NEW TECHNIQUES TO ANALYZE ENERGY USE AND INFORM SUSTAINABLE PLANNING, DESIGN, AND OPERATION OF PUBLIC WATER SYSTEMS

by

Robert B. Sowby

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STATEMENT OF DISSERTATION APPROVAL

The dissertation of **Robert B. Sowby**

has been approved by the following supervisory committee members:

Steven J. Burian	, Chair	**11/7/17** Date Approved
Michael E. Barber	, Member	**11/7/17** Date Approved
Thomas J. Cova	, Member	**11/7/17** Date Approved
Jeffery S. Horsburgh	, Member	**11/13/17** Date Approved
Zain M. Al-Houri	, Member	**11/7/17** Date Approved

and by **Michael E. Barber** , Chair/Dean of

the Department/College/School of **Civil and Environmental Engineering**

and by David B. Kieda, Dean of The Graduate School.

ABSTRACT

Public water systems face escalating energy requirements due to scarcer water supplies, stricter water quality standards, and population growth. As the challenges of managing finite water and energy resources continue to grow, new data, analyses, and models are needed to help water systems manage their energy use and operate more sustainably. This work offers three original contributions: 1) the discovery of annual, utility-scale energy intensities for public water supply from a panel survey of over 100 U.S. water utilities; 2) an empirical statistical model that accurately predicts a water system's energy use as a function of a few accessible variables and lends itself to fairer energy benchmarking; and 3) the development of a high-resolution method to model energy use within a water distribution network to inform energy management decisions at multiple scales. The survey showed an average water system energy intensity of 1,809 kilowatt-hours per million gallons (kWh/MG) but with substantial spread from 250 kWh/MG to 11,500 kWh/MG and with interannual changes up to 70%. These geographic and temporal variations should be considered in future work. The survey confirmed that a lack of adequate data is one of the greatest barriers to understanding energy-for-water demands. In the statistical model, the most important factors influencing energy use were found to be water system size, water source type, precipitation, and air temperature. By considering such internal and external variables, the model overcomes much of the difficulty in equitable energy benchmarking. The model is more accurate than those

developed previously and uses more-accessible variables to estimate energy use, features that are useful when actual observations are unavailable. The technique for modeling energy intensities within a water system, built on extended-period hydraulic modeling, provided specific and actionable energy management insights. A case study with a real water system illuminated energy inefficiencies, and their solutions were validated through actual energy savings. Where water and energy interactions are complex, the method is a valuable analysis tool. Overall, the development of strong datasets, empirical relationships, and modeling techniques helps advance sustainable water supply from an energy perspective, with value to both researchers and practitioners.

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

—T. S. Eliot, “Little Gidding”

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PREFACE

In 2014 two events collided to launch me on my journey into the water–energy nexus. One was taking an online course entitled “Energy Technology and Policy.” A recent MIT graduate, I was following MIT and Harvard’s new massive open online course (MOOC) venture, edX, and wanted to try a course. The course, taught by Dr. Michael Webber at the University of Texas at Austin, was one of the most popular and seemed the most relevant to my civil engineering field. A water resources engineer by education and profession, I enjoyed the course and found the “Energy and Water” unit particularly insightful and was drawn to further explore the intersection of these two critical resources. I can trace the beginning of my academic interest in the water–energy nexus directly to Webber’s course.

The other event was my assignment to several engineering projects in my consulting practice at Hansen, Allen & Luce dealing with the energy efficiency and optimization of public water systems. My colleague Steve Jones, after some 10 years of modeling and analyzing dozens of such utilities, had noticed that many of them shared the same inefficiencies and opportunities for improvement. Beyond the company’s usual engineering services, Steve began providing focused studies to help water systems identify, evaluate, and implement affordable energy-saving measures, all while maintaining or even improving their level of service and water quality. I happened to join Hansen, Allen & Luce about this same time and was assigned to many of Steve’s projects, thereby gaining a practical perspective on how water systems' management of energy use contributes to their sustainable planning, design, and operation.

The confluence of these two experiences—developing an academic interest in energy-for-water issues and seeing their impact on water systems in my daily work—led me to pursue a doctoral degree and study this very subject on which the existing research was so sparse. I chose the University of Utah and the Department of Civil and Environmental Engineering for, among other reasons, the department's mission to prepare students for professional practice and transfer knowledge to the public and private sectors. My experience here has defined for me a completely singular journey both challenging and rewarding for my research and consulting careers.

