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Key Points:

- We present a database of primary flow and energy data for over 160 U.S. water and wastewater utilities
- Average per person water flux is 560 L of drinking water and 500 L of wastewater per day
- Non-revenue water and its embedded energy accounts for 3,600 GWh of electricity loss annually

Supporting Information:

- Supporting Information S1

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The State of U.S. Urban Water: Data and the Energy-Water Nexus

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Abstract Data on urban water resources are scarce, despite a majority of the U.S. population residing in urban environments. Further, information on the energy required to facilitate the treatment, distribution, and collection of urban water are even more limited. In this study, we evaluate the energy-for-water component of the energy-water nexus by providing and analyzing a unique primary database consisting of drinking water and wastewater utility flows and energy. These anthropogenic fluxes of water through the urban environment are used to assess the state of the U.S. urban energy-water nexus at over 160 utilities. The average daily per person water flux is estimated at 560 L of drinking water and 500 L of wastewater. Drinking water and wastewater utilities require 340 kWh/1,000 m^3 and 430 kWh/1,000 m^3 of energy, respectively, to treat these resources. The total national energy demand for water utilities accounts for 1.0% of the total annual electricity consumption of the United States. Additionally, the water and embedded energy loss associated with non-revenue water accounts for 9.1×10^9 m^3 of water and 3,100 GWh, enough electricity to power 300,000 U.S. households annually. Finally, the water flux and embedded energy fluctuated monthly in many cities. As the nation's water resources become increasingly scarce and unpredictable, it is essential to have a set of empirical data for continuous evaluation and updates on the state of the U.S. urban energy-water nexus.

Plain Language Summary Energy in the form of electricity, natural gas, or fuel oil is needed to treat and distribute drinking water to consumers in cities. Additional energy is needed after using drinking water to collect and treat subsequent wastewater. Though most of the U.S. population lives in urban areas, there are no studies that collect and publish data from across U.S. cities to determine how much water is used or how much energy is used for that water. In this study, we collect data from over 160 drinking water or wastewater utilities in U.S. cities to determine water demands and their required energy. Through our study, we determined that almost 1 of every 6 units of water treated across the United States never reaches the consumer. The energy required to treat this lost water is enough to power 300,000 homes in the United States annually. Through this collection of data, we provide the first freely available database for further research and understanding of city-level water flows. Cataloging these data across the United States is important for conserving water and energy resources and promoting sustainable practices.

1. Introduction

Increasing water stress and climate change affects the global distribution of water resources (Oki & Kanae, 2006). As a result, cities face increasing challenges to water management constraints (Cosgrove & Loucks, 2015). Over half of the population of the United States is vulnerable to water resources risks (Padowski & Jawitz, 2012), and these water resources are integral to the life, economy, and social structure of urban environments (Gandy, 2004). Therefore, understanding the anthropogenic fluxes of water through the built environment (defined in this context as movement into and out of a city) is an important consideration of urban sustainability (Swyngedouw, 2004). Despite this importance of water resources fluxes, there are relatively few sources of publicly available urban water data. The data that are available are scattered and require a significant amount of synthesis (Elliott et al., 2000). Existing databases include the U.S. Geological Survey and its estimate of public water demand on a county level once every 5 years (Maupin et al., 2014) and state level estimates, such as the California Water Reclamation Board, which provides utility level data for drinking water production, but not embedded energy or wastewater resources (California Environmental

Protection Agency, 2016). Beyond water fluxes, embedded energy is also an important component of evaluating urban water resilience (Wisniewski, 2015) and understanding drivers of consumption (Kenway et al., 2011a). Therefore, a comprehensive study of urban water fluxes requires a new database (Chini & Stillwell, 2017) within the energy-water nexus. In this study, we provide and analyze a new database of primary data from water utilities including their water fluxes and embedded energy to assess the state of the U.S. urban energy-water nexus.

Recent studies of the energy-water nexus in the urban environment focus primarily on drinking water resources (Chini et al., 2017; Lam et al., 2017; Noiva et al., 2016; Sowby & Burian, 2017). However, to provide a full picture of water and energy in the urban environment, it is also necessary to understand corresponding wastewater discharges. Several studies have previously categorized the total energy for water use in the United States with estimates ranging from 4% to 16% of total U.S. energy demand (Goldstein & Smith, 2002; Sanders & Webber, 2012; Twomey & Webber, 2011). The variations in these estimates are based on the inclusion of residential water heating and the inclusion of energy for direct steam usage. Additionally, James et al. (2002) estimate that pumping and treatment of water requires 2–3% of the world's energy. A more recent study estimates energy consumption for water at closer to 1–2% of total energy consumption in the United States and 1.7–2.7% globally (Liu et al., 2016). However, these studies utilized limited primary data to extrapolate energy usage and do not concurrently assess water fluxes. Using a more robust set of primary data from drinking water and wastewater utilities and principles of material flow analysis (MFA), we aim to answer the following motivational research question: *What is the current state of the U.S. urban energy-water nexus, from the perspective of energy-for-water in public utilities*?

To evaluate this question, we focus on anthropogenic fluxes of water including water supply, water loss, and wastewater effluent and their embedded energy. The urban water cycle includes rainfall, drinking water imports, water loss, water abstraction, wastewater discharge, and stormwater runoff. Figure 1 shows these generalized fluxes of water through the urban environment and the multiple interactions of energy with the urban water cycle. Water is lost in the system due to non-revenue water, which provides an important layer of understanding to the flux of water in the urban water environment and has important implications

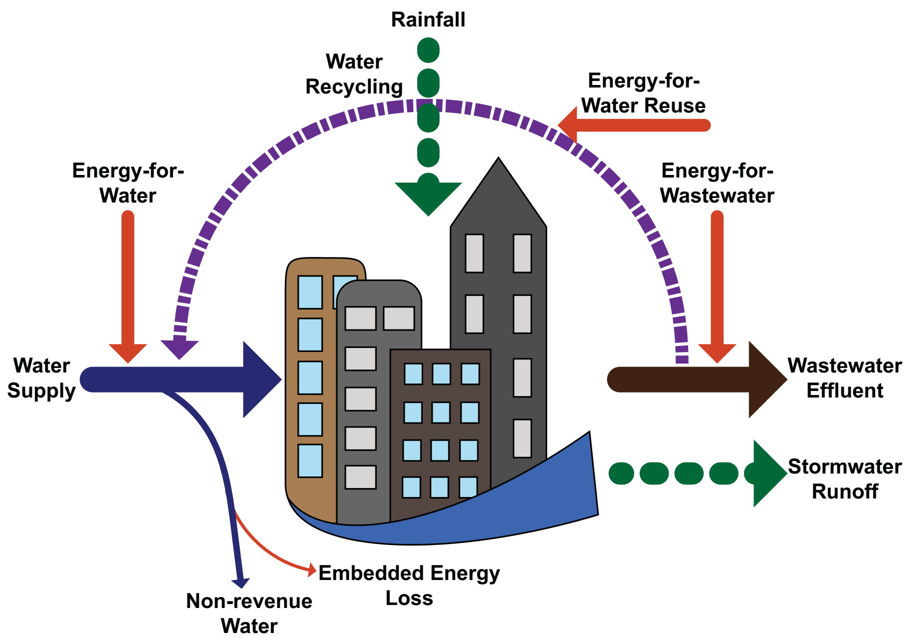

Figure 1. The urban environment receives water resources input from both rain and drinking water, discharging both stormwater and wastewater to the environment, with the potential for water reuse to push the linear system toward a cycle (shown with a dash-dot line). Orange arrows entering water flows indicate embedded energies within the system. Dashed lines for stormwater runoff and rainfall indicate flows not included in this study. However, in the case of combined sewer systems or rainfall infiltration into wastewater systems, there might be some stormwater runoff treated at wastewater utilities and, therefore, accounted for within the study.

in water savings (Chini et al., 2016). The American Water Works Association and International Water Association define two categories of water losses: apparent and real losses (American Water Works Association, 2012). Apparent losses are due to meter inaccuracies, data errors, and unauthorized consumption; this water is not properly measured, accounted, and paid for. Real losses are the physical losses of water due to leakage, high pressure, or storage overflows that never reach a consumer. Combining these two losses into a singular category defines non-revenue water (Texas Water Development Board, 2016). Thornton et al. (2008) estimated that, on average, U.S. water distribution systems lose 16% of their total treated water. Globally, the International Benchmarking Network for Water and Sanitation Utilities estimates that global non-revenue water percentages are closer to 30% (Danilenko et al., 2014), with conservative cost estimates of this non-revenue water at \$14 billion (10^9) U.S. dollars, annually (Kingdom et al., 2006). The water loss through non-revenue water contains embedded energy and could have important implications for efficiency of both energy and water resources, nationally.

