Although water on Earth is abundant, most of it, in its natural state, is salty, frozen, underground, remote, or otherwise unsuitable for human consumption. In modern water systems that reliably supply high-quality water, these challenges are overcome with energy. The processes of extraction, conveyance, treatment, storage, and distribution transform natural water resources into a usable product. This energy-for-water relationship is one facet of the water–energy nexus, a broad research area that explores the interdependencies of water and energy resources.

Water utilities’ energy footprints carry financial, environmental, and social impacts that suggest sustainability opportunities that typically have not been considered in their planning, design, or operation (Barry 2007). Energy is a significant cost, accounting for up to 40% of a water utility’s operating budget, or even more for small systems; this proportion is expected to increase with scarcer water supplies and stricter water quality standards (USEPA 2017). Environmental impacts include the emissions associated with generating power for water services, which affect local ecosystems and the global climate (Lane et al. 2015, Cooley et al. 2011, Ramos et al. 2010, Griffiths-Sattenspiel & Wilson 2009, Stokes & Horvath 2009). On the social side, stakeholders are demanding more transparency and responsibility from government, businesses, and utilities. Water users and the public expect their water utility to use energy and other resources wisely while fulfilling a social contract to provide a vital public service in a monopolized market (De Asís et al. 2009).

Many have studied the energy requirements of US public water supply from various angles and for various purposes. The US Department of Energy (USDOE 2012) published tables of energy intensities for water services in a few locations, and the Electric Power Research Institute (EPRI 2013, 2009, 2002) investigated typical energy intensities of certain processes in the urban water cycle. Plappally and Lienhard (2012) presented typical energy intensities for public supply, and Siddiqi and Fletcher (2015) focused on the energy consumed during end-use. A statewide study of Illinois water utilities (ISAWWA 2012) captured data from 44 water suppliers to inform energy- and cost-saving actions. Spang and Loge (2013) and Saliba and Gan (2006) highlighted differences in energy intensity at subcity scales as part of targeted water and energy conservation programs. Collectively, these studies show how energy intensities vary at multiple scales and why local observations matter.

Twomey and Webber (2011) estimated the energy use associated with the US public water supply. Using a top-down approach with aggregated energy and water data reported to various national organizations, they calculated that public water supply, end-use water heating, and
water reclamation consume 4.7% of the nation’s primary energy. Sanders and Webber (2012) estimated nationwide water-related energy use, again using aggregated data, and found that all water-related energy uses consume 12.6% of US primary energy. Both studies were the first to quantify such uses and reported that a lack of regional and local data limited the analyses, which require geographic and temporal fidelity to account for the country’s diverse topography and climates. Tidwell et al. (2014) recognized similar limitations when characterizing water-related electric loads in the western United States and resorted to using “broad averages” of energy intensity. Even Klein’s (2005) work, which produced one of the most complete studies to date on energy demands for water services in California, assumed a prototypical energy intensity for water distribution because no better data were available. Means (2004) observed that finer data than national estimates are needed to inform local policies and conservation measures. These studies all recognize that a lack of empirical, local data limits understanding of the water–energy nexus.

Several US government agencies have expressed the need for better data on energy use for public water supply. The US Department of Energy, in attempting to develop a broad water–energy nexus strategy, observed that reliable data are noticeably scarce in this field, being mostly the results of engineering calculations rather than actual observations that previous references illustrate (USDOE 2014). Another survey found that “few nationwide studies have been conducted on the amount of energy used to provide drinking water and wastewater services” (USGAO 2011). The US Geological Survey, which produces national assessments of water use and its impact, stated that “despite the national importance of energy use for water, comprehensive national studies of this topic are lacking” (Healy et al. 2015).

The private sector and national associations have identified similar data gaps. Young (2015) observed that “there are few data sources and reports analyzing the energy required to move and treat water, and the data generally are not publicly available.” The AWWA Research Foundation recommended compiling actual energy intensity observations, noting that such data could help influence policies, promote public awareness, and reduce water and energy demands (Means 2004). The AWWA Research Foundation later conducted a study to develop energy benchmarks for water and wastewater utilities (Carlson & Wallburger 2007). The study summarizes natural gas and electricity intensities for 125 water utilities but does not link individual observations to their location.

An Illinois study conducted by an AWWA local chapter concluded that improved data collection, especially of energy use, is critical to ongoing research in this field (ISAWWA 2012). Other national associations recommend improved data collection and auditing of water utilities as one step to improving the energy efficiency of the water sector (White 2013). Although past studies have been helpful, the industry “could benefit from higher-resolution analysis in this field” (Water in the West 2013).