In completing this journey I must thank many people. My wife, Dr. Christie Sowby, provided incredible wisdom and encouragement throughout the process. Not one to be deterred by even major obstacles, she inspired me to continue this work and generously gave me the time to do so. Though a pianist by trade, Christie is now more than conversant in water and energy issues after witnessing so many of my presentations, iterations, and exclamations. The anticipated arrival of our first child in the final semester of the program, needless to say, motivated me to finish quickly. My mother, Laurie Williams Sowby, a journalist, helped edit my writings. My father, Steve Sowby, also a civil engineer, reviewed my early manuscripts and provided immediate feedback on my ideas in countless casual conversations. My in-laws the Burgons graciously lent me their basement and rear patio where I spent much of the summer studying and writing.

My supervisory committee at the University of Utah, consisting of Drs. Steve Burian, Michael Barber, Christine Pomeroy, Tom Cova, Jeff Horsburgh, and Zain Al-

Houri was an excellent team for this undertaking. Their regular communications, meetings, and efforts in my behalf over the past few years are much appreciated. Dr. Burian in particular was an exceptional advisor, mentor, instructor, coauthor, and friend who understood my unique position as both student and practitioner and went out of his way to guide me through this research program.

Colleagues at Hansen, Allen & Luce—particularly Steve Jones, Gordon Jones, and Marv Allen—encouraged my studies, allowed me a flexible work schedule, and found ways to use my research to help serve our clients throughout the country. Associates at Cascade Energy, Pacific Northwest National Laboratory, Idaho National Laboratory, the Center for Advanced Energy Studies, the American Water Works Association, Aquaveo, and the University of Utah's Urban Water Group were likewise supportive and influential.

Countless others unnamed contributed to this effort in more subtle and indirect ways, and I sincerely thank them for their inspiration, service, and faith.

CHAPTER 1

GENERAL INTRODUCTION

1.1 Background

Modern water systems require energy to extract, treat, and deliver reliable, high-quality water. 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 planning, design, or operation (Barry 2007; CEC 2016). One definition of sustainability is the "triple bottom line" described by Elkington (1997), which encompasses economic, environmental, and social considerations. Water utilities' energy use touches all three. 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 (EPA 2016). Environmental impacts include the emissions associated with generating power for water services, which affect local ecosystems and the global climate (Lee et al. 2017; Stokes and Horvath 2009; Lane et al. 2015; UC–Berkeley 2011; Cooley et al. 2012; Griffiths-Sattenspiel and Wilson 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 be fiscally responsible and perform efficiently while fulfilling a social contract to provide a vital service in a monopolized market (De Asís 2009).

With increasing population, stricter water-quality standards, and rising energy costs, energy efficiency in the water sector is emerging as an essential solution (Tidwell et al. 2014; Liu et al. 2012; Jones et al. 2015; DOE 2014; Water in the West 2013; EPA 2016; Hoffman et al. 2015; Molina 2014). Potential and theoretical energy efficiency savings for water utilities have been studied extensively, and most estimates indicate that savings of 10%–30% are possible through combinations of operational (no-cost) and capital measures (Voltz et al. 2017; Horne et al. 2014; Liu et al. 2012; MassDEP 2016; EPA 2013; Alliance to Save Energy 2016; DOE 2014). Actual results confirm that the savings are indeed possible (Sowby 2016); see Appendix A for a more complete discussion. The energy savings come by implementing capital projects, operational changes, and efforts to deliver water by the most energy-efficient path.

Several best practices and resources are available to guide water utilities to more energy-efficient operations (DEC 2016; EPA 2008; Liu et al. 2012; NYSERDA 2010; Martin and Ries 2014; Chelius and McDonald 2016; UDDW 2014; Jones and Sowby 2014; Moran and Barron 2009; Arora and LeChevallier 1998; Hamilton et al. 2009). The most common include:

- Determining baseline energy intensity and monitoring regularly
- Auditing water and energy use simultaneously
- Upgrading old or improperly designed equipment
- Prioritizing efficient water sources
- Prioritizing efficient conveyance paths

- Increasing storage utilization to balance loads
- Adjusting pressure-reducing valves to minimize unnecessary flow
- Eliminating redundant pumping
- Controlling water loss

Still, the opportunity remains largely untapped, and much more can be done to reduce water utilities' energy use. While these case studies and general practices are helpful, each system is unique and requires individual attention and analysis.