Within this study, we utilize the underlying principles of MFA, a resource accounting method that tracks material flows into and out of geographic regions (Barles, 2010). MFA is an important educational and communication tool (Hendriks et al., 2000) and is highly relevant to describing socioenvironmental interactions in support of informing policy and action (Barles, 2009; Burstrom et al., 1998; Daxbeck et al., 1997). The study of urban metabolism is principally an application of MFA to the city-scale (Kennedy, 2012), originating in the 1960s by Abel Wolman (Wolman, 1965) to quantify water and energy flows through a hypothetical city of one million people. These problems have since expanded in scope with a focus on material balances (Douglas, 1983) and embodied energy or ecological footprint concepts (Goldstein et al., 2013). Measures of urban metabolism are necessary to address resource concerns within the context of global resource flow (Kennedy & Hoornweg, 2012). The database introduced and analyzed herein has important implications in furthering urban metabolism research, as a lack of data is a major obstacle in urban metabolism studies (Niza et al., 2009).

Over 80% of the population of the United States lives in urban environments (United Nations, 2014). By accounting for the water resources in cities, we can understand and better predict impacts of water shortages on a national scale. While water is generally managed as a local resource, it is increasingly broader in scope due to resource sustainability concerns, population growth and shifts, and interbasin water transfers, real or virtual (e.g., Chini et al., 2017; Konar et al., 2011). There is a significant gap associated with cataloging and analyzing water flux and its embedded energy through urban environments in the United States. Our work fills this knowledge gap by (i) using a unique database of primary data from drinking water and wastewater utilities across the country, (ii) assessing the overall state of the U.S. urban energy-water nexus, with respect to energy-for-water demands, and (iii) promoting data sharing between utilities and researchers through publication of our data in an open-access database. In this study, we provide nationwide statistics of annual and intra-annual water fluxes in cities, non-revenue water, and spatial grouping. Each of these statistics are presented for the first time using a robust database of primary data to provide important insights for understanding urban energy and water sustainability.

2. Materials and Methods

This section describes the approach to data collection, synthesis, and analysis of drinking water and wastewater utilities and their water use and embedded energy. Before discussing methodology specifics, it is important to identify geographical and accounting system boundaries. Our study of urban water flux utilizes drinking water and wastewater utility level data; therefore, each utility service area provides the geographical boundary for its respective city. As utility boundaries do not necessarily correspond to the political jurisdictions of cities and their city limits, the utilities might service some communities outside the main urban area. For instance, the Detroit Water and Sewerage Department provides service to nearly 40% of the State of Michigan's population, far more than the population of the City of Detroit. Additionally, drinking water and wastewater utilities in the same city do not necessarily have the same service areas. Therefore, in order to define the flux of urban water, we normalize the utility water flows by service population. For the accounting boundary, our study focuses on drinking water imports and wastewater exports, excluding the energy-for-water needs of water within buildings (e.g., domestic water heating). We only consider utility level energy consumption for the production, treatment, and pumping of water resources into and out of the city. These are necessary boundary adjustments due to the scope of the study and the goal of evaluating the state of the U.S. urban energy-water nexus from a water utility perspective.

2.1. Data Collection

We sent open records requests to utilities in 127 cities across the United States over the course of 2 years, representing 253 distinct water and sewer utilities ($127 \times 2-1$; Minneapolis and St. Paul, MN share a wastewater district, and therefore the data are combined). These cities represent major urban environments in each of the 50 states. Each city has a population of greater than 100,000, except in states where there were no cities meeting that criterion. In those states, we selected the largest cities to be a part of the database. Additionally, not every city with a population greater than 100,000 people was included in the data search. Our goal was to assemble a robust database and sample size for the urban environment in each state, and our requests tended to align with metropolitan statistical areas in each state, as defined by the U.S. Census Bureau. We requested water flow and energy data from both water and wastewater utilities for all cities. A copy of the letter requesting data is included in the supporting information; see supporting information Figure S3. The data from these open records requests are published concurrently with this article at a monthly timescale, when available, in an online and open database through the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) (Chini & Stillwell, 2018).

Data request methods included standard mail, email, telephone conversations, online forms, and social media. These data requests focused on water flow, energy consumption, service population, and, in the case of wastewater, energy recovery. Data were requested for the year 2012, based on its relative recentness and its correlation to other national data sets, such as the Commodity Flow Survey (United States Census Bureau, 2012a). The formal request process to receive data from water utilities has substantial communication, data availability, and data accessibility challenges, as described in a previously published commentary (Chini & Stillwell, 2017). Additionally, we assembled data outside of the formal records request process for non-revenue water. These data are available through multiple sources including news reports, end-of-the-year financial reports, state databases, and through first-hand communication via email and social media exchanges (i.e., Twitter).

2.2. Data Synthesis

Data received from open records requests came in a variety of forms and temporal scales. Often these data came in multiple formats such as scanned copies of utility bills, hard copies of reports, or in PDF files of tables. We aggregated water volume and energy data to monthly and annual scales for each utility, as necessary. Energy resources consumed by utilities include electricity, natural gas, fuel oil, and biogas. In previous studies on drinking water supply, only electricity was considered as a component of energy-for-water (Sowby & Burian, 2017), neglecting other energy sources. Natural gas, fuel oil, and biogas are considered primary energy sources, while electricity is a secondary energy source (i.e., generated from a primary energy source). Distinguishing between these sources and normalizing to a common form is necessary to accurately assess and compare energy-for-water at different utilities. We convert these energy portfolios to secondary energy (electricity in equivalent kWh) for comparison (equation (1), consistent with Chini et al. (2017)

$$E[kWh_{eq}]=e+0.45\times\left(29.3\left[\frac{kWh}{therm}\right]\times n+43.9\left[\frac{kWh}{gal}\right]\times f\right) \tag{1}$$

where e is the electricity consumption in kWh, n is the natural gas consumption in therms, and f is the consumption of fuel oil in gallons. The conversion factors are equivalent to the normalization factors used in the American Water Works Association's *Benchmarking Performance Indicators for Water and Wastewater: 2013 Survey* (American Water Works Association (AWWA), 2015). A factor of 0.45 is used in the conversion to account for efficiency in using natural gas, biogas, and fuel oil to produce electricity (Semiat, 2008). For biogas, values were often given in standard cubic feet (scf), where we utilized a conversion factor of 0.61 therm per 100 scf to account for the different thermal intensities of biogas and natural gas (United States Environmental Protection Agency, 2011).

2.3. Data Analysis

Data analysis consists of both statistical and spatial components. To calculate a national average of urban environments, we utilize a population weighted average. In addition, to provide corresponding weighted standard deviations for water volume, we artificially create data points based on population and treated volume. For example, a city with a population of 800,000 that uses 400 liters per capita per day (lpcd) would be represented by 800,000 data points with the value of 400 in the sample to capture the weighted standard deviation of an urban citizen in the United States. Therefore, a city with a low population but high water flux will not overly skew the average and standard deviation of the urban water statistics.

We include a spatial analysis of the database to both visualize that data and evaluate the effectiveness of regional benchmarking initiatives. We utilize a *k*-means clustering algorithm and vary the number of groups or clusters to determine appropriate geographic regions. The *k*-means clustering algorithm partitions data into *k* clusters where each observation belongs to a cluster with the nearest mean. The algorithm seeks to minimize an objective function based on Euclidean distance and variance of a mean. In other words, the algorithm spatially correlates utilities based on proximity to each other and water flux and embedded energy characteristics. A geographic information system provides the basis for this analysis that included drinking water and wastewater flows and corresponding embedded energy values as well as service population. The results of this analysis seek to justify regional or national scale benchmarking for utility level comparison.

