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A High-Resolution Approach to Mapping Energy Flows through Water Infrastructure Systems

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Summary

Using data from the water service area of the East Bay Municipal Utility District in Northern California, we develop and discuss a method for assessing, at a high resolution, the energy intensity of water treated and delivered to customers of a major metropolitan water district. This method extends previous efforts by integrating hourly data from supervisory control and data acquisition systems with calculations based on the actual structure of the engineered infrastructure to produce a detailed understanding of energy use in space and time within the territory of a large-scale urban water provider. We found significant variations in the energy intensity of delivered potable water resulting from seasonal and topographic effects. This method enhances our understanding of the energy inputs for potable water systems and can be applied to the entire delivery and postuse water life cycle. A nuanced understanding of water's energy intensity in an urban setting enables more intelligent, targeted efforts to jointly conserve water and energy resources that take seasonal, distance, and elevation effects into account.

Introduction

The water sector is an emerging target for energy efficiency (EE) efforts in the state of California. Whereas EE programs have focused on the water sector for many years, most focused on increasing the EE of component technologies, for example, more-efficient pumps, treatment technologies, and lighting fixtures for facilities (US EPA 2013; Liu et al. 2012). Though these programs retain their relevance, there is great potential in expanding the boundaries of EE intervention to include energy savings derived directly from water conservation itself (Elkind 2011).

Water system EE efforts require clear, defensible calculations of the energy embedded in the subject water system. Improved confidence in these calculations is necessary to advance the quality of design and ease of deployment of projects intended to save energy through targeted water conservation. Programs designed to yield "embedded" energy savings must account for energy inputs at all stages of the water life cycle: source extraction; potable treatment; distribution; end use; collection; and wastewater treatment (CPUC 2010a, CPUC 2010b). Implied in this life-cycle–based perspective is the concept that conservation anywhere in the water cycle can be associated with energy conservation both up- and downstream. This approach, however, adds a layer of complexity to EE programs because it requires a systems-based understanding of the water infrastructure, as opposed to focusing on discrete, easily accountable component technologies deployed within the system.

This study contributes to an existing, international body of literature on calculating energy use for urban water systems. In a study of Sydney, Australia, energy use was one of a suite of environmental indicators measured as part of an intensive life cycle assessment (LCA) of the integrated water and wastewater systems for the city (Lundie et al. 2004). Energy use has been similarly highlighted as a critical resource flow (and

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key metric for sustainability) in a number of additional LCA analyses of urban water and wastewater infrastructure systems, including Toronto (Sahely and Kennedy 2007), Alexandria (Mahgoub et al. 2010), and Oslo (Venkatesh and Brattebø 2011). Additional studies have expanded the LCA boundaries to incorporate energy-related air pollution and greenhouse gas (GHG) emission impacts from building and operating water infrastructure (Stokes and Horvath 2009; Herstein et al. 2011; Hendrickson and Horvath 2014). In fact, in a detailed review of the urban water-energy literature, the topic of energy use by water/wastewater infrastructure was categorized as "generally well studied" (Kenway et al. 2011, 1985).

However, though all of these studies provide an understanding of the overall energy and related environmental impacts for a given urban water provider, they all stop short of linking these impacts to site-specific water use within a water service territory. This study makes a unique contribution to the field by showing that energy use (and, subsequently, related air pollution and GHG emissions) can vary greatly across the geography and seasonal operations of a water system. Hence, understanding when and where water is being used is essential for understanding the energy impacts of water consumption or, conversely, for estimating the linked energy benefits of conserving water. The present analysis combines infrastructure design data with highly granular asset data, including hourly data from pumps and other infrastructure components embedded within the subject water utility. By doing so, this approach represents a novel methodology for estimating the energy and energy-related environmental impacts of water consumption (or conservation) at the scale of the district pressure zone and thus at the point of provision to individual water consumers.

Water's Energy Intensity

In 2005, the California Energy Commission estimated that 19% of all electricity and 32% of state-wide natural gas consumption (not including gas consumed at power plants) was used to extract, move, treat, heat, and post-treat water (Klein et al. 2005). Additional studies by the California Public Utilities Commission (CPUC) refined these estimates in 2010. The first study (CPUC 2010a) focused on calculating the energy intensity (EI) of major water transfer operations in the state, including the State Water Project, the Central Valley Project, and the Colorado Aqueduct. Owing to the scale of these projects, roughly 7.7% of state-wide electricity was estimated to be used exclusively by water infrastructure (this does not include end-use energy consumption for heating, additional treatment, and so on). This is significantly higher than the nation-wide average energy consumption for water service provision, estimated to be 1.6% of total energy consumption (Sanders and Webber 2012).

The second study (CPUC 2010b) estimated the EI of 26 individual water and wastewater providers in California. Although this study provided some very informative results about the range of EI values for various water system technologies within and between water agencies, it did not provide detailed information about what was driving the variation in the values within the broad ranges provided. We designed this study to provide a more detailed characterization of EI variance within a water utility, specifically focusing on temporal and spatial variability within the East Bay Municipal Utility District (EBMUD) service area. EBMUD provided a particularly interesting case study given its scale of operations and service area topography.