More generally, others have requested better data resources in the water–energy nexus. Bazilian et al. (2011) called for robust data sets on the use of energy, water, and food, noting that such efforts had been limited. Goldstein et al. (2008) identified data exchange as an important component of approaches to manage both water and energy. A group at Sandia National Laboratories found that water–energy nexus research suffers from a lack of consistent, detailed data and models and that better ways to collect and manage data are needed (Pate et al. 2007). The National Academies (2013) likewise stated that “the lack of data on energy–water linkages remains a key limitation to fully understanding the scope of this issue.”

Despite the importance of energy in the water sector, few data on energy-for-water demands are available. The literature indicates that such data are useful but scarce, limiting the type and accuracy of analyses that can be performed and hindering efforts to sustainably manage both water and energy resources. According to the literature, in the United States and elsewhere, energy intensities for public water supply have not been well characterized, although the research community, government agencies, and other groups have repeatedly acknowledged the need for adequate local, empirical data. The identification of similar research needs and applications by diverse stakeholders testifies to their broad significance.

This study extends previous work to quantify energy requirements for public water supply, contributing a national data set of annual and city-scale observations obtained chiefly through primary data collection.

**METHODS**

**Definitions.** In this article, a “water system” or “water utility” is defined as an entity that delivers potable water to the public. The entity may be publicly owned, as by a municipal government, or privately owned, as by a corporation. Self-supplied agricultural and industrial water uses are excluded from this definition. “Public water supply” means the activity such water systems undertake.

The “energy intensity” of public water supply is a type of energy footprint, a single metric that describes the energy requirement of water services (and therefore the dependence of a water system on the electric grid). It is the energy required to deliver a unit of drinking water to the end-user. Because water utilities consume energy predominantly as electricity (Twomey & Webber 2011), the energy data used in this report are limited to electricity. In Wilkinson’s (2000) words, “Energy intensity is the total amount of energy, on a whole-system basis, required for the use of a given amount of water in a specific location.” Because water delivery requires several operations—extraction, conveyance, treatment, distribution, and so on—the energy
for the entire process is cumulative. The water volume, however, is only that delivered to end-users (i.e., water that is beneficially used). The delivered volume is defined as the total volume consumed at all customer meters or their equivalent. Normalizing by delivered volume accounts for water loss between production and delivery and eliminates all effects of water demand, allowing comparison solely in terms of energy. Thus, for a complete water supply system, the energy intensity is

\[ I_S = \frac{\sum_{i=1}^{n} E_i}{V_D} \]

where \( I_S \) is the total energy intensity of the water system, \( n \) is the number of steps in the water supply process (e.g., extraction, treatment, pumping), \( i \) is the step in question, \( E_i \) is the energy required for the step in question, and \( V_D \) is the volume of water delivered to end-users.

This study accounts for energy expended in the provision of drinking water between the natural water source and the customer meter. It includes the energy associated with any imported water (defined as water procured by wholesale purchase or similar agreement from another water supplier) and extraction, transmission, treatment, and/or distribution by the water utility itself. End-use conditioning (such as water heating) and wastewater processes are excluded from this study, although their contribution to overall water-related energy demand is significant, as described previously.

Sample design. In their research on this subject, Twomey and Webber (2011) observed that “the United States is a difficult country to generalize” because of its size and incredibly diverse topography and climates and that national averages “do not capture the wide disparity between regional water systems.” In this study, the contiguous 48 states were selected as the study area, with sample points chosen on the basis of geographic coverage and water system size.

The sample design began with existing literature, including data for Los Angeles, Calif. (Blanco et al. 2012); New York City, N.Y. (NYDEP 2016, Yonkin et al. 2008); Bloomington, Ind. (ISAWWA 2012); Mishawaka, Ind. (ISAWWA 2012); Valparaiso, Ind. (ISAWWA 2012); and several Wisconsin cities (PSCW 2016). State-level observations for Illinois (ISAWWA 2012), Iowa (USDOE 2012), and Massachusetts (USDOE 2012) were available but were excluded from this study because of the aggregation. Primary data collection then followed. Water systems serving the 50 most populous cities were selected if not already included. At least one water system in each state was then selected if not already included. Finally, additional sites were selected to achieve denser and more consistent geographic coverage. The survey continued until successful responses represented at least 25 states, at least 20 of the 50 largest cities, and a total service population of at least 40 million.