3. Results and Discussion

We collected, organized, and analyzed primary flow and energy data from water utilities, representing a drinking water service population of 81.4 million and a wastewater service population of 86.2 million people. Of the 253 utilities for which data were requested, 76% responded with some form of data; Table 1 indicates the number of utilities that responded with data in each requested category. Monthly values for both water volume and embedded energy are available for 56 drinking water utilities and 70 wastewater utilities. Supporting information Table S1 contains the type of data included in the database. The following section discusses four key areas of results from the analysis of the database. The first section shows overall variations in the data across the country from an annual timescale, including national averages, non-revenue water, and a cumulative distribution function of both water fluxes and embedded energy. The second section evaluates and visualizes the data on a spatial scale. Next, we analyze intra-annual variations of the data across the country. Finally, we discuss the impacts of the urban energy-water nexus and its implications on a national scale.

3.1. Annual Water Fluxes and Non-revenue Water

Many urban metabolism studies previously categorized the flux of water through an urban environment. In his seminal study, Wolman (1965) described the water metabolism of a theoretical U.S. city of one million residents, estimating a drinking water consumption of 570 lpcd and a wastewater discharge of 450 lpcd. A 1990 assessment of Sydney estimated 490 lpcd of drinking water consumption and 430 lpcd of wastewater discharge (Newman & Kenworthy, 1999). In comparison, we determine the water and wastewater flux of U.S. cities, based on our primary data, to be approximately 560 and 500 lpcd, respectively; see Table 1. However, these water fluxes are highly variable between cities. To compare the variances of the two fluxes, we compute the relative standard deviation, the weighted standard deviation as a fraction of the mean (σ/μ). The relative standard deviation for wastewater volume (0.46) is greater than that of drinking water volume (0.37), illustrating a larger relative variation in wastewater versus drinking water fluxes. This difference is most likely due to large volumes of stormwater associated with combined sewers (carrying stormwater and wastewater) in large cities and varying amounts of inflow and infiltration. Of the 104 cities responding with wastewater flow data, we identified 38 cities with combined sewer overflow permits by the U.S. Environmental Protection Agency (United States Environmental Protection Agency, 2017). Supporting information Figure S1 shows a lower per capita flux of separated sewer discharge when compared to combined sewer systems. A non-parametric statistical test confirms a

Table 1
On Average, U.S. Cities Expel 88% of Their Drinking Water Intake Through the Wastewater System, not Accounting for Combined Sewers or Infiltration and Inflow

	Drinking water		Wastewater		
	Flow (lpcd)	Energy (kWh/1,000 m^3)	Flow (lpcd)	Energy (kWh/1,000 m^3)	Recovery (kWh/1,000 m^3)
Sample size, *n*	89	73	104	90	45
Mean, μ	556	342	498	432	63
Std. Dev., σ	210	268	227	292	182
25th percentile	449	148	326	363	48
50th percentile	519	346	408	463	205
75th percentile	645	499	641	648	303

Note. More energy is required per volume to treat wastewater than drinking water. Wastewater utilities, on average, recover about 14% of their required energy.

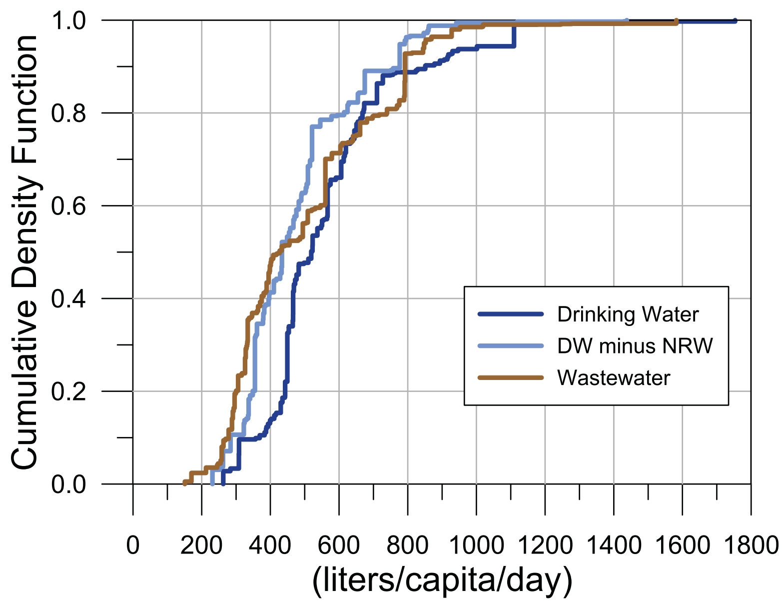

Figure 2. The dark blue and brown lines show the distribution of weighted, per capita drinking water, and wastewater averages, respectively. The cumulative distribution function is based on the total service populations of utility data received. The light blue line shows the CDF for drinking water flux after removing non-revenue water (NRW).

significantly larger per capita discharge for combined sewer systems over separated sewer systems ($p < 0.01$).

Non-revenue water also provides an important layer of understanding to the flux of water in the urban water environment. Of the 16.7 billion m^3 per year of treated drinking water tabulated in this study, we estimate that 15.7% of this volume is attributed to non-revenue water through our primary data. Our estimation of non-revenue water closely correlates to previous nationwide estimates by Thornton et al. (2008). Recalculating the mean and standard deviation of drinking water eliminating non-revenue water, we see $\mu = 420$ lpcd and $\sigma = 170$ lpcd ($n = 70$). Non-revenue water accounts for a large portion, nationally, of treated drinking water and, therefore, has important implications in water security and efficiency efforts.

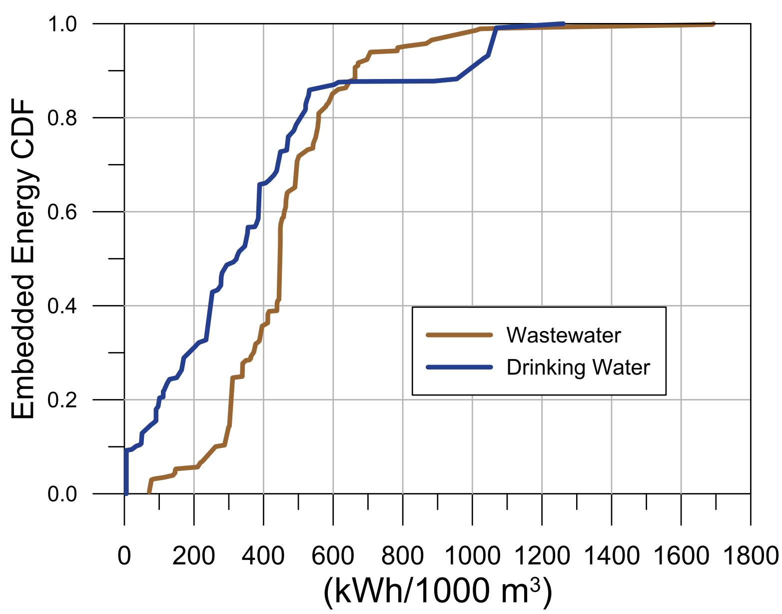

Figure 3. Cumulative distribution functions for the embedded energy of drinking water and wastewater resources show a skewed right tail of the distribution where larger embedded energy is required.