Study Area

The EBMUD water service area includes 1.3 million customers and extends across Alameda and Contra Costa counties, including the notable urban areas of Berkeley and Oakland (see figure S1 in the supporting information available on the Journal's website). Almost all of EBMUD's source water comes from the Mokelumne River watershed. Water is stored in the Pardee Reservoir before traveling 90 miles through the Mokelumne aqueducts to the EBMUD service area. The aqueduct consists of three surface and subsurface steel pipelines 61, 67, and 87 inches in diameter. EBMUD has a number of local water reservoirs within their service area for temporary storage, as well as six water treatment plants and one wastewater treatment plant. During the study period, EBMUD provided an average of 190 million gallons (MG) per day of potable water to its customers.

Topography provides EBMUD with ample operational challenges. Its service area is bifurcated by the Berkeley Hills, a range of steep hills that, in many places, exceeds 1,000 feet of elevation and descends to sea level at San Francisco Bay. The EBMUD service area consists of several sequential pump-station chains, or "cascades," many of which are interconnected and comprise several pressure zones. Owing to resource limitations, we could not study all of EBMUD's more than 130 pressure zones, so we selected two major cascades, the Almond and Apollo cascades, with a total of ten pressure zones (six and four zones, respectively), for high-resolution analysis. We selected these two cascades because they were large, showed high elevation variability, and because of their location. Whereas the Almond cascade is sited on the western slope of the Berkeley Hills, the Apollo cascade serves communities on the east side of the hills. Together, these two cascades provide 23.6% of EBMUD water deliveries by volume.

Though our methods can and do accommodate wastewater energy inputs, calculating the EI of the wastewater systems in the region was beyond the scope of this study. Whereas EBMUD provides wastewater services to a subset of its water customers, the utility's freshwater service areas and wastewater treatment service areas are noncoextensive. Thus, a detailed assessment of wastewater EI equivalent to our potable water EI evaluation would have required collection and integration of high-resolution data from multiple additional entities. Whereas modest assumptions concerning the ratios of freshwater delivered to wastewater volumes recovered and treated can yield meaningful results, we choose here to present a "clean" analysis of the EI of delivered potable water only. A comprehensive analysis of wastewater EI is both feasible and desirable, when all participating utilities are able to provide needed data.

Comparable Research

The method discussed in this study is not the only one for calculating the EI of water systems. Numerous studies have succeeded in estimating annual EI averages (or ranges) for water agencies as well as for many specific water infrastructure technologies. This study builds on these previous studies by increasing the data volume and analytical resolution of the energy intensity assessment of a water utility in both space and time.

As with other studies of energy consumption, the studies that have focused on the California context have generally relied on annual water provision and energy-use data for the inventory of all technologies deployed across the water system (Cohen et al. 2004; Klein et al. 2005; CPUC 2010a). Even in those cases where the researchers had access to higher-resolution data, they often aggregated to the annual level (either as a point estimate or a simple range) and/or across large regional geographies (Wilkinson 2000, CPUC 2010b). In contrast, the present study uses highly granular data to illuminate the temporal and spatial patterns of EI estimations in high resolution. Further, we transcend the simple inventory approach of cataloging water technologies by gathering operational data directly from the supervisory control and data acquisition (SCADA) systems deployed throughout EBMUD's potable water infrastructure. Operational data provide both a more accurate picture of the actual use of technologies in the system and provide the data stream necessary to monitor and verify water and energy savings over time. It also exposes subtleties in operation that may be missed by coarser analytic approaches.

Methods

The EI assessment involved calculating EI using both a "top-down" and "bottom-up" approach. The top-down approach was designed to produce high-level estimates of monthly EI across the entire EBMUD potable water service territory. The bottom-up methodology was developed to calculate detailed EI estimates for a subset of ten specific pressure zones within the broader EBMUD service area.

Water and Energy Source Data

EBMUD provided us water and energy data at the two scales required for top-down and bottom-up calculations. For the system-wide analysis of monthly energy intensity, they gave us 5 years (June 2006–May 2011) of total monthly water volume delivered (millions of gallons [MG]) and electricity consumption (kilowatt-hours; kWh) by water supply technology category, including raw water pumping, water treatment plants, and distribution pumps. For the high-resolution pressure zone study, we collected 5 years of hourly SCADA data representative of all the technology components (treatment and pumping) required to deliver water to ten representative pressure zones in the EBMUD territory.

The EBMUD hourly SCADA data for pump operations (both raw water and distribution pumps) included flow data (MG) and electricity consumption (kWh). The flow data were measured directly by flow meters connected to the SCADA system. The electricity consumption values were not measured amounts, but rather calculated estimates derived from the duration of operation (as a binary, i.e., either on or off) and the manufacturer-specified pump horsepower and efficiency. This calculation was already embedded in the existing SCADA database at EBMUD, so these estimates were not calculated by the authors, but rather directly downloaded from EBMUD and applied for use in this study. For the water treatment plants, the hourly flow data were collected directly from SCADA-linked flow meters, and hourly electricity data were collected directly from meter data provided by the regional electricity provider, Pacific Gas and Electric. All these data were stored as comma-separated values on local hard drives, and the data were consolidated, formatted, integrated, and analyzed using the open-source R computing environment.