Survey questions. Each water system identified in the sample was contacted via phone, e-mail, or letter and invited to contribute data. The following specific data were requested, similar to the ISAWWA (2012) study, but with the additional request for multiple time steps to produce a panel data set:

- Approximate service population
- General description of water sources, including proportions of surface water, groundwater, and imported water
- Three years of drinking water production data (annual totals)
- Three years of drinking water delivery data (annual totals)
- Three years of drinking water system electricity use data (annual totals in kilowatt-hours)

Survey response. In all, 351 water systems were invited to contribute. One hundred nine successful responses were received, including some obtained from the literature review. A response was considered successful if at least one year of energy and water delivery data were provided or able to be derived and if the per capita water use was within a reasonable range relative to that reported by the US Geological Survey (Maupin et al. 2014). If the respondent indicated imported water, the survey was extended to the supplier. Some respondents elected to remain anonymous, in which case the data were included in the analysis but were deidentified. The respondents represented drinking water services for some 46 million people, or 14% of the US population, in 36 states. The acquisition of primary data surpassed previous studies on the subject.

Statistical tests. Two statistical tests were used in this analysis. The first was a search for a variable transformation that would convert energy intensity into a normally distributed variable for the purposes of fitting a probability distribution. The test compares nine transformations from the ladder of powers (Tukey 1977) and reports the chi-square value of each; the transformation with the lowest chi-square value is the one that most closely matches a normally distributed variable. The second test was a two-sample \( t \)-test to determine whether the means of energy intensities in eastern and western US water systems were the same. Because the variances of the two samples differed, the version of the test with unequal variances (Welch’s \( t \)-test) was selected (Welch 1947).

RESULTS

Figures 1–5 and Table 1 show the results for a cross section of the panel data set, which are data for the most recent year available in the survey. Figure 1 shows the geographic distribution of results. A color scale from green to red indicates the energy intensity, and graduated symbols indicate the volume of water delivered. A histogram of energy intensities is shown in Figure 2. The best fit for the observed data was a log-normal distribution with
FIGURE 1  Geographic distribution of energy intensities for public water supply

FIGURE 2  Histogram of energy intensities for public water supply

- Observed histogram (bin = 250 kW·h/mil gal)
- Log-normal distribution ($\mu = 7.573, \sigma = 0.735$)

- Median = 1,925 kW·h/mil gal
- Average = 2,510 kW·h/mil gal
- Weighted average (by water volume) = 1,809 kW·h/mil gal
- Minimum = 250 kW·h/mil gal
- Maximum = 11,500 kW·h/mil gal
- Standard deviation = 1,971 kW·h/mil gal

$\mu$—mean, $\sigma$—standard deviation
\( \mu = 7.573 \) and \( \sigma = 0.735 \), where \( \mu \) is the mean and \( \sigma \) is the standard deviation, which is also shown in Figure 2. Figure 3 compares results from the eastern and western United States according to the division the US Geological Survey defined in its most recent water-use study and shown in Figure 1 (Maupin et al. 2014). The two-sample \( t \)-test yielded a \( p \)-value of 0.0001, leading to the conclusion that the mean energy intensities in these two regions are fundamentally different. A north–south comparison was performed but was not found to be statistically significant. Figure 4 compares results by primary water source type. Figure 5 shows the relationship of energy intensity to water system size, in which it should be noted that the largest systems are supplied by surface water. Figure 6 shows differences in energy intensity for the same water system for consecutive years.

Table 1 presents summary statistics.

Energy intensity appears to be a function of many variables, some of which are in the utility’s operational control (such as source choices and water loss) and some of which are not (such as topography and climate). Energy intensity does not indicate the efficiency of energy use and therefore should not be used to compare efficiency or performance among water systems unless an appropriate normalization could be provided (Vilanova & Balestieri 2015, Bolognesi et al. 2014, Giacone & Mancò 2012, Carlson & Wallburger 2007). High energy intensity does not necessarily indicate inefficiency; it may simply mean that clean water is not readily available and requires more effort. Conversely, low energy intensity does not necessarily indicate best performance because inefficiencies may still exist. It is, however, appropriate for internal benchmarking. Energy intensity does not describe the method of electricity production, so studies of emissions, carbon footprints, and climate impacts should consider the local fuel mix in addition to the energy intensity.