No two cities are identical in their water fluxes or embedded energy. To better illustrate the variation of water flux and its embedded energy across the United States, we provide cumulative distribution functions (CDFs) for drinking water, wastewater, and their embedded energy. Figure 2 shows CDFs for drinking water and wastewater volumes per capita, weighted by service population. The CDFs show a steeper slope when per capita water fluxes are clustered together, with a flatter slope indicating minimal clustering and possible outliers. For drinking water, Figure 2 (dark blue line), a majority of urban residents consume between 400 and 750 lpcd, which centers around the calculated mean (see Table 1). The high standard deviation of the sample could be driven by per capita drinking water consumption above 1,000 lpcd. Similarly, Figure 2 shows a steep slope between 300 and 600 lcpd of wastewater flux (brown line), which encompasses the calculated average (see Table 1). These CDFs show the variability of water flux on a per capita basis. Pairing

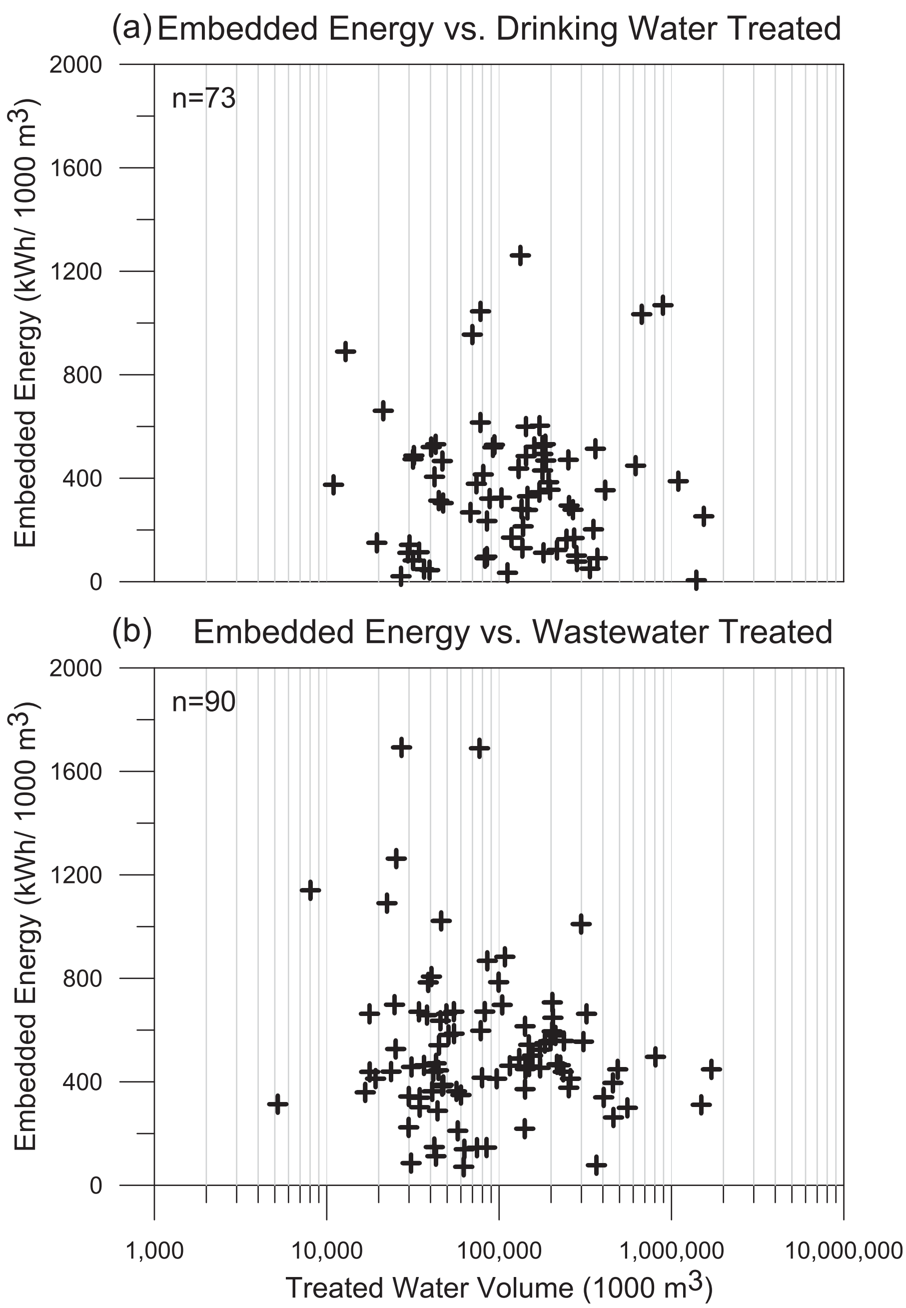

Figure 4. The embedded energy demand associated with total treated volume for both drinking water and wastewater does not suggest any economies of scale with regards to energy per treated volume.

the individual city values for non-revenue water with their declared water fluxes, we recalculate the CDF of drinking water excluding the volume of water not reaching consumers. Figure 2 (light blue line) shows a shifted CDF with lower overall flows. However, there are minimal changes to the shape of the curve, indicating the minimal impact non-revenue water has on the variability of drinking water demand across the country.

Similar to water volume, we show a CDF of the embedded energy of drinking water and wastewater, weighted by total volume treated (Figure 3). The embedded energy in drinking water has a large slope between 100 and 550 kWh/1,000 m^3 before jumping, suddenly, to a value of almost 1,000 kWh/1,000 m^3, indicating two clusters of energy-for-water consumption per volume among utilities. Similarly for wastewater, there is a steep slope centered around the mean from 300 to 600 kWh/1,000 m^3 before a skewed right tail for the remaining 15% of wastewater treated. Finally, plotting the embedded energy of both drinking water and wastewater against their annual volume treated (Figure 4) shows minimal economies of scale associated with energy for treatment. In other words, larger drinking water and wastewater utilities do not necessarily have lower embedded energy for treatment and distribution/collection of their resources (see also supporting information Figure S2). This finding reinforces the need for a larger, national database to facilitate utility comparisons as utility size is not an adequate indicator of similar embedded energy.

3.2. Spatial Analysis of the Urban Energy-Water Nexus

While the CDFs in Figures 2 and 3 show the variability of water flux on a per capita basis and embedded energy on a per volume basis, it is also necessary to visualize this variability on a spatial scale. Figures 5 and 6 display the spatial variability of drinking water and wastewater flux, respectively, across the U.S. cities in our database. The figures show both the volume of water and the embedded energy within the water

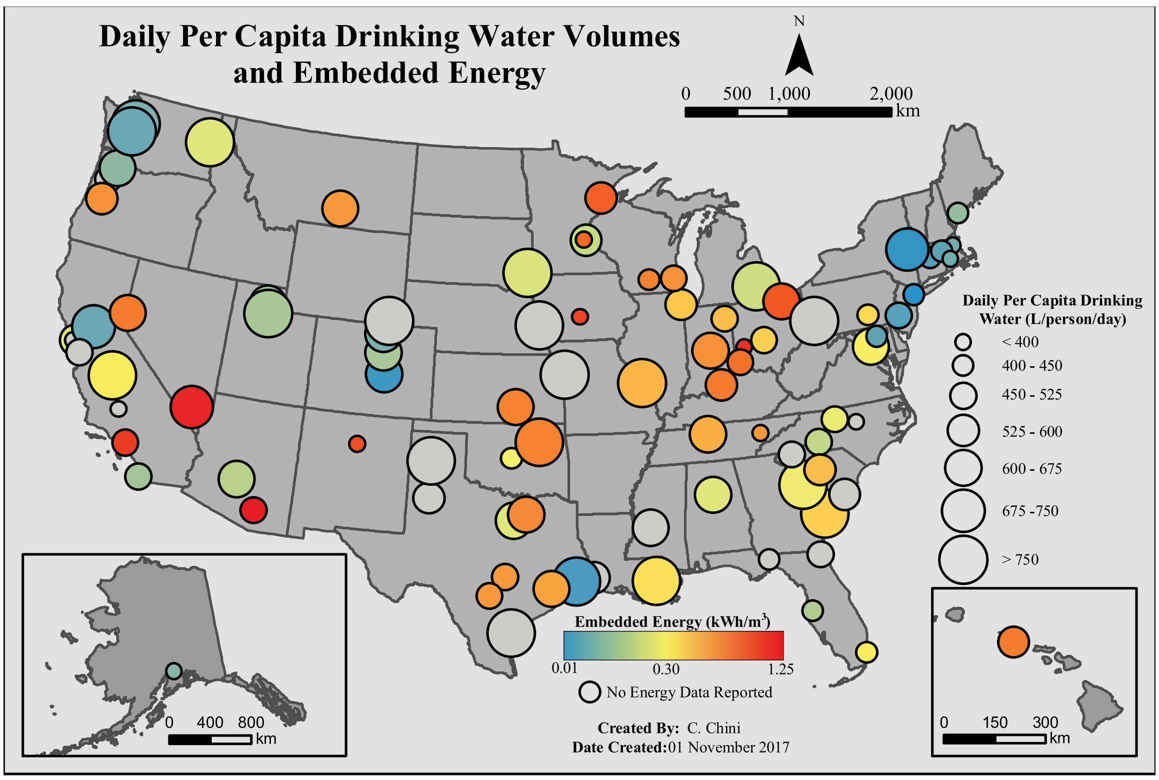

Figure 5. The volume of per capita drinking water varies across the country, with minimal correlation between geographic regions. The size of the circle on the map indicates the per capita water flux and the color of the circle represents its energy intensity. The color scheme ranges from blue to red, with blue indicating a lower embedded energy and red representing a higher embedded energy. A grey circle indicates a utility that responded with water volume but not required energy.