Monthly System-wide Energy Intensity

To determine system-wide EI (expressed as kilowatt-hours per million gallons [kWh/MG]) on a monthly basis, we initially summed the electricity consumption for raw water pumping, water treatment, and distribution pumping and divided this energy total by the total water provided to all EBMUD customers for each month of the study period. (1) below summarizes this calculation, for every month (i) in which both water and energy data were obtained:

$$\begin{aligned} \mathrm{EI_i[kWh/MG]} = {} & [(\text{Raw Water Pumping}_i + \text{Water Treatment}_i \\ & + \text{Distribution Pumping}_i\ [\mathrm{kWh}])/ \\ & (\text{Total Water Delivery}_i\ [\mathrm{MG}])] \end{aligned} \tag{1}$$

However, in reviewing the data, we noticed a strong seasonal pattern in the raw water pumping, whereby pumps were used to fill local reservoirs in the winter months to exploit cheaper electricity rates. Water consumed in the summer, however, is no less energy intensive (in terms of raw water pumping energy inputs); rather, the energy is "embedded" into the water during the winter season for summer use. Hence, we chose to aggregate raw water pumping monthly data to the annual level to accommodate the time lags between raw water pumping, storage, and eventual use that can span months and seasons. Water treatment and distribution pumping cycle within much shorter operational durations, and as such, could remain as monthly data. Equation (2) shows the adjusted the EI equation for every month (i) and year (j):

$$\begin{aligned} \mathrm{EI_{i,j}\ [kWh/MG]} = {} & (\text{Raw Water Pumping}_j\ [\mathrm{kWh}]/ \\ & \text{Total Water Delivery}_j\ [\mathrm{MG}]) \\ & + [(\text{Water Treatment}_{i,j} \\ & + \text{Distribution Pumping}_{i,j}\ [\mathrm{kWh}])/ \\ & (\text{Total Water Delivery}_{i,j}\ [\mathrm{MG}])] \end{aligned} \tag{2}$$

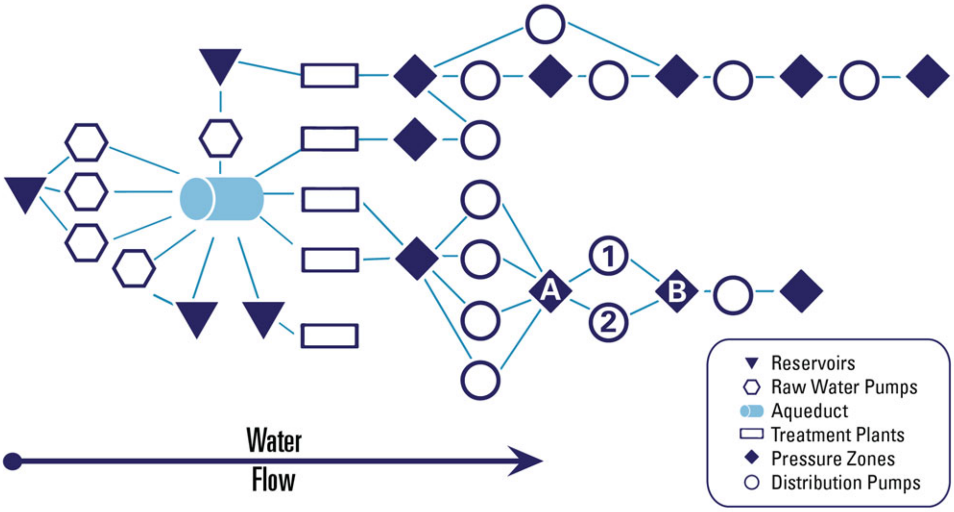

Figure 1 Abstracted schematic of a section of the EBMUD water distribution system. Triangles represent reservoirs, circles represent pumps, rectangles represent water treatment plants, and diamonds represent pressure zones. EBMUD = East Bay Municipal Utility District.