Two types of uncertainty accompany the results, one of which is associated with the survey responses. Because these are almost impossible to verify, it must be assumed that the respondents’ organizations exercise appropriate quality control in the collection, documentation, and reporting of water and electricity use data. The second type of uncertainty is that associated with the actual electric and hydraulic measurements, and only a general estimate can be provided. Two power companies serving some of the respondents report that electricity meters are accurate within 2%, which is also the ANSI C12.1 standard (ANSI 2016) for acceptable performance. Research by Barfuss et al. (2011) indicates that most water meters are accurate within 5%. Because the data are aggregated from numerous meters in a given system, even a few major inaccuracies at individual meters are not significant in the overall calculation. Applying propagation of errors (Ku 1966) to the energy intensity calculation, the results carry a relative uncertainty of approximately 5%.
DISCUSSION

Variability. The statistics of Figure 2 and Table 1 depict a wide range of energy intensities among the respondents, from 250 to 11,500 kW·h/mil gal, with an average of 1,809 kW·h/mil gal when weighted by water volume. These averages are consistent with previous studies. A US Department of Energy publication (USDOE 2014) indicated that in 2011, 0.1 quads of electricity were expended for 44 bgd of public water supply, which equates to 1,825 kW·h/mil gal—very near the weighted average of 1,809 kW·h/mil gal observed here. Young (2015) reported an average of 2,300 kW·h/mil gal and Twomey and Webber (2011) reported an average of 1,960 kW·h/mil gal, whereas EPRI (2013) cited weighted averages of 1,400–2,000 kW·h/mil gal. Although the maximum observed in this study was 11,500 kW·h/mil gal, the right-skewed histogram of Figure 2 and the fitted log-normal distribution imply that even higher values are possible.

Figure 1 illustrates the geographic variability, confirming what others have observed from more limited data. The east–west comparison of Figure 3 indicates that water systems in the western United States typically require more energy to deliver the same amount of water. These systems exhibit overall higher energy intensities and a wider range of energy intensities than those in the eastern United States. This pattern is at least partially attributable to the topographic and climatic differences between the two regions. Causes of the geographic variability will be the subject of future work.

Classified by source type (Figure 4), systems supplied by surface water show the lowest average energy intensity and the narrowest range. The energy intensity of those with groundwater sources is more variable, depending on the depth to groundwater, among other factors. Imported water is generally the most energy intensive, presumably because of the greater conveyance distance and/or lift.

The energy intensity of a given system may change over time (Figure 6). Mixed interannual increases and decreases were observed throughout the panel data set, but the net change was near zero. The causes of such changes, although not fully investigated here, appear to be highly individual combinations of internal and external factors. In one case, the system experienced acute drought conditions in one particular year, prompting the use of higher-intensity

TABLE 1  Summary statistics of survey

| Variable                          | Units                      | Median | Average | Standard Deviation | Minimum | Maximum | Sum           |
|----------------------------------|----------------------------|--------|---------|-------------------|---------|---------|---------------|
| Approximate service population   | People                     | 68,000 | 422,194 | 1,049,403         | 100     | 8,000,000| 46,019,100   |
| Surface water supply             | Percentage of entity's total supply | 40     | 47      | 47                | 0       | 10      | NA            |
| Groundwater supply               | Percentage of entity's total supply | 33     | 50      | 46                | 0       | 100     | NA            |
| Imported water supply            | Percentage of entity's total supply | 0      | 3       | 15                | 0       | 90      | NA            |
| Other water supply               | Percentage of entity's total supply | 0      | 0       | 2                 | 0       | 15      | NA            |
| Annual energy expended           | Kilowatt-hours             | 6,446,036 | 35,570,060 | 111,374,803 | 12,803 | 1,075,926,791 | 3,877,136,587 |
| Annual water delivery            | Million gallons            | 2,920  | 19,658  | 46,544            | 3       | 367,555 | 2,142,701    |
| Annual energy intensity          | Kilowatt-hours per million gallons | 1,925  | 2,510   | 1,971             | 250     | 11,500  | NA            |

NA—not applicable

FIGURE 6  Histogram of differences in energy intensity for public water supply (same system, consecutive years)
sources. In another case, the system switched from groundwater to imported water. Decreasing energy intensities could result from a climatically wet year in which low-intensity sources abound, or from deliberate efforts to manage energy such as those described by others (Jones et al. 2015, Mundt & Dodenhoff 2015, UDEQ 2015, Yarosz & Ashford 2015, Jones & Sowby 2014, USEPA 2013).

