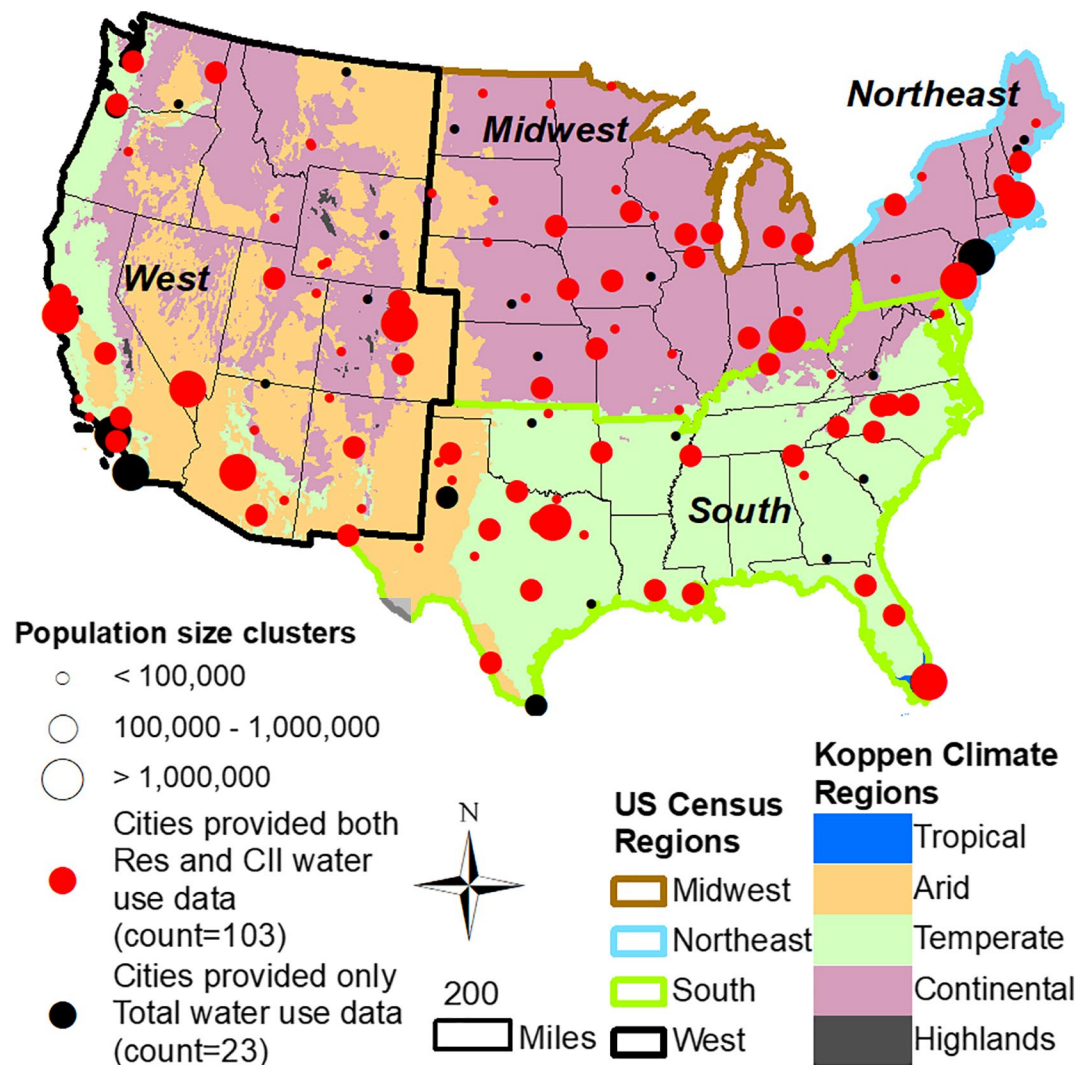


Figure 1. Map of the study cities clustered by U.S. Census regions and Koppen climate regions. Cities in this map are also differentiated by population size and the type of municipal end-water use data collected through survey.

- Population size clusters: Small (<100,000 people), Medium (100,000 to 1,000,000 people), and Large (>1,000,000 people).

The location of study cities—classified by population and type of municipal end-water use information, and spatially clustered by the U.S. Census regions and Koppen climate regions, is illustrated in Figure 1. With respect to clustering the study cities by Koppen climate regions, there are no cities present in the Highlands climate region, and only one county's (Miami-Dade) municipal water use data was collected for the Tropical climate region within the CONUS.

2.3. Characterizing Trends and Patterns in Historical Municipal Water Use

Three characteristics of municipal water use data are calculated: (a) temporal trends in liters of water use per capita per day; (b) the ratio of outdoor to total water use; and (c) the ratio of CII to residential water use. Data analysis and visualization were carried out primarily using the R software. Then, spatial overlays, visualization and mapping were carried out using ArcGIS software.

2.3.1. Municipal Water Use Trends—Aggregate Residential, CII, and Total Water Use

Monthly municipal water use data were annualized, and water use in terms of liters per capita per day (LPCD) was calculated annually for the residential, CII and total water use categories for the period 2005–2017. Residential LPCD estimate of a city is calculated by dividing the total annual water supplied to the residential sector by the total number of days in that year and the total population served by the city's water utility that year. Then using this annual LPCD time series data set, trends in municipal water use were computed using the unbiased and non-parametric trend analysis method—Mann-Kendall Sen's slope (Sen, 1968; Hipel & McLeod, 1994). Sen's slope computes the median linear rate of change of a time series data set. Finally, the LPCD and median annual LPCD rate of the cities were clustered by U.S. Census regions, Koppen climate regions and population size clusters, to obtain the characteristics of different sub-regions across the CONUS.

2.3.2. Municipal Water Use Trends—Outdoor to Total Water Use

The present study characterizes percent total outdoor water use from total water use in residential and CII sector, and represents the median annual rate of reduction in outdoor water use in LPCD across the study regions.

Water use data surveyed from the study cities were provided as aggregate monthly water use under residential, CII, and master meter categories. Typically, cities in regions with distinct winter seasons do not irrigate the outdoor green spaces when snow or near frost conditions prevail, that is, mid-November to March. Indoor municipal water use in these regions are often estimated by the average water use over the December to February period (Sharville et al., 2017). Other methods include billing-based methods, dual water meter methods, remote sensing methods, and flow trace methods (DeOreo et al., 2016; Gleick et al., 2003; Mini et al., 2014). Although these methods can prove very effective for a small-scale study area or for a single city, they become complex and expensive to deploy for large-scale and multi-city analysis.