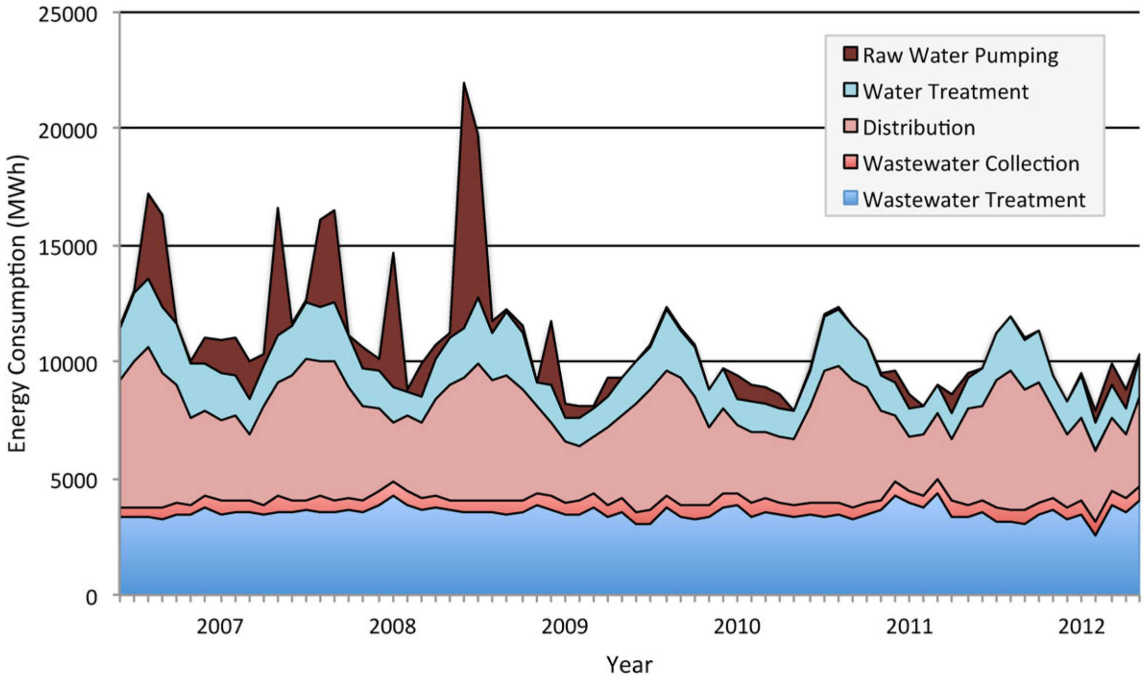

Figure 2 EBMUD energy consumption for potable water delivery by energy consumption category, June 2006–May 2012. EBMUD = East Bay Municipal Utility District; MWh = megawatt-hours.

Energy Intensity Estimates for Pressure Zone Cascades

The higher-resolution, bottom-up analysis seeks to spatially disaggregate the monthly EI estimates by focusing in on ten subject pressure zones using hourly data. Pressure zones represent subsets of the broader service area and are delineated by a shared direct water input (generally a water pump or a direct gravity feed from a water source or treatment plant), much like branches spreading from a tree trunk. We selected ten pressure zones across the service area differentiated by key characteristics, most notably elevation, but also in the number and types of customers in each pressure zone. Elevation is especially important because it requires more energy to pump water farther uphill, so water in pressure zones at higher elevations has a significantly higher EI value than at lower elevations.

Figure 1 provides an abstracted schematic of the EBMUD pressure zone study area. As shown in the network schematic, the EBMUD pressure zones are not independent of one another, but rest along an interconnected network. As water travels from the source through the raw water pumps, treatment plants, and successive distribution pumps, EI steadily increases.

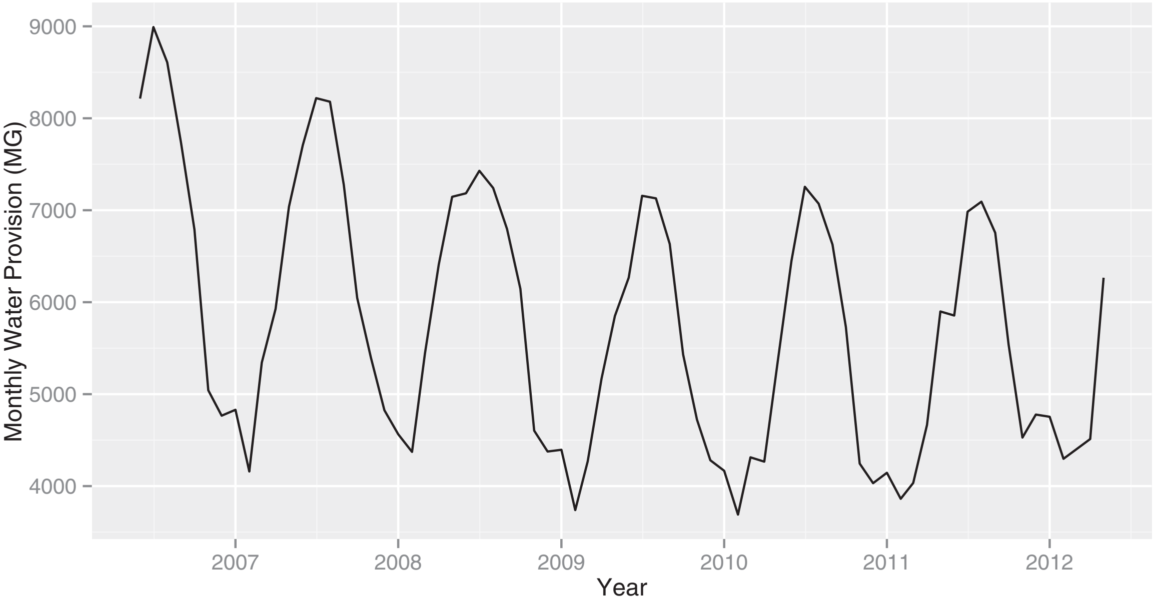

Figure 3 EBMUD monthly water provision, June 2006–May 2012. EBMUD = East Bay Municipal Utility District; MG = million gallons.

Hence, to calculate the EI of any particular pressure zone, one must add the flow-weighted EI inputs that precede the pressure zone.