The following literature review identifies several research needs, among which are quantifying water systems' energy requirements to better characterize energy-for-water demands, determining how certain factors influence the energy intensities to better estimate the energy requirements of unobserved systems, and developing a method to model energy intensity at the subsystem scale to improve energy performance. The work presented here addresses these needs, respectively, through 1) the collection of annual, utility-scale energy intensities for public water supply in the United States through a panel of water and energy observations; 2) a statistical analysis of the variables and relationships that influence these energy intensities and the development of an accurate statistical model for predicting energy intensity; and 3) the development and application of a method to rapidly compute system-wide energy intensities with node-and-link resolution in a water distribution network by tracing the entire service chain from energy demand to water delivery.

1.2 Literature Review

1.2.1 Energy Intensity and Related Studies

Water services consume a substantial amount of energy worldwide, accounting for 0.5% to 17% of a country's energy use profile, with higher values usually corresponding to developing nations (Gerbens-Leenes et al. 2014). In the United States, this value is about 2%, though significant regional variations have been observed (Sanders and Webber 2012; Tidwell et al. 2014). The California Energy Commission found that water supply consumes 19% of the state's electricity and 30% of its natural gas, underscoring the significance of the water sector's role in energy consumption, especially amid California's current multiyear drought (Klein 2005; Navigant Consulting 2006).

An important metric in these and related studies is energy intensity, which describes a water system's energy footprint in the most basic sense and is used in numerous calculations, models, and planning scenarios. Energy intensity is energy required to extract, treat, and deliver a unit of water to the end-user. 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." Normalizing by volume eliminates all effects of water demand and allows comparison solely on terms of energy. Also called embedded energy, the value is often expressed in kilowatt-hours per million gallons (kWh/MG). For a complete water system, the average energy intensity over a given time period is the sum of all energy input divided by the total water delivery volume. If accounting for true source-to-customer energy intensity as in this research, the numerator must also include the energy expended for imported water.

Several studies have investigated energy intensity for water services at various scales. Plappally and Lienhard (2012) presented a comprehensive assessment of average water-related energy intensities that include public supply, end use, agriculture, and rainwater harvesting. Siddiqi and Fletcher (2015) compared energy intensities for agricultural and residential water use in Australia and Europe. Wakeel et al. (2016) and Gerbens-Leenes et al. (2014) reviewed the literature for energy consumption of water-use cycles globally (by country) and found great variation, with developing countries usually spending a larger share of their national energy use on water supply than developed countries. EPRI (2002, 2009, 2013), DOE (2012a, 2012b), and Twomey and Webber (2011) estimated U.S. averages of water-related energy intensity. Others have compared energy intensities among cities or regions in the same state (Wilkinson et al. 2006; Sowby et al. 2015; Bennett 2010a, 2010b; Blanco et al. 2012). Scanlon et al. (2017) observed that while broad data are welcomed, local-to-regional analyses are more valuable for policy, decision making, and action.

State-level data for California, Idaho, Utah, Texas, Iowa, Illinois, Indiana, Wisconsin, New York, and Massachusetts are also available (Cohen et al. 2004; Klein 2005; Navigant Consulting 2006; Wilkinson et al. 2006; Larsen and Burian 2012; UDWR 2012; Stillwell et al. 2010; PSCW 2016; Twomey and Webber 2011; ISAWWA 2012; Yonkin et al. 2008; DOE 2012a, 2012b). The results range over an order of magnitude depending on the location and give only a partially complete portrait of how much energy water services require. These few, broad averages, based mostly on calculations rather than observations, represent almost all of the publicly available information on this subject, which, given the magnitude of the associated electric load, is surprisingly limited.

Differences also exist in energy intensities within an individual system since delivering water from different sources to different elevations requires different amounts of energy. Saliba and Gan (2006) and Spang and Loge (2013, 2015) have illustrated such differences with so-called energy maps, which they used to benchmark performance and evaluate water and energy conservation measures. This type of analysis, while useful, is computationally intensive and therefore rare.