To support national scale analysis of water use, an approach is needed to estimate the ratio of outdoor to total water use based on readily available water use data. The approach applied for this study to estimate outdoor water use utilized two methods, one for cities with distinct irrigation seasons and one for cities with outdoor water use where seasonal variation is not observed. For cities with distinct irrigation seasons, the quantiles of monthly total water use are computed to represent indoor water use. The validity of this approach was corroborated in each study city by comparing water use quantiles in each city with the reported monthly values over the winter months. In general, the analysis shows that ~12%–30% quantiles may be used based on the prevailing climatic conditions to separate indoor water use from total water use, under residential and CII categories, across the study cities.

A different approach was required for cities and towns in the South and West Census region, especially those in the states of Arizona, southern California, Florida, Louisiana and Texas. In these cities, separation of indoor and outdoor water use is confounded by year-round irrigation activities. For example, outdoor water uses in Miami-Dade County, Florida, remains nearly at the same level throughout the year—exhibiting lack of seasonality. In order to maintain data integrity while separating the indoor-outdoor water uses for these cities and towns, indoor LPCD results from Mayer et al. (1999), Rockaway et al. (2011), DeOreo et al. (2016), and Chang et al. (2017) were used to corroborate and adjust when warranted, the estimated outdoor water use as a fraction of the total municipal water use.

The approaches applied for estimation of indoor and outdoor demand are subject to some error that may result from regional seasonal trends in water use, for example, car washing, running water during cold months to prevent freezing, small garden irrigation, etc. However, the goal of this research is to identify trends in water use at the temporal resolution of seasonal and annual. Thus, small changes in daily water use patterns are resolved through the methodology applied that utilizes averaging.

2.3.3. CII to Residential Water Use Ratio

For the 103 cities that provided both residential and CII water use data, the CII/Res ratio was estimated for the period 2005–2017 on both monthly and annual time steps. From the annual CII/Res ratio timeseries data set, the relationship between residential and CII water use in a city was explored. The median rate of change in annual CII/Res ratio was estimated from the annual CII/Res ratio timeseries data set using the

Sen's slope method (Hipel & McLeod, 1994; Sen, 1968). Finally, the generalized CII/Res ratio and the rate of change of CII/Res ratio were used to characterize the trends in CII/Res ratio across the U.S. Census regions, Koppen climate regions and population size clusters within the CONUS.

2.4. Identification of Key Factors Governing the CII to Residential Water Use Ratio

A multivariate statistical analysis was used to develop a classification tree model to explain the CII/Res ratio in relation to the 81 climatic, socio-economic and urban-geologic parameters summarized in Table 1. First, a rigorous data multidimensionality reduction was carried out using random forest and principal component analyses to identify the most influential factors that explain the variability of CII/Res ratio in the study cities. Subsequently, these influential factors were used to build a classification tree model to classify the CII/Res ratio for cities across the CONUS.

In the random forest analysis, multiple decision trees (or, a forest, in the order of hundreds of trees) are built by selecting a random set of variables from a multidimensional data set that is provided as input. In the present study, a random forest analysis consisting of 1,000 random decision trees was built. A random forest error plot was used to reduce the size of the random forest from 1,000 trees to a smaller number of trees that result in minimum prediction error and maximum variance in explaining the CII/Res ratio. All the variables used in this reduced random forest are ranked in order of their node purity, which is a loss function of the mean square error.

Node purity value of each variable represents its dominance in the random forest. The higher the node purity value of a variable, the more significant that variable is in effectively predicting the CII/Res ratio (James et al., 2013). A threshold value, based on the node purity of the ranked variables, was then arbitrarily selected to obtain a smaller subset of variables. This threshold value is randomly selected to be a low node purity value with an aim to select maximum number of variables that have high variability and relevancy in building a classification tree model for the CII/Res ratio. If a higher node purity value is used, the smaller subset of variables selected might not capture the total variability in explaining the CII/Res ratio.

Although random forest analysis helps to minimize the total number of predictors to build a classification tree model, it does not effectively prevent the selection of variables with multi-collinearity. The reason being that the principle behind random forest analysis is randomness, and with a high-dimensional data set, the problem of inter-dependency or multi-collinearity of predictor variables is extreme (James et al., 2013). Collinearity or multi-collinearity causes redundancy, introduces complexity and impacts the efficacy of statistical analysis (Farrar & Glauber, 1967; Lafi & Kaneene, 1992). To effectively build a classification tree model of the CII/Res ratio for CONUS using unique variables that have high variance and non-collinearity, Principal Component Analysis (PCA) was applied to obtain influential variables that are not correlated (Jolliffe, 1986; Lafi & Kaneene, 1992).

The idea behind PCA is to reduce the dimensionality of a large data set with many interrelated variables, while retaining as much of the variation present in the data set as possible. This is achieved by transforming the original data set of variables into a correlation and covariance matrix consisting of principal components (PCs). Each PC is uncorrelated from the others, and consists of a set of variables that retain most of the variation present in the original variables (Hotelling, 1933; Jolliffe, 1986; Lafi & Kaneene, 1992). The PCs obtained are ranked by the total variance (or, eigen value) explained by each component. With the help of a scree plot and elbow method, a PCA biplot was then built by selecting the first few PCs that can explain at least 80% of total variance in the observed variable—CII/Res ratio. A scree plot is a line plot of the eigen values of the PCs in the analysis, and it is used to retain just a handful of PCs at the point where the eigen value of PCs reach an inverted plateau resembling an elbow (Cattell, 1966).