Where water travels through a single chain, these calculations require a straightforward sum of previous energy intensities. However, in a more networked system, energy intensities must be weighted by the volume delivered by each component. For example, to calculate the EI for pressure zone B (PZ_B), served by the two distribution pumping (DP_1 and DP_2) plants delivering water from pressure zone A (PZ_A) as shown in figure 1, the following equation was applied (equation 3):

$$\begin{aligned} PZ_B\,EI = {} & PZ_A\,EI + DP_1\,EI * [DP_1\,Flow/(DP_1\,Flow + DP_2\,Flow)] \\ & + DP_2\,EI * [DP_2\,Flow/(DP_1\,Flow + DP_2\,Flow)] \qquad (3) \end{aligned}$$

Results

We analyzed EBMUD energy consumption categorically and EI temporally and geographically. Previous studies (EPRI 2000; CPUC 2010b) provided useful benchmarks against which we could validate some of our results.

Energy Consumption by Category

As figure 2 shows, overall EBMUD energy use by category indicates that distribution pumping was the largest energy consumer on average, followed by water treatment and raw water pumping. However, raw water pumping showed the greatest energy variability in terms of monthly consumption. From discussion with EBMUD staff, we learned that the Walnut Creek aqueduct occasionally requires the use of booster pumps to propel water from the reservoirs when gravity pressure is insufficient (Beyer 2013). This usually occurs in the summer months when system-wide demand exceeds the reservoirs' hydraulic head. EBMUD staff also advised that the pumps are occasionally turned on for testing purposes. However, as stated previously, we chose to use the annual averages of raw water pumping in our calculation of EI to address the seasonal time lag between pumping to reservoirs and end use, so these spikes in energy use for raw water pumping were distributed more evenly throughout the year.

Further, there is a clear seasonality in the monthly data, with peak total energy consumption occurring during the mid-summer months and lowest energy consumption occurring in mid-winter. This ~±33% deviation from the annual mean lines up with the total volume of water provided in the region, which also shows a summer time peak and winter low (figure 3).

System-wide Energy Intensity Over Time

To provide an EI overview, we used the 5-year, system-wide monthly data set of total EBMUD water provision and total energy use by technology. Figure 4 provides a direct comparison of the monthly EI values for the three main energy consumption categories across the EBMUD water system: raw water pumping; water treatment plant; and distribution. To understand the variability of embedded energy use by water process category, we box-plotted the energy-use categories. Based on this analysis, the water distribution system demonstrates the greatest average energy intensity. Whereas raw water pumping has the lowest median value of all the categories, it demonstrates some high individual values (characterized as outliers in figure 4). These high values are from intermittent use of high-powered pumps to manage system hydraulics during periods of maximum demand, as discussed previously. The results in figure 4 also align closely with a previous study of EBMUD (CPUC 2010b) that estimated EI ranges for raw water pumping

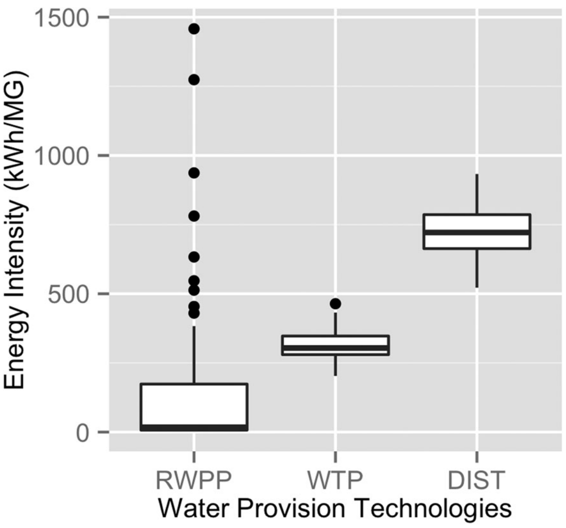

Figure 4 Energy intensity estimates (kWh/MG) by EBMUD water process category: raw water pumping plants (RWPP); water treatment plants (WTP); and distribution pumping stations (DIST). Box plot shows the median value (thick black line), first and third quartiles (box), range (whiskers), and estimated outliers (points). kWh/MG = kilowatt-hours per million gallons; EBMUD = East Bay Municipal Utility District.

Table 1 EBMUD monthly water provision, energy use, and energy intensity statistical summary

Data category	*Units*	*Minimum*	*Median*	*Mean*	*Maximum*
Total water delivery	MG/Mo.	3,690	5,492	5,742	8,992
Total energy use	MWh/Mo.	3,525	5,666	5,977	9,829
Energy intensity	kWh/MG	814	1,205	1,197	1,539

Note: EBMUD = East Bay Municipal Utility District; MG/Mo. = million gallons per month; MWh/Mo. = million watt hours per month; kWh/MG = kilowatt-hours per million gallons.

(10 to 597 kWh/MG), water treatment (135 to 310 kWh/MG), and distribution pumping (319 to 699 kWh/MG).

By summing the EI data for each energy category, we were able to calculate the monthly EI for the entire EBMUD potable water system from June 2006 to June 2011. Mean annual energy intensity estimates for the entire EBMUD potable water system ranged from 1,075 to 1,349 kWh/MG (with an estimated mean value of 1,197 kWh/MG)—lower than, but relatively close to, a benchmark value for surface water supply systems (1,406 kWh/MG) provided in an early report on this topic by EPRI (2000). Summary statistics for water provision, energy use, and calculated EI values are given at the monthly scale in table 1. The complete set of monthly, seasonal, and annual EI calculations and the associated summary statistics are provided in table S1 in the supporting information on the Web.