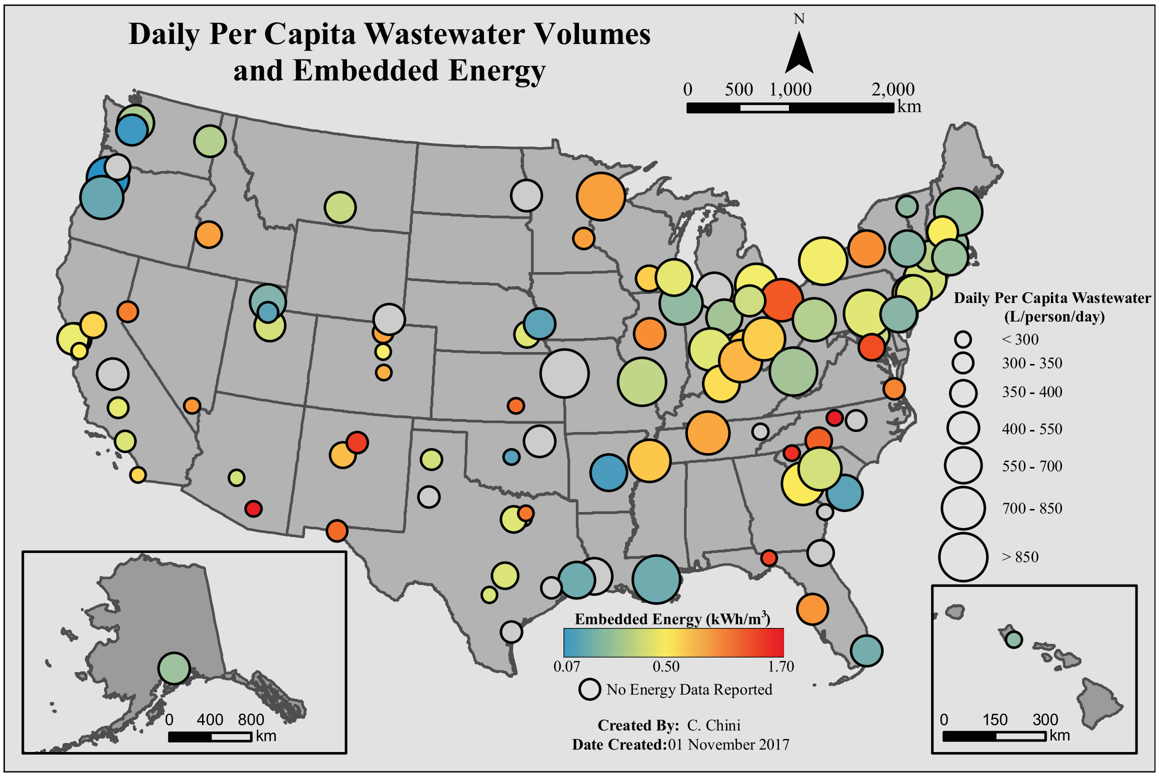

Figure 6. The volume of wastewater discharged varies across the country, but there are some instances of correlation with climate (such as in the southwest). Additionally, the embedded energy in wastewater is lower in the Northeast and Northwest. The size of the circle on the map indicates the per capita water flux and the color of the circle represents its energy intensity. The color scheme ranges from blue to red, with blue indicating a lower embedded energy and red representing a higher embedded energy. A grey circle indicates a utility that responded with water volume but not required energy.

resources of each city. Visually, there are minimal regional correlations associated with drinking water and wastewater fluxes and their embedded energy. Wastewater fluxes (Figure 6) in the northeastern portion of the United States are generally greater than those of the rest of the country, indicating a prevalence of combined sewer systems in a generally older portion of the country.

The AWWA benchmarks water utilities based on four geographical regions (AWWA, 2015). To determine the appropriateness of these geographical regions, we conducted *k*-means clustering analysis on four different sets of data: (i) drinking water and embedded energy, (ii) wastewater and embedded energy, (iii) non-revenue water, and (iv) summer peaking factor. The summer peaking factor is the percent increase of the average summer month (June–August) over the average winter month (December–February). For drinking water, there is minimal regional clustering (optimal group number is 12), aside from the Northeastern United States. Wastewater analysis generally grouped utilities into the eastern and western half of the country, aligning with typical wetter/dryer climate patterns. Grouping based on non-revenue water percentage had an optimum of two groups: the Northeastern United States and rest of the country. However, visually, there is generally lower non-revenue water in the western United States (Figure 7).

Clustering based on summer peaking factor grouped cities into two groups: (i) the eastern states, Texas, and Oklahoma and (ii) the western states. This grouping is visually apparent based on Figure 8. It is interesting, however, that cities in Texas and Oklahoma, with similarly arid climates to neighboring southwestern states, exhibit lower increases in summer water demand. Overall, multiple applications of the *k*-means spatial statistics test based on different values of the energy-water nexus revealed limited regional correlation. Outside spatial correlation, there are no visible trends of cities when comparing water flux and embedded energy to service population (see supporting information Figure S2). Therefore, there is minimal statistical evidence to justify grouping of utilities on a regional geography basis or by utility size with respect to energy and water resource use.

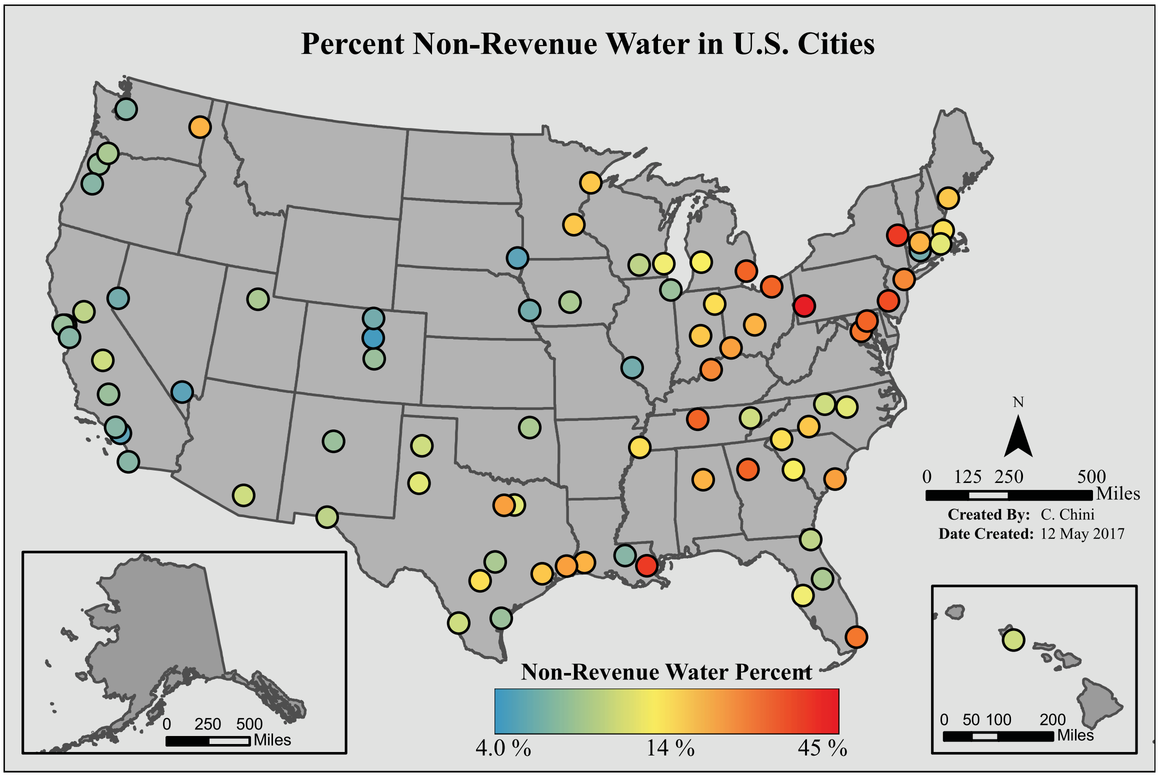

Figure 7. Non-revenue water tends to be lower in cities in the western half of the United States than in cities on the eastern half.