Based on the number of PCs selected from the PCA analysis using a scree-plot, at least two variables with high correlation are selected from each PC, or from a group of variables that are clustered around a unique axis (Husson et al., 2017; Jolliffe, 1986). A classification tree model for CII/Res ratio was developed by including only one variable from each PC and by splitting the data set into training and testing subsets. The classification tree model's adequacy was evaluated by the coefficient of determination (R^2), a non-parametric Mann-Whitney U test of the medians with a significance level of 95% and a goodness of fit tests by (a) visual comparison of cumulative frequency distributions, (b) Chi-Square test, and (c) Kolmogorov-Smirnov

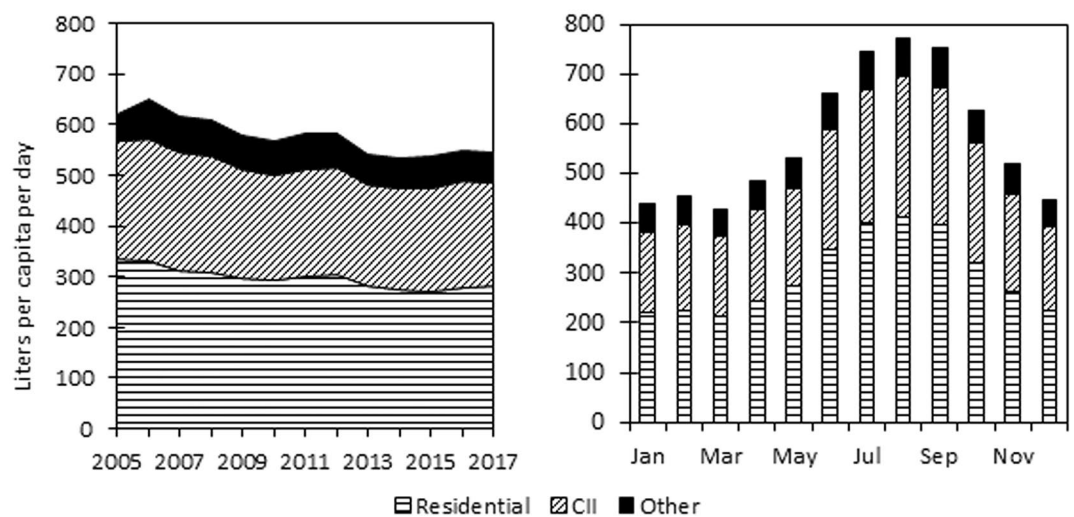


Figure 2. Average municipal water uses in the study cities over the 2005–2017 period: (Left panel) average annual water uses time series; (Right panel) average monthly water use.

test to present a robust and parsimonious classification tree model to explain the variation in CII/Res ratio across the CONUS.

A flowchart of all methodology described above has been illustrated in Figure S2.

3. Results and Discussion

The water use information compiled in this study provides one of the most comprehensive municipal water use datasets in the CONUS to date and is made available as an open access database to foster further studies on municipal water uses. The city-level monthly water use database obtained and processed in this study can improve the use of other data sets such as the U.S. Geological Survey Water Use Estimates for the Nation (Dieter et al., 2018), which is provided at county-level on a 5-years time interval and lacks the capability to explore temporal trends in municipal water supply systems as monthly or daily water use data is unavailable.

The study shows that total municipal water use in cities and towns across the CONUS has declined at a rate of ~ 9.8 liters per capita per day on an annual basis over the last two decades, with prominent water use reductions achieved in the residential use and is similar to the findings of DeOreo et al. (2016) and Dieter and Maupin (2017). Per capita water use reduction is highest in the large population size cities, Arid climate region and in the West Census region of the CONUS. Notable differences in total water use across the study regions is attributed to outdoor water use. April precipitation, annual vapor pressure deficit, employees in manufacturing sector, number of single-family houses, and number of buildings built before 1950 best explain the variation in CII to Residential water use ratio. The following sub sections will elaborate on these results.

3.1. Trends in Municipal Water Uses by Population, Climate, and Census Regions

There is an overall significant downward trend in the total water use amongst the study cities between 2005 and 2017 with a Mann-Kendall's tau of -0.44 and p -value < 0.05 . Figure 2 provides the average value of LPCD for different categories of municipal water use within the 126 study cities across the CONUS. Residential water use dominates municipal water uses in the CONUS. The average annual residential, CII, and total water uses are 299, 220, and 541 LPCD, respectively. The median annual rate of water use reduction, measured in liters per capita per day per year, is at 5.7 amongst residential water users, 4.5 amongst CII water users, and overall, at 9.8 for total municipal water use (Figure 2-Left panel). Total water use includes wholesale water trades to other utilities or large industries.

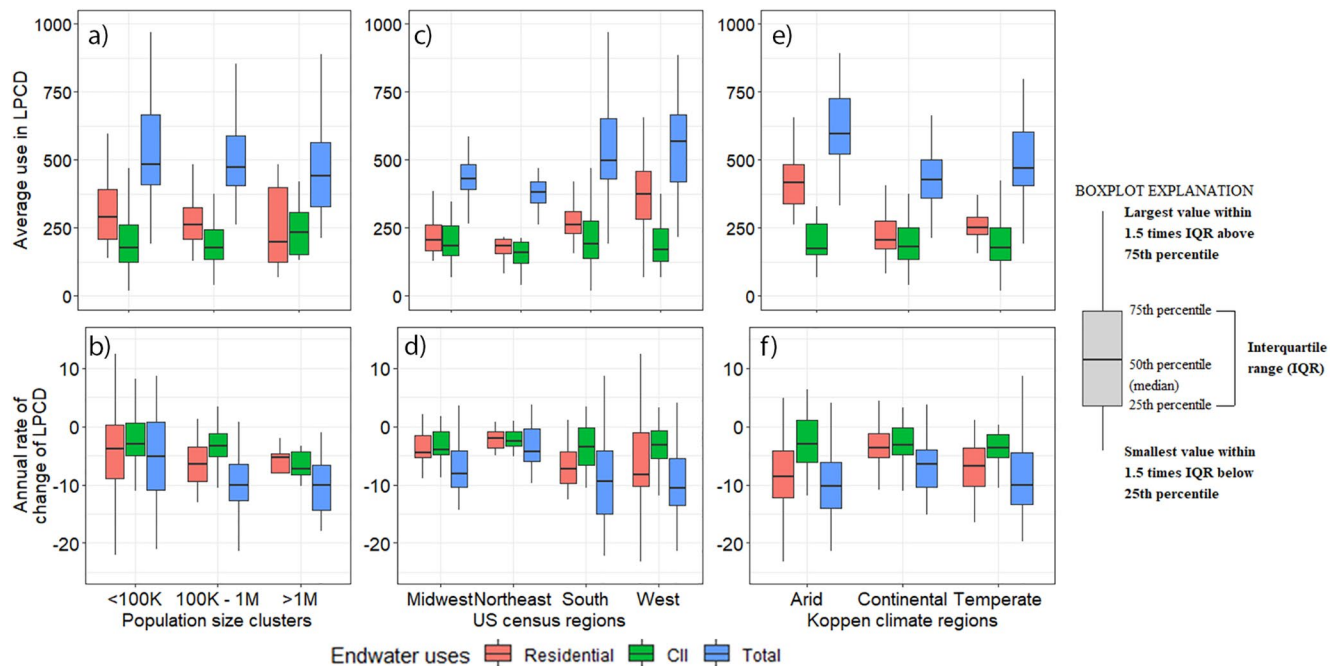


Figure 3. Characteristics of municipal water uses highlighting the per capita per day use and median annual water use reduction rate by study regions.