Beyond the geographic variations, energy intensities can also change over time. According to unpublished data from Hansen, Allen & Luce, Jordan Valley Water Conservancy District's energy intensity in 2013 was 50% greater than in 2012 and 2014. According to unpublished data from Park City, Utah, the energy intensity of the city's water system increased by 73% between 2011 and 2014. For Wisconsin water systems, energy intensity has increased almost 25% in the past 15 years (PSCW 2016; Elliott et al. 2003). Few such time series are available, limiting the investigation and interpretation of such phenomena, though the information could help water systems understand energy use patterns, improve efficiency, and anticipate future changes.

Though past research has advanced the knowledge of the water sector's energy requirements, the data are limited in terms of 1) spatial resolution, 2) temporal resolution, and 3) quality. In spatial resolution, the published data are either broad averages that blur local differences or isolated local observations that do not apply elsewhere. Tidwell et al. (2014) recognized these important limitations when estimating energy requirements for water services in the western United States: "Due to the limited availability of data, the use of broad averages of key factors important to calculating electricity use had to be employed…. The electric intensities of different drinking and wastewater unit processes relied on national-level averages.” In their research on water supply energy intensities, Twomey and Webber (2011) observed that “the United States is a difficult country to generalize” due to its size and incredibly diverse climate and topography. Even Klein’s (2005) group, which produced one of the most complete studies to date, “assumed prototypical water distribution energy intensity to be about 1,200 kWh/MG” since no better observations or modeling methods were available. In their study of the water–energy nexus in Texas, Stillwell et al. (2010) concluded that “substantially more site-specific data are necessary for a full understanding of the nature of the energy-water nexus.”

The published data are also limited in time. With a few exceptions, all of the energy intensities found in the literature describe only a single time period for each system. Even the few time series available indicate that the energy intensity varies from year to year—perhaps as much as 50%—and possibly at finer temporal scales still. The lack of time series on energy intensity is particularly profound. One tool for modeling urban water–energy interactions acknowledges the limitation of its “simplifying assumption of constant values” for energy intensity when in reality there are cases where it “varies considerably” (Baki and Makropoulos 2014). Spang and Loge (2013, 2015) are among the few to attempt temporal characterization of energy intensity.

Data quality is another limitation since the underlying methodologies differ. Some, for example, ignore the effect of water loss between production and delivery, leading to an underestimation of actual energy intensity. With typical water loss values ranging from 5% to 35% (EPA 2010), this is one issue that can significantly affect the results and introduce error into subsequent calculations. Incidentally, one recent study found that reducing water loss represents a substantial energy savings potential (Lam et al. 2017). After its statewide study, the Illinois Section of the American Water Works Association (ISAWWA 2012) 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." Indeed, a major finding of the literature review was the lack of consistent empirical data to describe energy use in the water sector.

1.2.2 Factors Influencing Energy Requirements

Beyond the general data needs, there is a specific need to advance the knowledge of water-related energy intensities and their driving forces. Past studies have focused on snapshots of several cities or an in-depth analysis of a single city; they do not explain the variability. Many have assumed that water source type, utility size, conveyance distance, climate, technology, infrastructure age, and topography are important factors (Wakeel et al. 2016; Tidwell et al. 2014; Water in the West 2013; Twomey and Webber 2011; Klein 2005). Of these, only size has been formally investigated, and that on only a small scale, which showed that larger water utilities generally exhibit lower energy intensities (Young 2015; ISAWWA 2012; PSCW 2016). This finding is consistent with studies of water and wastewater treatment facilities (DOE 2012a, 2012b). General data from others indicate that surface water systems have lower energy intensities than groundwater systems (Twomey and Webber 2011; EPRI 2009). None of these patterns are tied to specific locations, and, with the exception of Wisconsin (PSCW 2016; Elliott et al. 2003), all of these studies have captured mere snapshots of water utilities' energy intensities, with little or no context or consideration for how these values change over time. Even where fine observations exist, the context may be insufficient for analysis. Data that describe only the energy intensity and not the context (such as the geographic setting, water source, or utility size) are not as useful. In order to compare energy intensities, one must understand the conditions in which the observations were made.