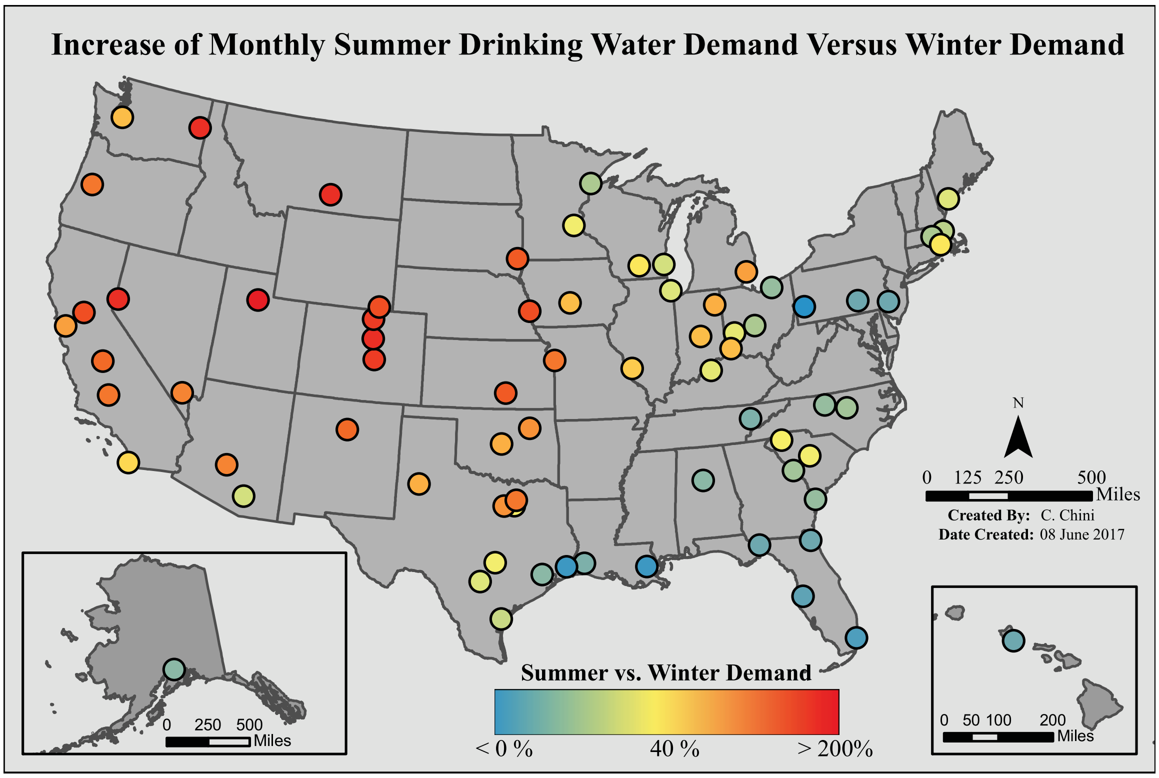

Figure 8. There are larger summer peaking factor in western cities than in eastern cities.

3.3. Intra-annual/Temporal Statistics of the Urban Energy-Water Nexus

We collected monthly volume and energy data from over 50 cities for drinking water and 70 cities for wastewater. This sample size provides opportunities to evaluate monthly changes in treated water volume and embedded energy for both drinking water and wastewater utilities. Figure 9 shows the monthly variations aggregated across the United States for drinking water and wastewater utilities. As one might expect, drinking water demand in the summer months is greater than the monthly average, with the winter months being lower. This heightened demand in the summer is most likely due to outdoor water demand (Mini et al., 2014). The visibility of this difference is interesting at this geographical scale (Figure 8) and to this extent, considering the data do not exclude non-residential consumers and are aggregates of cities across the multiple climates in the United States. The visible demand differences in the data support MFA capabilities to analyze urban water metabolism without large data sets of individual meter readings. Additionally, further supporting the outdoor watering hypothesis, monthly treated wastewater varies minimally across the year (Figure 9). Focusing on a few representative cities, Figure 10 shows four cities with a relatively constant wastewater discharge and large spikes in drinking water demand during the summer months. These four urban environments—Cheyenne, WY, Denver, CO, Salt Lake City, UT, and cities in North Texas—have generally dry climates.

Figure 9 shows relatively minor variation at a national level for average embedded energy of wastewater and drinking water resources. However, there is a very slight difference in drinking water energy as it lowers minimally during the summer months. When focusing on a few individual cities, this difference in embedded energy for drinking water becomes more pronounced (Figure 11). For cities in colder climates such as