Strong seasonality is evident in municipal water uses across the CONUS (Figure 2-Right panel). Residential water use is notably higher between April and November, plausibly due to increased use for outdoor irrigation of lawns and green spaces. Note that, seasonality is also seen in the CII sector, since CII outdoor irrigation is cumulatively accounted with CII indoor use. Water use in December, January and February are higher than water use in March as some cities experiencing pipe freeze conditions in winter keep the faucets running and thereby, have an increased indoor water use compared to other months. Similarly, the CII/Res water use ratio shows seasonality averaging at 0.69 between April and October, while for rest of the year this ratio averages at 0.75. The “Other” water use category shown in Figure 2 is the master meter use which includes wholesale water transfers from a water utility to private companies, neighboring towns and/or other water utilities, and it does not show notable seasonality.

Significant differences are depicted in municipal water use patterns among the cities differentiated by population and across the U.S. Census and level-1 Koppen climate regions (Figure 3). As the city population increases, the average per capita-day water use decreases (Figure 3a). The lower total water use in cities with higher population is primarily associated with lower residential water use. However, large cities on average tend to have higher CII water use than small and medium size cities. Moreover, larger cities have achieved greater reduction in total water use over the analysis period (Figure 3b). The median annual rate of reduction in total water use increases with increasing city population. Thus, large cities with more than a million people tend to use less water compared to small size cities, while continuing to reduce their average per capita-day water use annually. These patterns can be attributed to the fact that large cities encompass higher population and housing density compared to small and medium sized cities. These results, in congruence with previous studies, underline that multi-density housing can effectively improve the water supply efficiency and reduce overall water use in cities (Gordon & Richardson, 1997; Wirth, 1938).

Contrasts in water use patterns are also evident among cities in different census regions (Figure 3c and 3d). The Northeast region has the lowest average residential and CII per capita-day water use, while the West region has the highest average residential per capita-day water use among all the other census regions, presumably due to outdoor irrigation. However, the median annual rate of total water use reduction (Figure 3d) in the Northeast census region is the lowest owing to the aging infrastructure (about 51% housing units were built before 1950) and old plumbing codes which do not incorporate water efficiency programs. The climate in the West census region is dominated by Arid and Temperate conditions (Figure 1), which

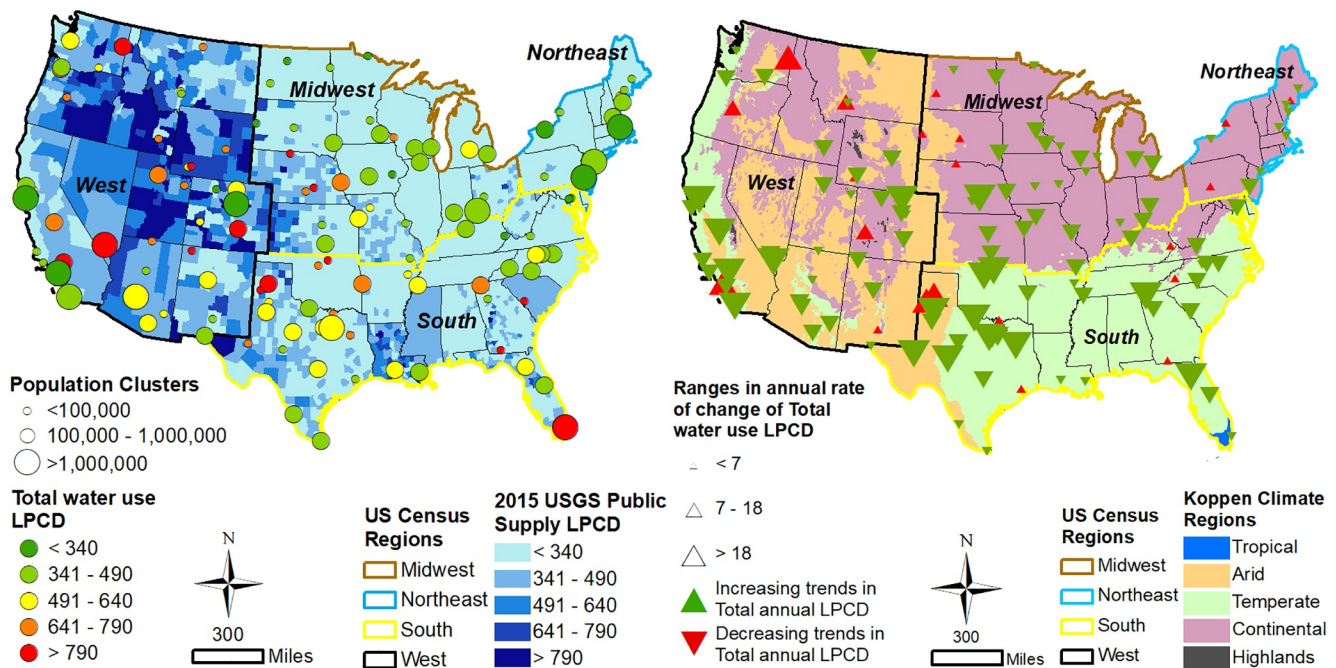


Figure 4. (Left panel) Map of CONUS showing the comparison between city-level total municipal water supplied in LPCD and county-level total public water supplied in LPCD. (Right panel) Map of CONUS showing the range of increasing and decreasing trends in annual rate of Total water use LPCD in the study cities.

show on average a high per capita-day total water use. The South census region, dominated by the Temperate climate type, is second to the West census region in terms of high per capita per day total water use. Also, the South and West census regions, which have higher average per capita per day total water use, also undergo highest levels of median rate of reduction in per capita-day total water use. These patterns may be explained by percentage of housing units that are built after 1950 in the regions with improved plumbing codes to promote water efficiency and water use reduction despite having the highest percentage of single-family houses.

Clustering by climate region, the Arid climate region in CONUS has the highest average residential water use, followed by the Temperate climate region and then the Continental climate region (Figure 3e). Highest median rate of residential water use reduction has been achieved in the Arid climate region (Figure 3f). Arid and Temperate climate regions have the highest total municipal water use reduction rates - above 9.5 LPCD per year.