For a lack of data, past studies have had to assume average and/or static energy intensities for public water supply, leading to results that blur important differences. Because energy intensity varies in both time and space as shown here, it is recommended that such variability be considered in future work. For example, rather than assign the same average energy intensity to several water systems, one might use actual observations if available, consider their energy intensities to be randomly drawn from a sample with a log-normal distribution as shown in Figure 2, or apply the constraints described in the following section.

Constraints on energy intensity. Previous studies have produced typical energy intensities for certain processes or coarse state and national averages of a static nature. Given the spatial and temporal variability observed in this study, there is a need to develop mathematical models that can predict energy intensities beyond the observed data set. The properties of known systems may be used to predict the energy intensity of others, or at least to constrain the range of probable values. The many variables that define such relationships will be the subject of further work, although a few key constraints are described here.

One constraint is location (Figure 1). The data set itself offers unprecedented spatial detail and captures many major US cities. If the desired water system does not exist in the data set, energy intensity from a nearby water system in a similar geographic setting, or at least the east–west differences of Figure 3, may be used to inform a better estimate. Once sufficient data have been collected, more refined interpolations and multivariable relationships may emerge. The availability of the data set produced by this study enables others to explore related questions.

Another constraint is a water system’s source type (Figure 4). This is a distinct constraint from location because source type and location are not strongly correlated. Knowledge of the primary water source may further refine an energy intensity estimate, because surface, ground, and imported water vary in intensity.

One key constraint identified in this analysis is a water system’s size (Figure 5). Although there is considerable scatter throughout the data set, an economy of scale can be observed, in which energy intensity generally decreases with system size (expressed as water deliveries, population, or similar metrics). This finding is consistent with studies of water and wastewater treatment processes (USDOE 2012, Twomey & Webber 2011, EPRI 2002).

All of the high-intensity systems are small, and most of the large systems exhibit lower-than-average energy intensities. Energy intensities for smaller systems vary widely, whereas those of larger systems are confined to a narrower range. With one exception (Los Angeles), no large, high-intensity systems were observed. This produces a field of probable values that can be used to estimate, or at least constrain, the energy intensity of an unknown system.

If data for a particular water system are not available, estimation combining the previously mentioned constraints—location, source, and size—offers an alternative to the coarse averages used previously.

Energy data reporting. For almost all respondents, the most difficult step in the survey was providing the requested energy data. Some first indicated that they needed time to search for the energy data. Some responded promptly to the other questions and provided the energy data later. Still others, even after diligent searching, failed to locate their energy data although the other information may have been readily available. ISAWWA (2012) observed similar behavior in its own study, where nearly one-third of respondents who began the survey stopped at the energy portion.

There are several possible explanations. First, the process can be complex. Energy records, if they exist at all, often reside in a department separate from water operations, such as finance. Accessing this information requires interdepartmental communication and a specific query. If a given entity also operates wastewater, irrigation, or non-water facilities, these must be separated from drinking water facilities. Multiple electric uses on a single meter also complicate the process. Electricity is usually billed monthly, and if the records are not already tabulated, annual totals require deliberate calculation, the effort of which increases with the number of facilities.

Second, most water systems are not accustomed to regularly reporting energy use. Unlike water data, few regulatory agencies require such reporting. Requests for such data may be few and infrequent, leading to a custom query each time. Without clear motivation to do so, most water systems have not established mechanisms for regular energy tracking and reporting.

The execution of this study confirmed the claims mentioned in the introduction: that the lack of accessible data may well be the largest obstacle to understanding these water and energy relationships. The Illinois study concluded that “a consistent and comparable data collection methodology is needed across Illinois and nationally to gather and track water and energy data at the utility level” (ISAWWA 2012). The methods used here followed the Illinois study and may inform utility and regulatory policies for reporting. Such practices, when established, will benefit researchers, government agencies, and water utilities by providing a much-needed data stream (Chini & Stillwell 2017). It is therefore
recommended that water utilities begin tracking monthly water and energy observation for each facility, or annual systemwide data at a minimum.

Applications. The potential applications of this panel data set are broad and will improve as it grows. Of particular interest are uses by federal agencies, researchers, local communities, and national security practitioners.

The US Geological Survey, US Environmental Protection Agency, and US Department of Energy periodically study water use, energy use, and the related infrastructure and operations. The methods and results of this study may inform future work by these and other agencies in national assessments on water and energy issues. The data may also be used to plan efficiency and conservation grant programs that consider local potential and electricity prices. The data challenges discussed previously should be considered when forming policies for reporting, data management, and accountability by public water and wastewater utilities.