No research has yet quantified the relationships between a water utility's energy intensity and geographic or time-variant variables that describe the conditions that may affect energy intensity. Determining energy intensity is one of the first steps to realizing energy savings and the associated benefits, but actual data are difficult to obtain. Research and practice are also limited by available data and could benefit from a method to estimate energy intensity for any system. Such capability could inform national-level evaluations of the water–energy nexus (such as those by the U.S. Department of Energy, the U.S. Geological Survey, and national laboratories) as well as capital or operational improvements for energy management at local water utilities.

1.2.3 Subsystem Energy Modeling

Drawing on the best practices listed earlier, water utilities can improve their sustainability by identifying and implementing the most energy-efficient scheme for water delivery that still satisfies the prescribed level of service and water quality (Jones and Sowby 2014). However, without a detailed and efficient modeling method that considers system-specific issues, the optimum scheme is difficult to determine, especially for complex systems with many pressure zones, water sources, and pumping facilities. The difficulty of computing energy intensity increases with both system complexity and level of spatial and temporal detail.

A related but more developed field is that of energy density maps and community energy mapping. Combining mildly aggregated (e.g., by city block) energy consumption data with spatial data, energy mapping has become a useful tool for community energy planning and sustainability engagement (Webster et al. 2011; Reul and Michaels 2012; Ea Energy Analyses and GRAS 2012; Gilmour and McNally 2010). Energy mapping helps “create benchmarks, expose patterns, and display building performance” and reveals “energy gushers” where a large potential exists for energy savings (Reul and Michaels 2012). Gilmour and McNally (2010) observed that a central component of energy mapping is the ability to visualize the results.

Saliba and Gan (2006) and Spang and Loge (2013, 2015) applied these concepts to study energy intensity differences within an individual water system at the pressure-zone level using facility energy data and geographic information systems (GIS). Both enabled energy calculations at finer geographic resolution to prioritize site-specific water and energy conservation actions that would not have emerged from a lumped, system-wide analysis. However, their spatial analyses did not penetrate to individual nodes and links and did not capture changes over time—an important consideration when trying co-optimize hydraulics and energy use at these same scales and time steps.

The spatially and temporally dynamic nature of water system behavior merits a more detailed method that considers the energy consequences of system fluctuations that would not be apparent in a static snapshot or broad analysis—in other words, a simulation-based approach.

1.2.4 Research Needs

Many research needs in the water–energy nexus are well documented and consistent with those already discussed. One recurring theme is the paucity of data, analysis, and models related to the water sector and its energy use. The U.S. Department of Energy defined the optimization of water systems as one of its six strategic pillars in the water–energy nexus; the report observed, however, that “reliable data is noticeably scarce” in this field, being mostly the results of engineering calculations rather than actual observations (DOE 2014). Goldstein et al. (2008) identified data exchange as an important component of current and future approaches to manage both water and energy. Bazilian et al. (2011) suggested developing “robust analytical tools, conceptual models, appropriate and validated algorithms, and robust datasets that can supply information on the future use of energy, water, and food,” noting that such efforts have been limited to date. Sandia National Laboratories found that the water–energy nexus suffers from the “lack of consistent and detailed data and the lack of 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.” 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). Another survey found that “comprehensive data about the energy needed for each stage of the urban water lifecycle are limited. In particular, few nationwide studies have been conducted on the amount of energy used to provide drinking water and wastewater services” (GAO 2011). Young (2015) similarly observed that “the energy intensity of water and wastewater systems is relatively undocumented. There are few data sources and reports analyzing the energy required to move and treat water, and the data generally are not publicly available.” While past studies have been helpful, the industry “could benefit from higher-resolution analysis in this field" (Water in the West 2013). A recent U.S. Geological Survey report on the water–energy nexus stated that "despite the national importance of energy use for water, comprehensive national studies of this topic are lacking" (Healy et al. 2015).

Even in sophisticated systems models like PRIMA (Kraucunas et al. 2015), water and energy systems are not explicitly linked and do not reach the granularity of individual water systems needed for decision-making at the utility level. In other systems models, only a static, rudimentary link between energy and water may be specified (Lubega and Farrid 2013). In physics-based system models there are many variables and assumptions that must be made in the absence of empirical relationships and adequate data. These assumptions may not be appropriate and could affect the accuracy of such models (Lubega and Farrid 2014). These and similar models could benefit from finer data at the intersection of water and energy use. The author's own interactions with researchers at Pacific Northwest National Laboratory, Idaho National Laboratory, the Center for Advanced Energy Studies, and the U.S. Environmental Protection Agency confirm this great need for data and models.