In Figure 4 (Left panel), city-level LPCD estimates are compared with the county-level LPCD values which were estimated by United States Geological Survey (USGS) for the 2015 municipal water supply year. The USGS estimated LPCD data for CONUS counties is representative of “Public Supply.” Overall, the city-level water use volume revealed in the present study demonstrate similar regional patterns when compared with the county-level public supply data from USGS. However, in an analysis undertaken to identify the usability of USGS data for this study (Figure S3), the USGS estimates of water withdrawn at county level are, in most cases, higher in volume than the actual amount of water supplied at city or municipal level and are also poorly correlated - correlation coefficient was 0.2 with p -value < 0.05. Hence the USGS water withdrawal estimated does not directly help in capturing the actual water use volume or trends in a city within a particular county.

The reason for this order of difference in volume between municipal level water supply data and the USGS water withdrawal estimated for Public Supply in 2015 at county-level are assumed to be, (a) use of county level data where water use within municipal water supply boundaries may differ from water characterized as municipal use by USGS, (b) that there are many cities/towns within that county boundaries with different socio-economic traits, and/or (c) cities get their water from an outside, neighboring county through

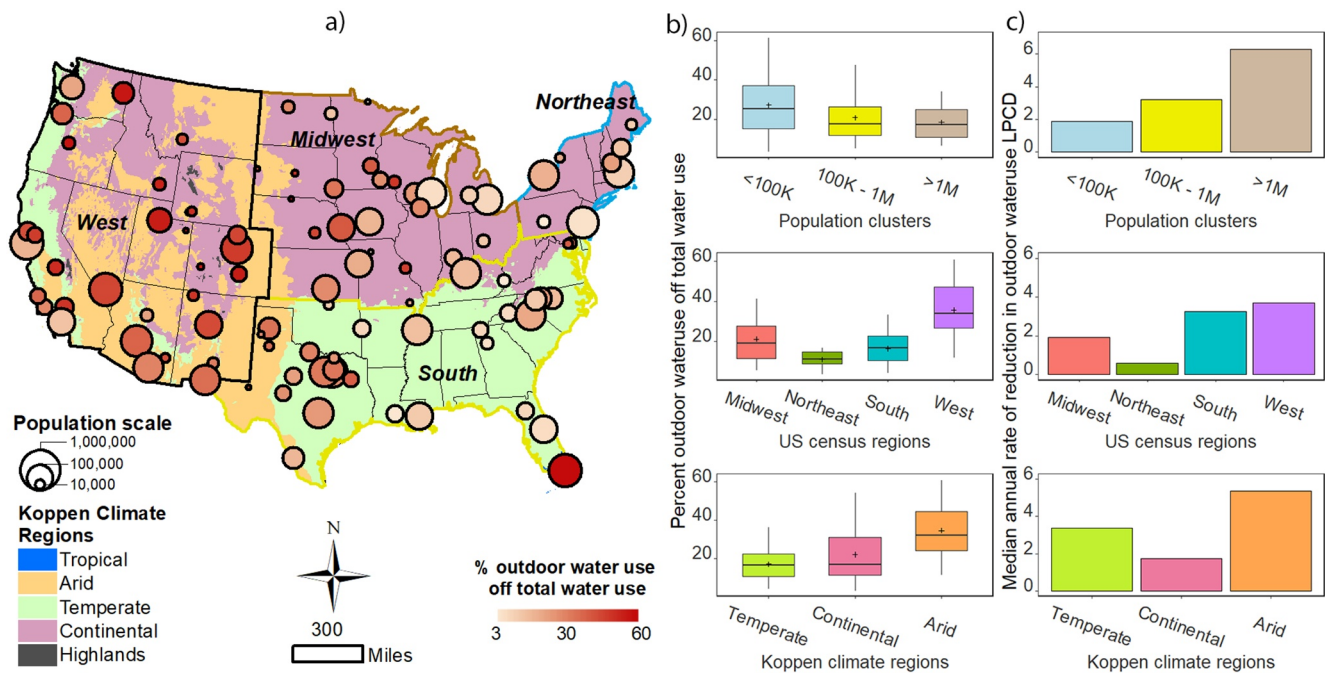


Figure 5. (a) Map of CONUS highlighting percent outdoor water use to total water use in cities distinguished by their population size, (b) Boxplot showing the characterization of percent outdoor water use to total water use by study regions, and (c) level of median annual rate of reduction in outdoor water use LPCD across study regions. CONUS, Contiguous United States; LPCD, liters per capita per day.

water trades. Since USGS public supply water withdrawal estimates at county-level are tallied on a bi-decadal period with estimates projected/compiled for a single year, it does not help in addressing the objectives of this study to characterize temporal trends in municipal water use other than the monthly water use data obtained from directly the cities.

Figure 4 (Right panel) shows the range of annual rate of change of LPCD estimates across the study regions. In some cases, water use patterns and reduction trends deviate from other cities within the same population, climate and Census regions. For example, it may be observed that cities with strong recreation and tourism economies, including Miami and Las Vegas, tend to have the highest residential, CII, and total water uses. Overall, this figure captures the general downward trend in total municipal water use across the cities in all the US Census and climate regions as indicated by the temporal trends in Figure 2.

Water use reduction could be attributed to factors like implementation of updated plumbing codes, water saving fixtures (e.g., low flow toilets and faucet fixtures), drought policies, water conservation in outdoor irrigation through voluntary or mandatory restrictions, and water conservation using pricing schemes, etc., (Breyer et al., 2018; DeOreo et al., 2001, 2016; Fortier & Mailhot, 2015; Magionni, 2014; Mayer, 2016; Niemczynowicz, 1999; Olmstead & Stavins, 2009). Aging infrastructure, rising cost of municipal water, and affordability are among the social and economic factors that affect municipal water use patterns and trends (Butts & Gasteyer, 2011; Etale et al., 2018; Mack & Wrase, 2017; Raj, 2005).