To further explore the monthly/seasonal trends in fluctuating EI values, we overlaid the monthly EI estimates for each of the 5 years to make direct year-to-year comparisons of EI estimates (figure 5). Six years of actual monthly EI values are overlaid across the same 1-year timespan, while the thick black line shows the average monthly values across all 6 years (the gray shaded area represents the standard deviation). Figure 5 clearly highlights an October peak and May low for system-wide EI values.

The month-to-month variability in energy intensity (approximately ±12% around the annual average) suggests that an annual estimate offers insufficient resolution to capture effectively the variability in EI. In other words, the aggregated annual estimate shows a wide variance because it does not account for the real monthly/seasonal fluctuations in the EBMUD EI. This result implies that EE programs designed around annual EI values are likely to under- or overestimate potential energy savings generated through water conservation programs that demonstrate any seasonal variation in water savings.

The Spatial Distribution of Energy Intensity

A spatial analysis enables disaggregation of EI estimates by distribution pressure zone. EBMUD is an illustrative case study, given that nearly all its water comes from a single source, specifically the Pardee Reservoir through the Mokelumne aqueducts. The selected pressure zones, however, do differ in terms of raw water pumping pathways (two distinct pathways), water treatment (four different water treatment plants), and elevation (ranging from 50 to 900 feet above sea level). Although we examined the aggregate data for these energy categories in the monthly analysis, this section addresses the EI for each component in our network study calculated from 3 to 5 years of hourly energy and flow data extracted from EBMUD's SCADA archives.

The network structure of the pressure zones requires calculating the accumulating EI as water passes through cascading pump systems, as described by equation (1). Applying this approach systematically from source to use across the Almond and Apollo cascades generates EI estimates for the ten different pressure zones examined for this study. The total pressure zone EI estimates (not incremental—the EI values are cumulative from preceding pressure zones) are provided in figure 6.

The results show a clear pattern of increasing EI as water moves from pressure zone to pressure zone through a chain of pumps, where EI increases by roughly 1,000 kWh/MG for every 200 feet of elevation. The range of EI values between zones in the EBMUD system is quite pronounced, from roughly 400 to 5,000 kWh/MG. In other words, the EI in the highest elevation zones can be more than twelve times greater than in lower-lying service zones.

Using the R platform, the mean EI values for the pilot pressure zones were joined to the attribute table of a geographical information systems (GIS) shapefile of the EBMUD service area to generate the map of the EI values shown in figure 7 (the gray area represents EBMUD territories not analyzed as part of our spatial assessment). The map clearly shows how the EI of the water increases as it moves through the system from the

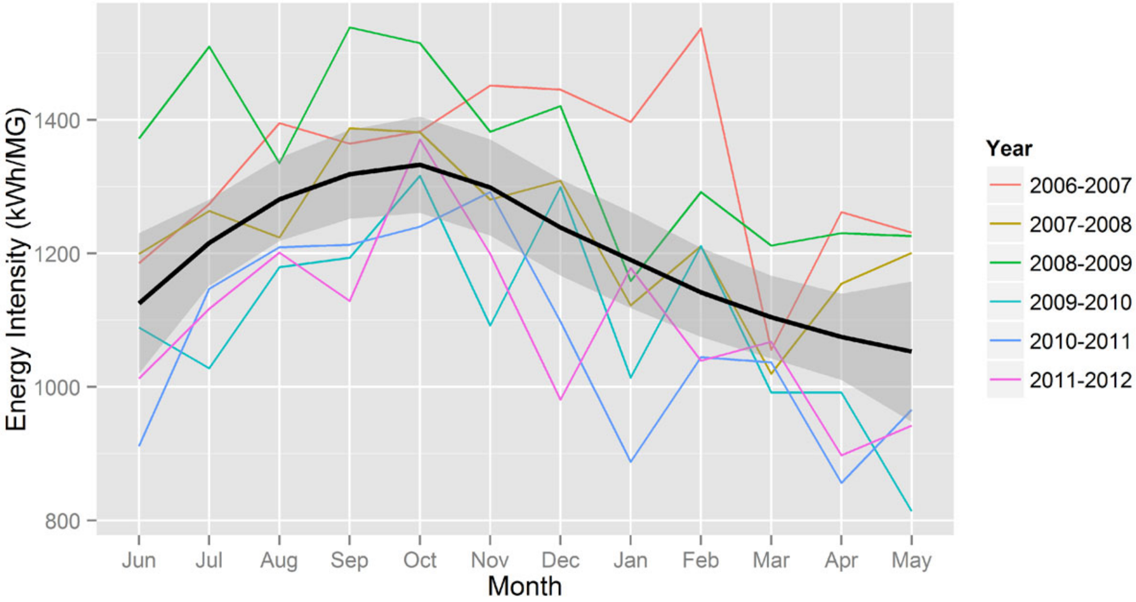

Figure 5 Year-to-year comparison of energy intensity (EI) estimates for EBMUD Water Provision. The colored lines show the actual monthly EI values for each of the 1-year timespans, while the black line shows the average monthly values across all 6 years (the gray shaded area represents the standard deviation). EBMUD = East Bay Municipal Utility District; kWh/MG = kilowatt-hours per million gallons.