Policy considerations are also relevant. The heretofore fragmented and siloed policies that have governed water, energy, and other resources like food and land are breaking down with "nexus" thinking that recognizes their interdependencies and therefore need to be revisited. The purposes or outcomes of many studies in the water–energy nexus have clearly stated a need to integrate water and energy research and to unify their policies and governance (Ernst and Preston 2017; Scanlon et al. 2017; Chini and Stillwell 2017; King et al. 2013; Stillwell et al. 2010; Hussey and Pittock 2012; Wakeel et al. 2016; United Nations 2014; Finley and Seiber 2014; Young 2014; Gude

2015; Webber 2015; Bazilian et al. 2011; Cooley et al. 2011; Ramos et al. 2010; Webber 2008; Scott et al. 2011). One specific policy question concerns public and private ownership of water utilities and whether the ownership structure imparts any significant energy performance benefit. If so, this difference may affect the content and audience of future policies to manage energy in the water sector. Appendix C addresses this question.

The literature review indicated that few studies have addressed the energy used to supply water and that more research on this topic is needed in order to control costs, reduce environmental impacts, and manage interdependent water and energy resources. Reliable energy-for-water data will inform engineering recommendations to conserve energy while still providing adequate water service (and thereby reduce energy production and the associated carbon emissions). They will also support local, state, and federal policies on improved management of water and energy and help identify and prioritize further research opportunities.

The identification of similar research needs by diverse stakeholders testifies of their broad significance and of the opportunities to contribute. The research program outlined below addresses some of these needs.

1.3 Research Program

Based on the literature review and the researcher's professional and academic experience, the following research program was designed to advance the body of knowledge. The tripartite program consists of a national energy intensity survey, the development of a statistical model and benchmarking tool (based on the survey results) relating a water system's energy use to a few key variables, and a high-resolution modeling method for analysis of energy intensity within a water distribution system.

1.3.1 National Energy Intensity Survey

The purpose of the energy intensity survey was to collect annual, utility-scale water and energy observations to better characterize energy-for-water demands in the United States and enable further scientific study. The literature review revealed a clear need to acquire empirical data describing water utilities' energy use. Without adequate local and time-specific data, one may resort to using an energy intensity from another location or time, or perhaps an average, and assume that the data are valid for the intended conditions. This spatial and temporal extrapolation ignores important differences and introduces uncertainty into the results, but there have been few or no options to do otherwise. An improvement is the collection and publication of data at finer spatial scales and multiple time steps. This offers a greater selection of specific local data, more formally quantifies the water sector's energy use, and leads to estimation of energy intensity for unobserved systems.

To this end, a national panel survey of water utility energy intensities in the contiguous United States was undertaken. Chapter 2 presents the results of the survey.

1.3.2 Statistical Model

The purpose of this phase was to produce a statistical model, based on empirical relationships between energy intensity and other variables discovered from the survey data, that can estimate energy intensities for unobserved water systems and facilitate fair energy benchmarking of diverse and otherwise incomparable water systems.

While several reasonable factors have been suggested to explain observed variability in water systems' energy use, the literature review indicated that the relationships have not been investigated formally, and certainly not to the point of quantification. Further, since water systems vary greatly in water source type, climate, and size, comparing their energy performance to each other without normalizing for such factors is both unfair and misleading. The empirical statistical model developed as part of this research is an improvement that enables estimates of a water system's energy use as function of a few key variables and also enables fair comparisons and benchmarking by considering such variables. The model lends itself well to both energy use estimation and fair energy benchmarking of water utilities. Chapter 3 describes the model and its applications.

1.3.3 Energy Intensity Modeling

The purpose of this phase was to develop and demonstrate a method for modeling energy intensity in complex water distribution systems with node-and-link resolution to inform energy management decisions at the same scales.