3.2. Outdoor Water Use Patterns and Trends

Outdoor water use makes up a significant portion of the total water use ranging between 3% and 64% (Figure 5). From Figure 5, it can be seen that generally cities in western part of CONUS have high outdoor water use. Cities in the Arid Koppen climate and West Census regions exhibit a higher ratio of outdoor to total water use compared to other cities across the CONUS. Small cities with population less than one hundred thousand residents have notably higher outdoor to total water use ratio (Figure 5b). The results underline that outdoor water use is a predominant driver for varying demands in municipal water supply systems, since DeOreo et al. (2016) have established that indoor water use remains to be, on average, plateaued

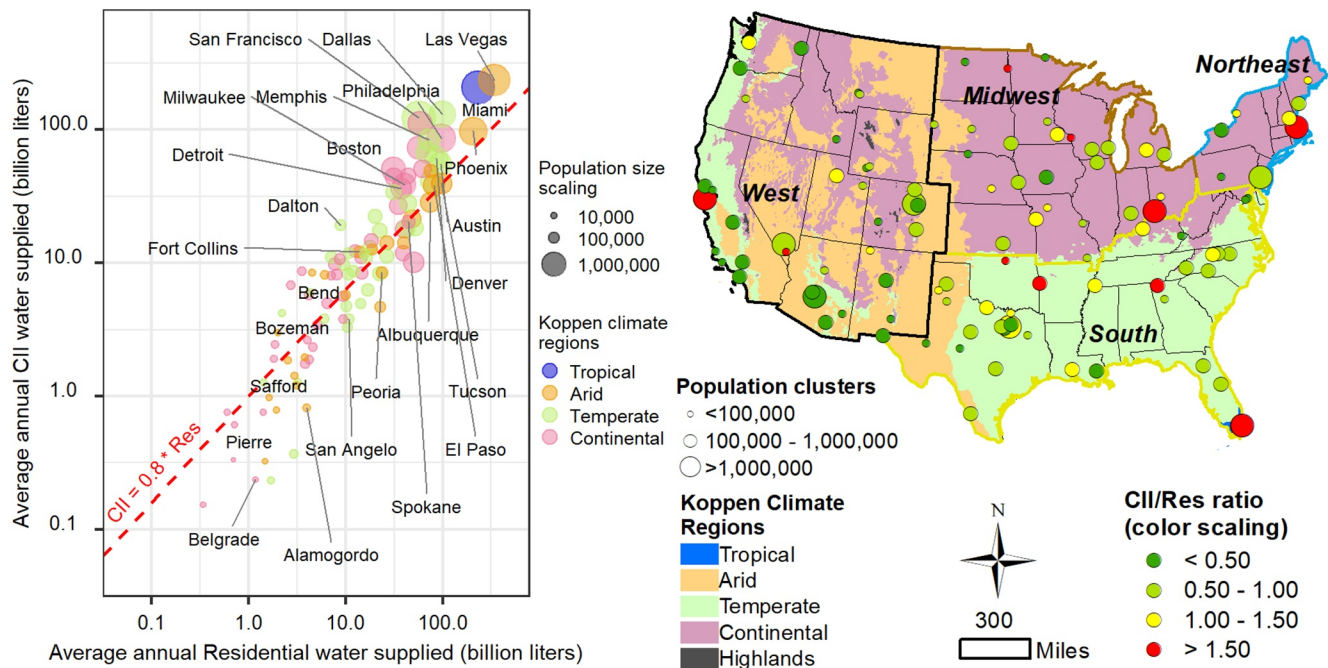


Figure 6. (Left panel) Bubble plot of study cities showing the variation in water use by population size and climate region type. (Right panel) Map of CONUS showing the variation in CII/Res ratio across the study cities clustered by U.S. Census regions and Koppen climate regions. CONUS, Contiguous United States.

across the country. Similar to the total water use trends discussed in Section 3.1, the median rate of reduction in outdoor water use is higher in cities within the Arid and South climate regions, and it increases with increasing city population (Figure 5c). Thus, the hypothesis assumed in Section 3.1 about outdoor water use contributing to the higher volume of total water use in cities in Arid climate and West Census regions and cities with less than 100,000 residents is verified by the trends discussed in this section. A MANOVA test of means of outdoor water demand amongst different classification within a cluster proved that there is significant difference in the means ($p < 0.05$).

3.3. The CII/Res Municipal Water Use Ratio by Population, Climate and Census Regions

Using the annual CII/Res ratio estimates of the study cities, an average annual CII/Res ratio for the entire CONUS was estimated to be 0.82. This average CII/Res ratio for the CONUS does not show seasonality or variability within the study period, and on average this ratio remains constant at ~ 0.8 . To reiterate, the lack of seasonality and lack of temporal change in the CII/Res ratio can be attributed to the fact that residential and CII water use exhibit similar seasonality (Figure 2).

The CII/Res ratio tends to be highly variable even within the same Koppen climate and U.S. Census regions (Figure 6-Right panel). However, larger cities generally have a higher CII/Res ratio, above 0.8, compared to cities with lower population (Figure 6-Left panel). Large cities with population above 1 million people also experience the highest variation in CII/Res ratio, since they are undergoing different trajectories of population growth and economic development. While residential growth is the primary driver of changes in municipal water uses in some cities, industrial activities have increased CII water use in some other cities. These factors along with other consideration such as tourism result in higher CII/Res water use ratio in Las Vegas, Miami, Phoenix, Philadelphia, and San Francisco. An economic census data for number of establishments in Accommodation and Food Services with NAICS code 72 was used as proxy for level of tourism in a city—data is not shown in manuscript or SI.

Among U.S. Census regions, the Northeast shows the highest median level of CII/Res ratio (Figure S4). One inference for this trend is assumed to be the influence of outdoor water demand. Northeast region has the lowest outdoor water demand leading to a higher CII/Res ratio estimate (Figure 5b). The West census