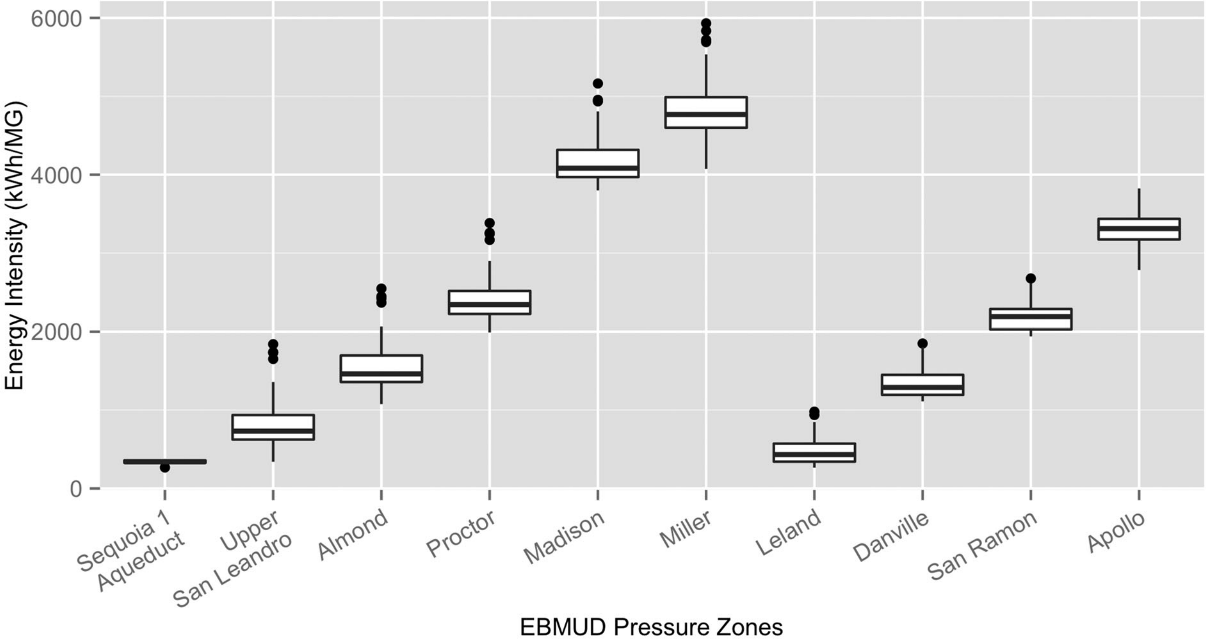

Figure 6 Box plots of energy intensity estimates for EBMUD pressure zones organized by pumping cascade (Almond and Apollo). kWh/MG = kilowatt-hours per million gallons; EBMUD = East Bay Municipal Utility District.

northwest entry point to its customers in the southeast (and uphill).

Discussion

The analysis of EBMUD over the study period shows that system-wide monthly EI varied ±13% around the annual average and that high-elevation pressure zones had EI values more than twelve times higher than low-elevation pressure zones. Given this scale of variability, a high-resolution assessment of EI values should be the fundamental starting point in an effort to design programs for saving energy through water conservation. For example, the energy impacts of programs that deliver seasonal water savings (e.g., summer irrigation) will be more accurately estimated using monthly EI estimates, as opposed to a generalized annual estimate. Further, campaigns to effect water conservation through specific infrastructure upgrade or

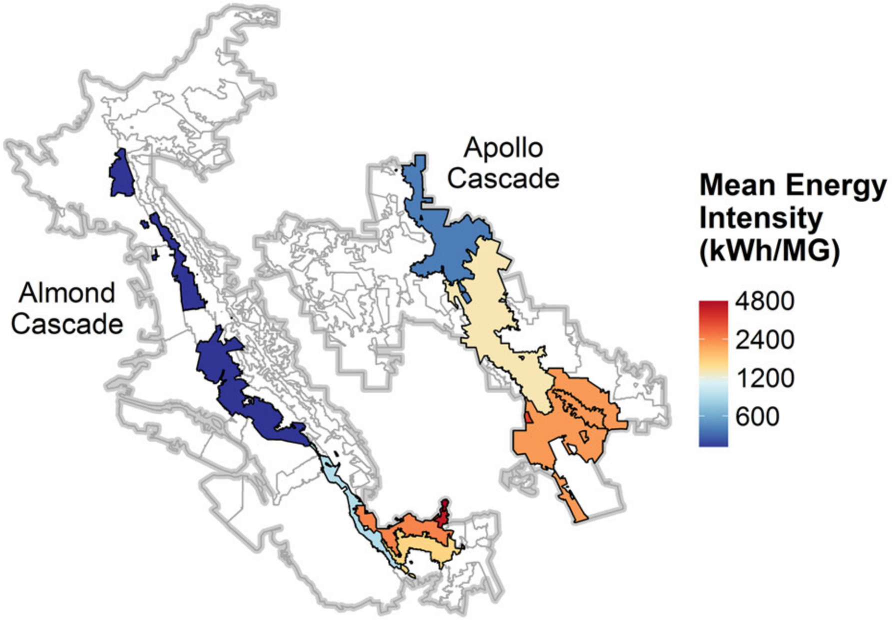

Figure 7 Map of energy intensity for EBMUD pilot study pressure zones. EBMUD = East Bay Municipal Utility District; kWh/MG = kilowatt-hours per million gallons.

changing consumer behavior can leverage this information to target energy-intensive neighborhoods that will yield the greatest energy conservation return on investment.