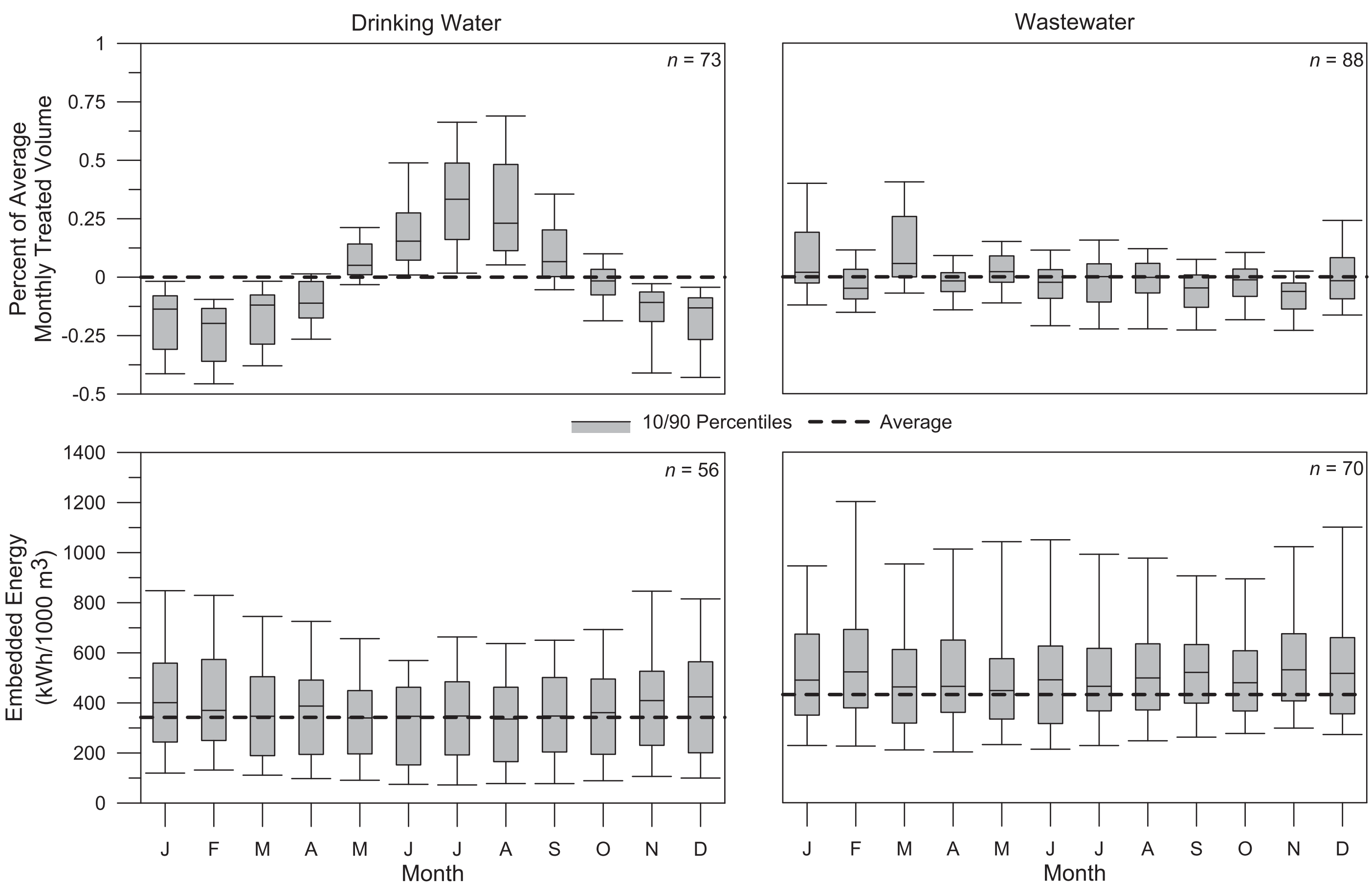

Figure 9. Drinking water volume increases across the country during the summer months, with minimal changes in wastewater volume and drinking water and wastewater embedded energy. Monthly treated water volumes are normalized for each city based on their average monthly flow and plotted based on their percent difference from the mean. Embedded energy, due to its inherent normalization based on total volume, is plotted as a strict average across all cities. The box-and-whisker plots show the monthly mean and the 10th and 90th percentiles.

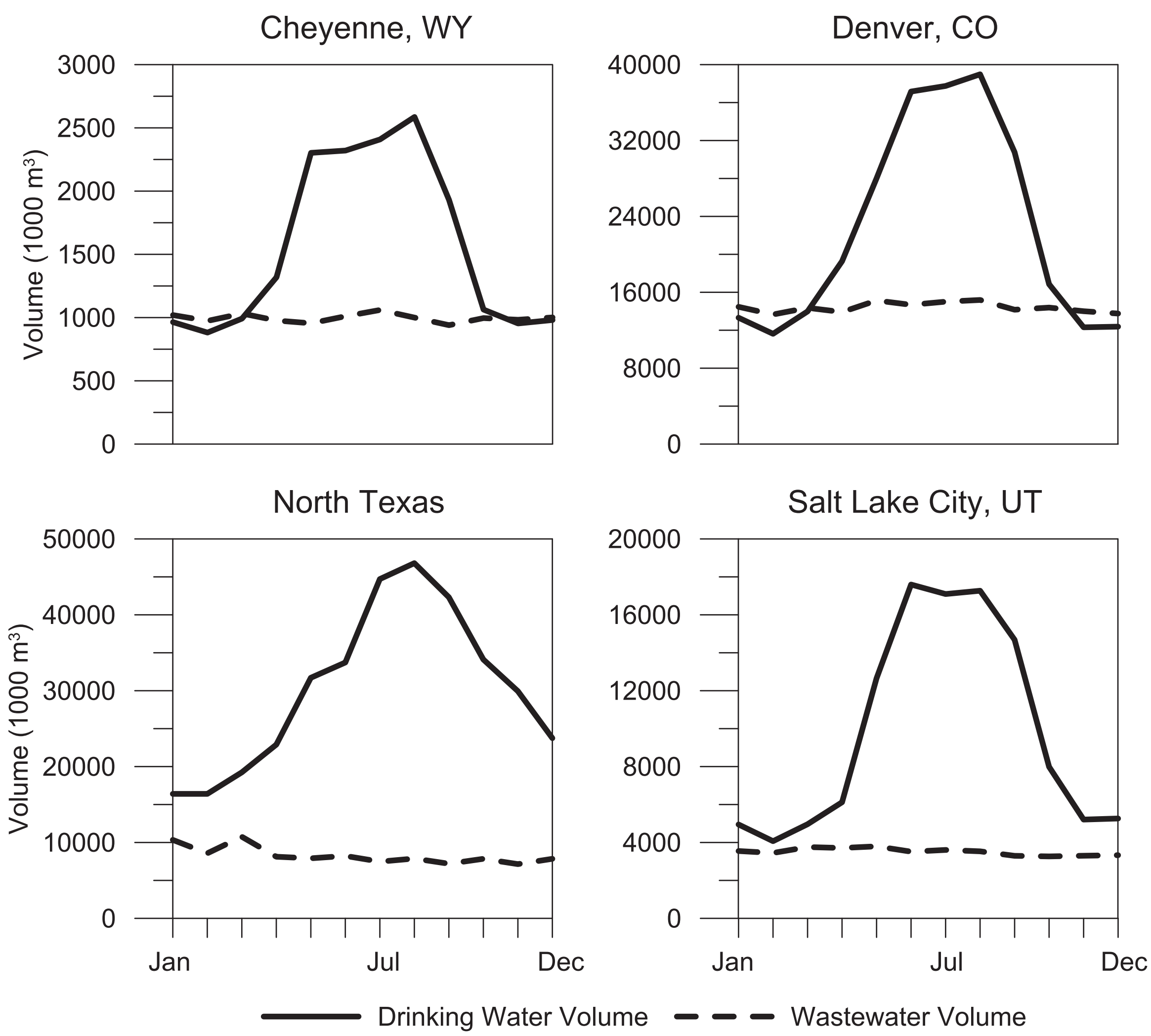

Figure 10. Cities in relatively dry climates exhibit large differences in summer drinking water demand and wastewater discharge. North Texas refers to cities served by North Texas Municipal Water District which services 24 communities that are north and east of Dallas including: Plano, Allen, Rockwall, and Frisco.

Anchorage, AK, Boston, MA, Colorado Springs, CO, and Salt Lake City, UT, there is a pronounced change of embedded energy in drinking water lowering during the summer months, despite increases in demand. This difference is due to generally lower natural gas demands during the summer months, as natural gas is predominantly used for heating drinking water and treatment facilities. For cities in warmer climates, such as Dallas, TX and Oklahoma City, OK, embedded energy increases during the summer months coinciding with an increase in drinking water demand. Therefore, it is important to consider not just secondary energy (electricity) in the treatment of water resources, but to also consider primary energy (natural gas and fuel oil) when developing a database of energy and water for cities.

3.4. Impacts of the Urban Energy-Water Nexus

The latest water use survey by the U.S. Geological Survey estimates that 86% of the population is served by centralized drinking water systems (Maupin et al., 2014). About 74% of the United States is served by centralized wastewater systems (American Society of Civil Engineers, 2011). Acknowledging that there is wide variation in embedded energy within drinking water and wastewater resources, we extrapolate embedded energy to the estimated U.S. population served by public utilities (270 million people), since drinking water from private wells and sewage treatment via septic systems are not accounted for in the data set. Our primary data for drinking water resources represent 81.4 million people (30.6% of the population served by centralized drinking water systems) and account for 16.7 billion m^3 of water (28.9% of total public supply,