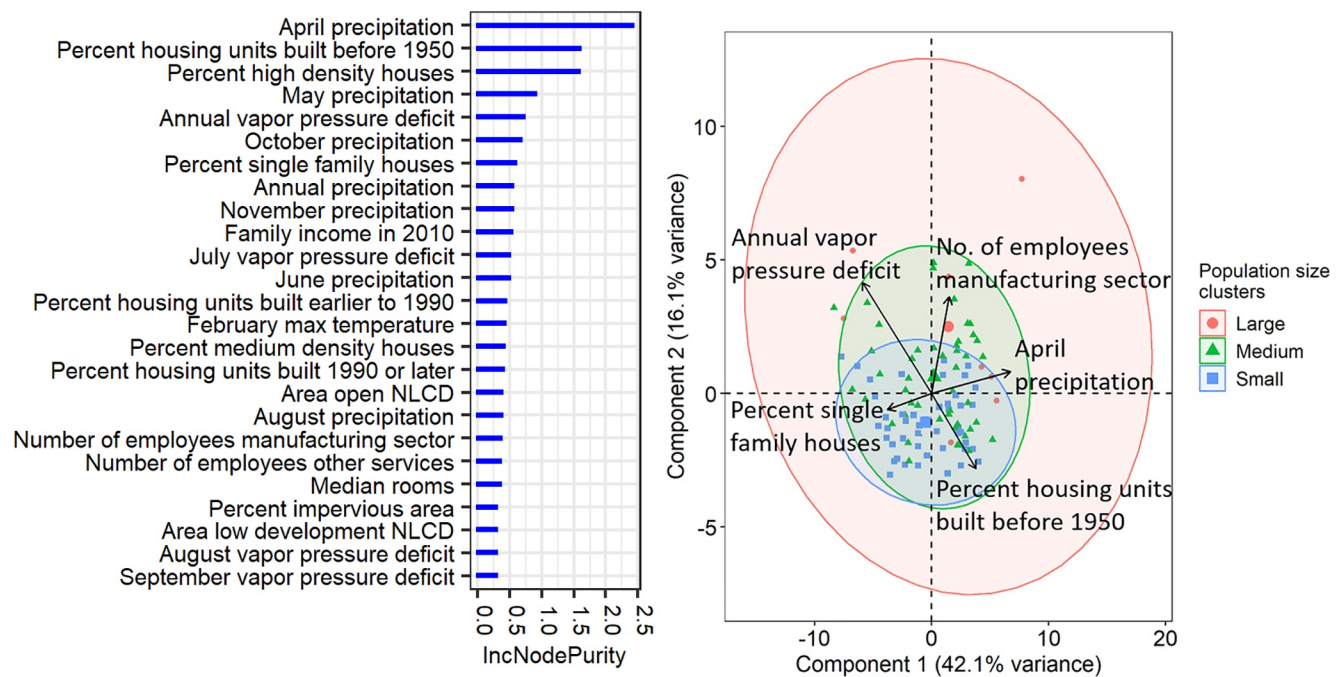


Figure 7. A principal component analysis biplot (right panel) of important variables from random forest analysis (left panel). The PCA biplot shows the cities clustered by their population size and their relation to the top five variables that best explain their CII/Res ratio characteristics.

region has the lowest average CII/Res ratio in contrast to the highest total LPCD water use. The West is also the census region with the least variation in the CII/Res ratio. This low CII/Res ratio in the West implies that residential water use dominates the municipal water use in the West as outdoor water use is highest in this region (Figure 5b). This characteristic is similar in the South, which is the second highest residential water user in the CONUS, with higher average CII water use by some cities leading to high variation in its CII/Res ratio.

Examining the CII/Res ratio trends in level-1 Koppen climate regions (Figure S4), CII water use, on average, dominates residential water use (i.e., CII/Res ratio $\gg 1$) in the Temperate and Continental climate types; residential water use is highest in the Arid climate region. The Continental climate region has highest variation in CII/Res ratio, while the Arid climate region has lowest range of CII/Res ratio which can be attributed to the highest amount of water needed for residential outdoor irrigation compared to other climate regions (Figure 5b). Also, the median rate of change of CII/Res ratio for Continental climate region tends to indicate economic growth resulting in increased CII water use compared to other climate regions for the period 2005–2017.

3.4. Influential Factors and a Classification Tree Model for CII/Res Water Use Ratio

Top 25 variables, illustrated in Figure 7 (Left Panel), were selected from the random forest analysis built using 200 trees from the initial 1,000 trees (Figure S5-Left panel) with a node purity value of 0.35 as threshold. With the help of a scree plot and elbow method (Figure S5-Right panel), top five PCs were identified as optimal to build a classification tree for the CII/Res ratio, which include: “April precipitation,” “Annual vapor pressure deficit,” “Number of employees in manufacturing sector,” “Total houses built before 1950,” and “Total single-family houses” from all the other variables denoted originally in the PCA biplot (Figure S6). It should be noted that the “Number of employees in other services (except public administration),” that is, workers in mechanic repairing, photofinishing, NGOs, personal/pet care, laundry and parking services, may be a substitute with the same fidelity for the “Number of employees in manufacturing sector.” Figure 7 (Right Panel) represents cities clustered by population sizes and by the factors that were selected to build a classification tree.

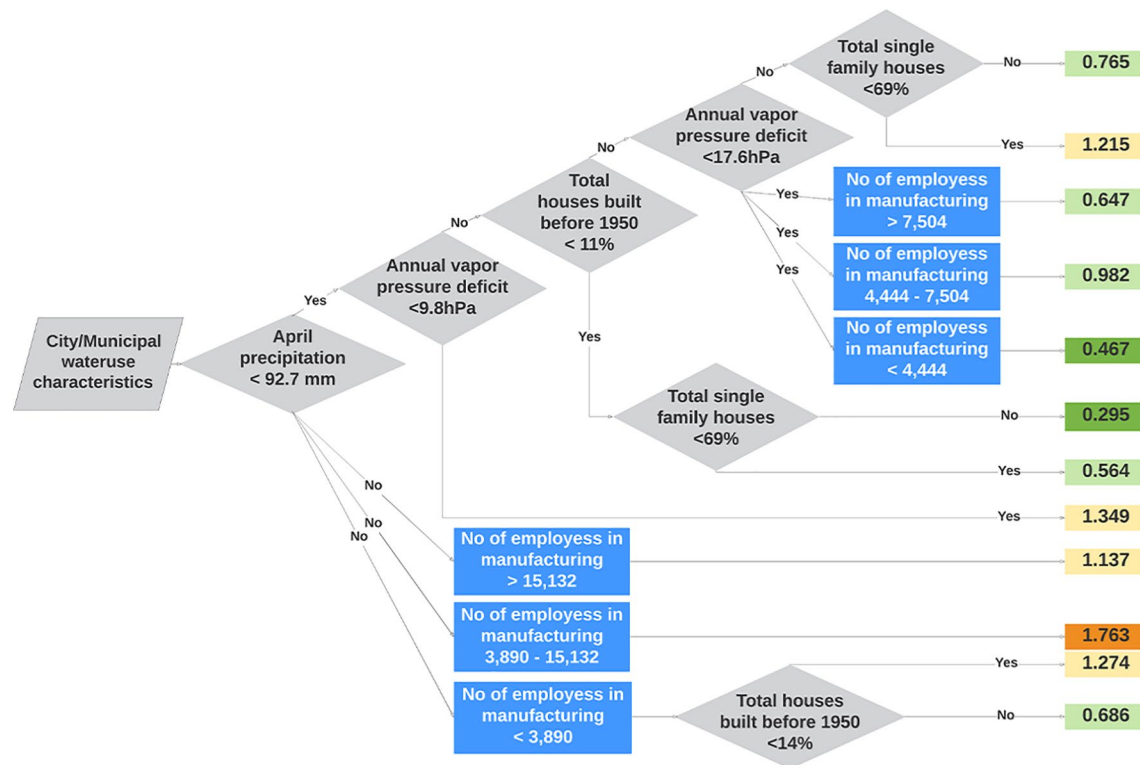


Figure 8. A classification tree model built to estimate the CII/Res ratio, based on the top five factors from the PCA analysis, for any city or town within the CONUS. CONUS, Contiguous United States; PCA, Principal Component Analysis.