As the magnitude, location, and timing of water demands changes in a given system, the interactions among multiple water sources, pressure zones, and facilities complicate the determination of site- and time-specific energy intensities (i.e., how much energy was input to deliver water at a point within the system). The results are unique to each system configuration and demand scenario, making the identification of optimal operations computationally intensive.

This research led to a method for rapid computation of system-wide energy results in high resolution to help uncover efficiency opportunities not apparent from a lumped system analysis. Such a method facilitates the testing of alternative operational schemes, lends itself to optimization techniques for research or engineering, and informs energy management decisions at relevant scales. Applications have already been explored for implementing targeted efficiency initiatives and assessing the energy required or saved through design choices. This contribution will further develop such methods to enable better prediction, targeting, and monitoring of energy savings at local levels within a water distribution system.

Chapter 4 describes this new method for subsystem energy intensity modeling based on the principles of extended-period hydraulic modeling, energy maps, and general property concentrations.

1.4 Conclusion

As one facet of the water–energy nexus, the dependence of water systems on energy systems is a subject of increasing interest. The literature review identified several pertinent opportunities, notably the need for a consistent national dataset, the investigation of influential factors, and a method to model energy intensities at subsystem scales. The research presented here addresses these topics.

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CHAPTER 2

SURVEY OF ENERGY REQUIREMENTS FOR PUBLIC WATER SUPPLY IN THE UNITED STATES[1]

2.1 Introduction

Though 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 (EPA 2017). Environmental impacts include the emissions associated with generating power for water services, which affect local ecosystems and

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the global climate (Lane et al. 2015, Ramos et al. 2010, Cooley et al. 2012, 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 2009).

Many have studied the energy requirements of U.S. public water supply from various angles and for various purposes. The U.S. Department of Energy (DOE 2012a) 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 in order 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 U.S. 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 U.S. primary energy. Both studies were the first to quantify such uses and acknowledged that a lack of regional and local data limited their 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) group, 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 since 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 U.S. government agencies have expressed the need for better data on energy use for public water supply. The U.S. 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, which the five previous references illustrate (DOE 2014). Another survey found that "few nationwide studies have been conducted on the amount of energy used to provide drinking water and wastewater services" (GAO 2011). The U.S. 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 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 the local chapter of the American Water Works Association (AWWA) 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). While 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 datasets 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 managing 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, though 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 of their broad significance.

This study extends previous work to quantify energy requirements for public water supply, contributing a national dataset of annual- and city-scale observations obtained chiefly through primary data collection. The following sections describe the study methodology, the study results, a discussion of observations and applications, and recommendations for further work.

2.2 Methods

2.2.1 Definitions

Here, 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. Since 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." Since 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 also eliminates all effects of water demand, allowing comparison solely in terms of energy. Thus for a complete water supply system, the energy intensity is

$$Y_s = \frac{\sum_{i=1}^{n} E_i}{V_D} \tag{2.1}$$

where Y_S is the total energy intensity of the water system, E_i is the energy required for a given step of the process (extraction, treatment, pumping, etc.), 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, though their contribution to overall water-related energy demand is significant as described earlier.

2.2.2 Sample Design

In their research on this subject, Twomey and Webber (2011) observed that "the United States is a difficult country to generalize" due to 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 based on geographic coverage and water system size.

The sample design began with existing literature, including data for Los Angeles, CA (Blanco et al. 2012); New York City, NY (DEP 2016, Yonkin et al. 2008); Bloomington, IN (ISAWWA 2012); Mishawaka, IN (ISAWWA 2012); Valparaiso, IN (ISAWWA 2012); and several Wisconsin cities (PSCW 2016). State-level observations for Illinois (ISAWWA 2012), Iowa (DOE 2012a), and Massachusetts (DOE 2012a) 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 in order 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.

2.2.3 Survey Questions

Each water system identified in the sample was contacted via phone, email, 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 dataset:

- 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)

2.2.4 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 U.S. 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.

2.2.5 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-squared value of each; the transformation with the lowest chi-squared 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-U.S. water systems were the same. Since the variances of the two samples differed, the version of the test with unequal variances (Welch's *t*-test) was selected (Welch 1947).