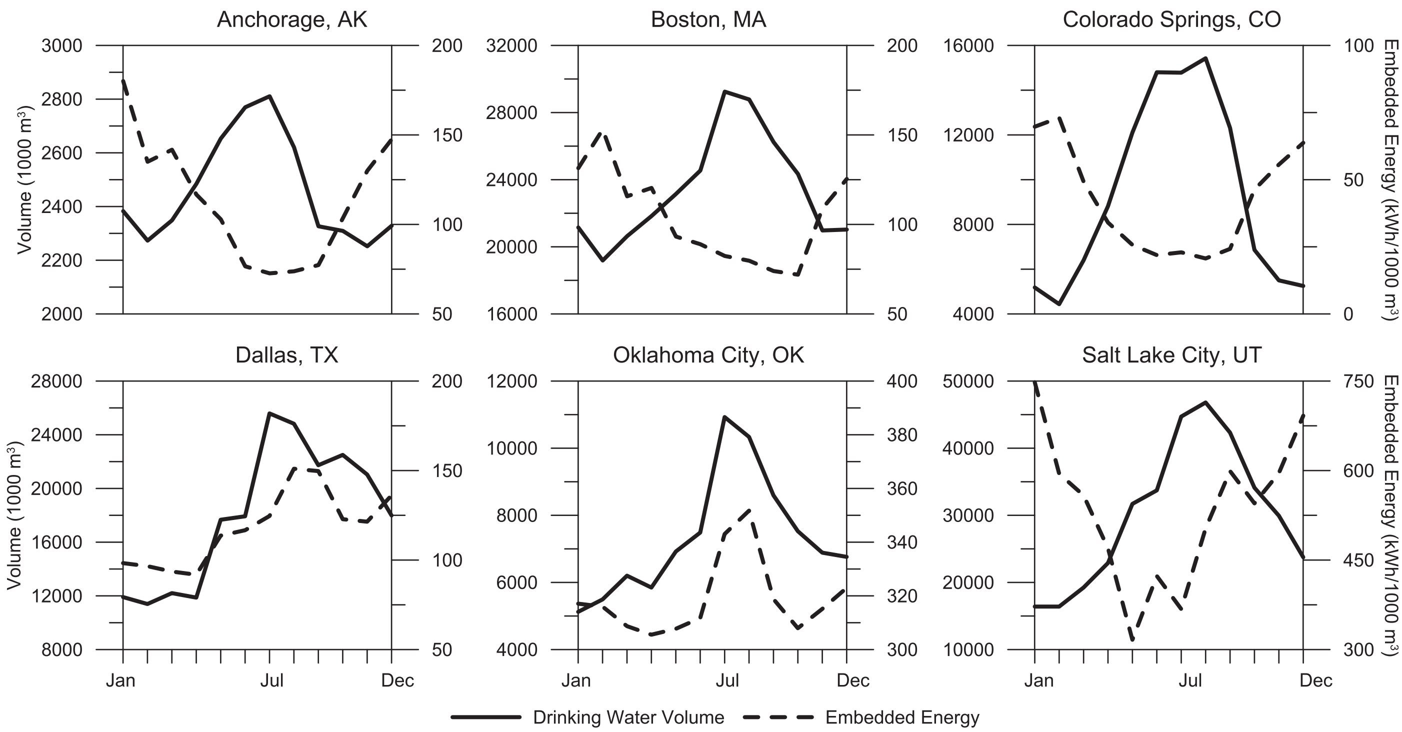

Figure 11. Cities in colder climates that use natural gas as part of their treatment and distribution processes for drinking water have much higher embedded energy in the winter than in the summer. The shapes of these curves show the importance of natural gas in the embedded energy of some cities' drinking water.

2010 estimate) (Maupin et al., 2014; United States Census Bureau (USCB), 2012b). Extrapolating based on both population and volume yields a total electricity consumption of 18,800 GWh and 19,900 GWh/yr, respectively, for urban drinking water supply, treatment, and distribution. Additionally, we received wastewater data for 86.2 million people, 37.0% of the population served by centralized wastewater utilities (USCB, 2012b). Extrapolating based on population yields an estimate of 18,200 GWh/yr of electricity consumption for urban wastewater collection and treatment. Combined (37,000–38,100 GWh/yr), the extrapolated energy consumption for U.S. drinking water and wastewater utilities account for approximately 1.0% of the total 2012 electricity consumption of the United States (United States Energy Information Administration, 2016a). While extrapolating nationally from this sample size of approximately 30% is not ideal, the extrapolation is comparable to previous estimates by Liu et al. (2016) and James et al. (2002), which utilized much smaller sample sizes for their extrapolations. We increase the robustness of national estimates with our large sample of primary data.

Using similar assumptions of extrapolation, there is a significant impact of non-revenue water. Extrapolating to all public water supply using the calculated 15.7% average, we estimate 9.1 billion m^3 of water are lost as non-revenue water in the United States annually. This water loss is equivalent to the water demands of 44.5 million average U.S. urban residents for 1 year. Additionally, using the calculated average embedded energy and non-revenue water, the United States wastes approximately 3,100 GWh/yr through water loss, equivalent to a 360-MW power plant running at full capacity for a year or the annual electricity consumption of nearly 300,000 average U.S. households (United States Energy Information Administration, 2016b). Reducing non-revenue water will have substantial benefits toward increasing sustainability of the urban energy-water nexus.

4. Conclusions and Broader Impacts

With increasing stress on resources, there is a need for improved resource accounting through data to ensure equitable and safe access of necessary resources for both humans and the environment. Previous studies determined that water resource fluxes through the urban environment dominate and comprise approximately 90%, by mass, of all flows (Decker et al., 2000; Kenway et al., 2011b; Wolman, 1965). However, these studies often evaluate one city at a specific point in time. Some studies do evaluate cities temporally, across multiple years (e.g., Kennedy et al., 2007) showing an increasing urban metabolism; however, to our knowledge there are no temporal studies of metabolism within a given year (seasonal analyses). Additionally, there are few studies that combine the energy-water nexus and material flow analysis (Kenway et al., 2011b, 2015; Scott et al., 2016). A monosectoral approach to urban metabolism is insufficient for material and sustainability analyses (Beck et al., 2013). This necessary inclusion of principles from the energy-water nexus provides an additional level of understanding and decision making. We demonstrate the relevance of input/output frameworks such as MFA to evaluate characteristics of cities with respect to their water flux. We analyze the urban energy-water nexus on annual, intra-annual, and spatial scales, providing an important first step in cataloging the trends of U.S. urban water resources and evaluating the effectiveness of urban water conservation and sustainability policies across the country.

Anthropogenic water consumption occupies a central component of the global water system (Vörösmarty et al., 2004; Vörösmarty & Sahagian, 2000), especially considering the large human impact in urban areas. Determining values of anthropogenic urban water flux fills an important knowledge gap associated with the global water system. We particularly emphasize the relationship of urban water flux and its embedded energy, both primary and secondary energy sources. Studies of the energy-water nexus continue to grow in the literature (Hussey & Pittock, 2012; Sanders, 2014). It is necessary to promulgate this trend in data collection efforts at a utility level with open access. These important metrics provide opportunities for academia, utilities, and government to develop and improve the understanding of the urban water cycle. Future studies should include all sources of energy to fully quantify the urban water flux and evaluate the urban energy-water nexus.

Moving forward, there are significant future opportunities for sustainability and resilience studies and initiatives associated with holistic, national analyses of urban water and embedded energy. Expansion of collected data could include on-site electricity generation through biogas turbines, solar panels, or alternative energy sources. Additionally, water quality and water source data would make large contributions to the analysis of urban water and its embedded energy. Water source information could also include water reuse, which is important in creating a circular and sustainable urban economy as opposed to the predominantly linear inputs and waste discharges (Cooper, 1994; Hermanowicz & Asano, 1999). Water reuse and recycling have many implementation challenges, including energy intensity. However, recycled water use for non-potable applications remains relatively low in the United States, even for water stressed cities such as Tuscon, AZ (10% of total water supplied) (Chini & Stillwell, 2018) or San Diego, CA (3% of total water supplied) (Mo et al., 2014).

We provide the first assessment of the state of the U.S. urban energy-water nexus to study changing demands throughout a year. It is necessary to continue collecting these data either as part of academic studies or as a funded, central database (Chini & Stillwell, 2017). The difficulty of acquiring these data necessitate open access data efforts with utilities and either academic, professional, or governmental organizations. To help advance open access efforts in the energy-water nexus, we have published all of our data in an open forum through HydroShare by CUAHSI (Chini & Stillwell, 2018). In the future, periodic updates of the state of the nation's water through an expanded database would allow for continual urban water studies to assess its sustainability. Increases in the collection of these urban water data have significant potential benefits for management of infrastructure and sustainability goals (Eggimann et al., 2017). Gleick (2016) highlights data collection as an important strategy in advancing water policy at the national level. Ideally, trends would develop that show decreasing urban water use over time across the entire country, consistent with urban metabolism definitions of sustainability (Pamminger & Kenway, 2008). We provide the first step in identifying trends toward sustainability in urban water through this study and its accompanying open access data.

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