Of course, it is important to remember that some zones may have very high EI values, but relatively low water consumption, and therefore may not be the best targets for capturing energy savings. In other words, the dynamics of the EI values across the network must be aligned with the dynamics of water use (when, where, how much, and by whom) to design effective programs.

Leveraging existing SCADA system data was essential for producing high-resolution EI results. Though utilizing SCADA system data can be relatively cumbersome, it would be possible for water utilities to automate these calculations for ongoing monitoring of EI. This effort would not only allow the utility to have ready access to up-to-date estimates of EI across their system, but it would also provide an opportunity to monitor and verify the energy and associated GHG savings associated with any water conservation programs, either on the infrastructure side (e.g., reducing leaks and pressure management) or on the customer side (e.g., installation of efficient appliances and behavior-based conservation).

In the meantime, data and information technology (IT) limitations present a significant obstacle to rolling out comprehensive EI analysis more broadly. As mentioned in the *Methods*, this study does not include wastewater EI, but rather focuses on the delivery potable water. With limited resources for the analysis, the ability to integrate data from physically and jurisdictionally discrete water and wastewater service delivery infrastructures proved too burdensome. These limitations should not be taken to imply that extending our approach to the full water system would be unworkable; rather, that integrating the additional data would require additional resources, either for direct research effort or for more-streamlined data-sharing systems.

Despite the challenge, there is distinct value to including wastewater EI (associated with energy use by lift stations and wastewater treatment processes) into this approach. An understanding of wastewater EI enables the distinction between the EI of indoor versus outdoor water use (i.e., by considering the discrepancy between total metered/delivered water and "indoor" volumes returned as wastewater for treatment). This additional resolution allows for finer-tuned targeting of water conservation with a higher potential for energy savings returns earned from avoided wastewater conveyance and treatment. Disaggregating indoor and outdoor use would also be a preliminary step toward incorporating end-user energy inputs into water (e.g., water heating).

Finally, it is important to note that EBMUD, and many other water utilities, are not just energy consumers, but producers as well. EBMUD's Mokelumne conveyance generates hydroelectric power, the utility's water treatment facilities generate significant electrical power by photovoltaic arrays, and the wastewater treatment facility produces significant energy from digester gas (in fact, it approaches zero net energy). Whereas this study focused purely on the total direct consumption of energy (regardless of energy source or carbon content), future EI studies may have a more targeted interest in net energy consumption (total energy consumption minus energy generated directly from the water infrastructure) or the carbon intensity of the water system. In fact, these values are not mutually exclusive, and it would likely be useful to calculate all of these metrics to gain a more complete picture of the energy implications of a given water infrastructure system.

Conclusion

Earlier studies established a significant amount of energy involved in the extraction, treatment, and transport of water in potable water systems, especially in California. Within this context, the aim of this study was to provide a more detailed characterization of this energy, which is embedded in water systems. Improving the estimation and measurement of the energy intensity of water as it moves through a water system can provide energy utilities with the information they need to partner directly with water utilities to establish joint programs that save both water and energy.

Policies or agencies that seek to allocate energy efficiency and GHG reduction dollars to water efficiency programs require clear, defensible methods for calculating the EI of water, as well as reliable, verifiable monitoring of energy and carbon savings. This is no small challenge, because energy use varies significantly depending on where and when it is used. No two water agencies are the same, so no one-size-fits-all EI number can be given to a gallon of water.

The complexity of major water providers' infrastructure and operations means that calculating system-wide energy intensity from the top down can obscure significant seasonal and spatial effects on energy. This study of the EBMUD system introduces a way to represent the spatially and temporally dynamic characteristics of water system energy intensity by leveraging information from water utilities' existing SCADA systems. SCADA platforms provide operators with real-time control over the water infrastructure, enabling them to manage flow and pressure across the network. Our approach repurposes SCADA data streams toward calculating and monitoring the energy consumed across the water system network.

Although the effort to make these calculations is substantial, applying this analytical method provides greater resolution and more "actionable" data, including the estimation of defensible EI values and the categorization of seasonal and/or geographic EI "hotspots" within a water service territory to be used to yield maximum energy returns on water savings investments. Further, this system-wide approach provides water-energy equivalences that enable—policy permitting—quantification and trading of carbon emissions reductions in cap-and-trade markets.

While California has led the way toward enabling such programs, both water and energy utilities have struggled with the uncertainty of anticipated energy savings through water conservation. Part of the challenge is that, as opposed to deploying individual energy-saving technologies on the consumption side, supply-side water-energy programs require a systemic approach to resource use. Owing to differences in size and complexity, water system energy intensities vary significantly between water agencies, but also significantly *within* water agencies in time and space, as this study as shown. However, with this approach available, these complexities should not impede further progress.

Acknowledgments

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information shows the East Bay Municipal Utility District (EBMUD) water and wastewater service areas and provides a monthly, seasonal, and average statistical summary of energy intensity (EI) in the EBMUD.