The research community uses energy intensity to investigate many questions, of which the most common involve the impacts of urban growth or climate variability on water and energy systems. In such studies, researchers use energy intensity in a system dynamics model, spreadsheet, or other tool, often as a single static input. The greater spatial and temporal detail of energy intensity offered here could improve the accuracy of study results and the validity of the insight they produce. Of emerging importance is the need to investigate the water–energy interconnections associated with smart networks in which relationships between water and energy need to be defined with greater spatial and temporal resolution.

Water system planning for local communities should carefully consider energy requirements to improve sustainability. This data set can help water system personnel develop energy awareness, evaluate their energy footprints relative to similar systems, and identify best practices from systems that have successfully decreased their energy intensity. When combined with local electricity rates, energy intensity translates into energy costs for water provision similar to the work by Tidwell et al. (2014) and can inform planning decisions and cost-saving strategies. Detailed analysis of individual systems could lead to offset recommendations for net-zero energy. The discussion also suggests consistent energy reporting practices to facilitate benchmarking, tracking, and improvement of energy performance. In the absence of their own observational data, water utilities may apply the three practices to facilitate benchmarking, tracking, and improvement of energy performance. In the absence of their own observational data, water utilities may apply the three constraints described previously (location, source type, and size) to estimate a probable range of energy intensities based on system characteristics.

This study confirms that US public water supply relies heavily on the electric grid. This near-total dependence carries implications for national security: even a localized grid failure, whether accidental or intentional, can cause cascading failures in water services, public health, and the economy, effectively amplifying the impact of the initial failure (Ouyang 2014, Chen et al. 2009). The energy intensities presented here indicate the water system’s degree of dependence on the grid and may be used in vulnerability assessments, critical infrastructure models, and other national security applications.

Limitations and further work. Although it represents a significant improvement over previously available information, the data set presented here seems to raise more questions than it answers. This study’s empirical approach differs from others on the subject, which have relied on estimates and engineering calculations to describe energy demands in the water sector. The data set presented here is limited by its geographic coverage, the length of the historical records, and the coarseness of annual- and city-scale observations.

Further work may add other data points of the same resolution, extend the records of existing locations, refine the spatial scale to subcity detail, or refine the temporal scale to seasonal or monthly intervals. An appropriate normalization is also needed that considers both internal and external factors to enable fair comparison of energy intensity among water systems. Above all, this research area could benefit from consistently reported and easily accessible energy data as described previously.

This data set will enable further scientific analyses of the water–energy nexus and related areas. Specifically, further work should analyze the geographic drivers of energy intensity, be they climate, topography, or other external factors, as well as internal factors such as equipment, infrastructure, policies, and operational choices. Separate from the geographic drivers, the lengthier historic data sets compiled in this study may illuminate the causes of interannual variation of energy intensities at the same location. Ultimately, a model may be developed to estimate energy intensities as a function of a few key parameters.

SUMMARY AND CONCLUSIONS

This study compiled observational data on the energy requirements of public water supply in the United States, relying heavily on new data collected from numerous water systems. The resulting data set helps bridge a longstanding data gap in the water–energy nexus, contributing considerable spatial and temporal resolution to the body of knowledge. The results show how the energy intensity of public water supply varies in time and space.

The observations of energy intensity appear to be log-normally distributed. Western US water systems are generally more energy intensive and display a wider range of energy intensities than eastern US systems. Energy intensity was observed to change over time, with mixed increases and decreases presumed to be the result of both internal and external factors specific to each system. The spatial and temporal variability observed here should be considered in future work by others.
Three constraints were identified to help estimate the energy intensity of unknown water systems: location, water source type, and size. East–west differences are significant, as are local variations. Systems supplied by surface water have lower energy intensities and a narrower range of energy intensities than those supplied by groundwater and imported water. A size relationship was observed in which energy intensity tends to decrease with the size of the water system. A combination of the three constraints improves the estimation of unknown energy intensities over the broad averages previously available.

The survey indicated that many water systems struggled to produce energy data, even if all other data were readily available. This finding is consistent with that of similar surveys and prompts more consistent reporting practices. Collection of monthly, or at least annual, water and energy observations for each water facility is recommended to facilitate further work.

The data and conclusions produced during this study can apply broadly to several stakeholders. Several applications were suggested for government agencies, researchers, local communities, and national security practitioners.

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