The impact of climate variables—April precipitation and annual vapor pressure deficit, on municipal water uses can be explained by their variation among the U.S. Census and Koppen climate regions. These two climate variables primarily influence the total volume of municipal water used for outdoor irrigation based on the applied approach to partition indoor and outdoor water use in this study, and are prevalent in warm climate regions and regions with high number of single-family housing. The average total number of employees in the manufacturing sector is highest in the Northeast census region and large size cities, thereby highlighting the prevalence of CII water use. The total percentage of housing units built before 1950 is also highest in the Northeast census region and in large cities, while cities in the South and West census regions and smaller population size cities have relatively high percentage of houses that were built post 1950 with improved plumbing codes. The total percentage of single-family housing also plays a crucial role in deciding the level of residential water use in a city, as discussed in Sections 3.1 and 3.2. Thus, these five physical and readily available variables describe a variety of municipal water use characteristics across the CONUS when summarized by the study regions. Basker et al. (2019) and Becker (2016) also highlight the importance of the bi-decadal water estimates in the manufacturing and mining sector, while Mayer et al. (1999) and DeOreo et al. (2016) have shown the importance of building plumbing codes, which are tied with the age of the building, in estimating the water efficiency of a house or an apartment complex.

Ultimately, a classification tree model was developed using these influential factors as depicted in Figure 8. The classification tree's coefficient of determination (R^2) for the training and testing datasets were 0.68 and 0.76 respectively. The Mann-Whitney test on the medians of observed and decision tree classified CII/Res ratio values yielded a p value > 0.05 to validate that these two CII/Res ratio sample sets were not significantly different. Comparison of the empirical and modeled cumulative distribution functions of the CII/Res ratio indicates an adequate fit between the observed data and the fitted classification tree model—(a) decent visual goodness of fit (Figure S7), (b) passed the Chi-Squared test ($p > 0.05$), but (c) failed the Kolmogorov-Smirnov goodness of fit test ($p < 0.05$). Thus, it has been observed that for a few cities, the classification tree model over-estimates the CII/Res ratio for empirical values less than 0.6 and under-estimates the ratio for empirical values above 1.7 (Figure S7).

Overall, the tree classification model provides a new approach to using readily available dataset. along with the municipal water use data to be incorporated in existing urban water modeling tools, such as the that described by Sharvelle et al. (2017). Improved estimates of CII/Res ratio expands existing predictive capabilities of water demand-supply chain under varying future development scenarios, and foster capacity to assess opportunities to minimize use of traditional water supplies and maximize fresh water availability. The developed CII/Res ratios cannot be applied to identify distinct trends in each water use category, but rather to identify the expected CII/Res ratio under distinct conditions of interest (e.g., climate, socio-economic, and urban development variables).

4. Conclusions

This study investigates factors that influence residential and CII water use in the municipal water supply system across the CONUS. Thus, data from a comprehensive survey of monthly municipal water uses from 126 cities and towns, across ecohydrologic regions between 2005 and 2017, were compiled to explain the spatial and temporal trends in municipal water uses based on different climatic, urban-geologic, and socio-economic factors.

Notable water use reduction in the residential sector compared to the CII sector was evident over the 2005–2017 period. Cities with larger populations have lower total water use per capita-day than small and medium size cities, while those in the Arid Koppen climate region have higher per-capita water use. The CII water use per capita-day also tends to increase with population. Eventually, the trends evident in outdoor water use for landscape or lawn irrigation appear to be an important source of variability in total water demand across the population size clusters, U.S. Census regions and Koppen climate regions across CONUS.

The results also suggest that larger size cities and cities in hot, arid climate regions simultaneously achieve pronounced reductions in absolute per capita-day water use relative to smaller cities with low volume water use and cities outside arid climate regions. Although marked differences in the median rate of municipal water use reduction were characterized across different regions, strategies used by water supply providers to achieve these reductions were not investigated. Future studies focused on improving the current municipal water use data with more cities (>126) and more recent water use data could help to unravel more trends in water use characteristics and offer better insights in modeling municipal water use.

Another major outcome of this study is the collection of 81 factors to explain the influence of climatic, socio-economic, and urban-geographic characteristics of a city on the CII to residential water use ratio. This is a novel approach to unify the two major municipal water users and the characterization of CII/Res ratio has the potential for various city-level planning and governance to build a prediction model for projecting future water needs of a city under varying scenarios of development patterns. Ultimately, the amount of precipitation in April, annual vapor pressure deficit, number of employees in the manufacturing (or other services except public administration), total number of single-family houses and housing units built prior to 1950, adequately explain the variability of the CII/Res ratio. These factors serve as surrogates for climate (e.g., precipitation and temperature), infrastructural conditions such as aging water systems, economic development, and other drivers of municipal water uses in cities.

The methods provided in the present study may be used to predict the CII/Res water ratio and to separate outdoor to indoor water use ratio for other cities and towns across the CONUS. The CII/Res ratios are appropriate for estimates of water use with a monthly or annual temporal resolution. Future work related to water supply and demand planning that use projected population, climate and land use changes will benefit from the methods and results of this study. Also, municipal water use trends presented here can readily be used for model parameter estimations to enable estimation of CII water use based on residential water use. Lastly, a noteworthy facet of this work is its potential to apply the approaches to assess impacts of economic development on municipal water use. The methodology used to build a classification tree model for the CII/Res ratio in this study could easily be translated to temporal anomalies observed in 2020, civil restrictions due to corona virus lockdowns, in order to study the forces morphing municipal water uses due to significant impacts on social and economic activities.

Data Availability Statement

The study data may be accessed at <https://doi.org/10.4211/hs.feb5af8990914ce2b28f18b10d65c2a2>.

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