2.3 Results

Figures 2.1 through 2.5 and Table 2.1 show the results for a cross section of the panel dataset, being data for the most recent year available in the survey. Figure 2.1 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 2.2. The best fit for the observed data was a log-normal distribution with $\mu = 7.573$ and $\sigma = 0.735$, which is also shown in Figure 2.2. Figure 2.3 compares results from the eastern and western United States according to the division the U.S. Geological Survey defined in its most recent water-use study and shown in Figure 2.1 (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 2.4 compares results by primary water

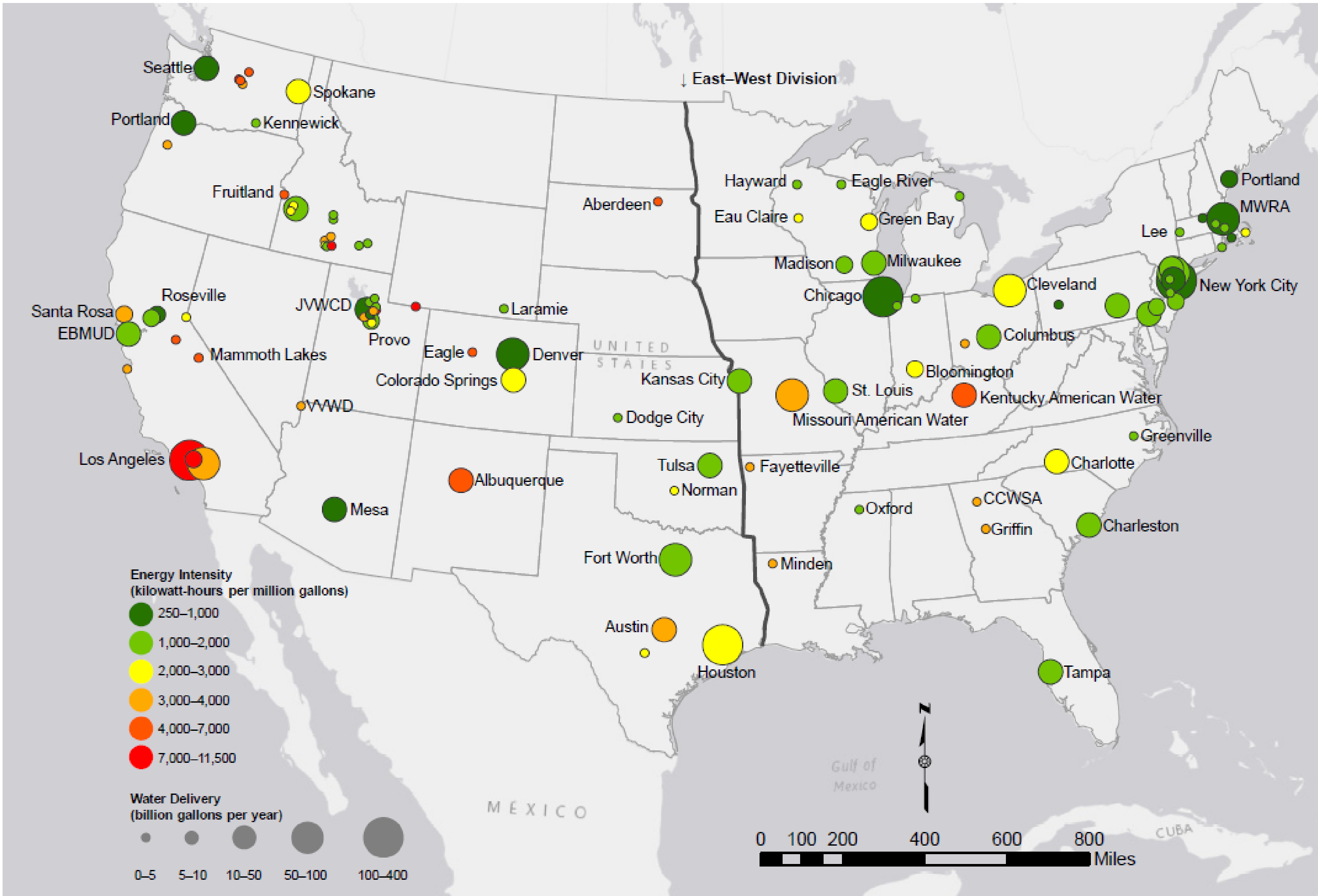

Figure 2.1 Geographic Distribution of Energy Intensities for Public Water Supply

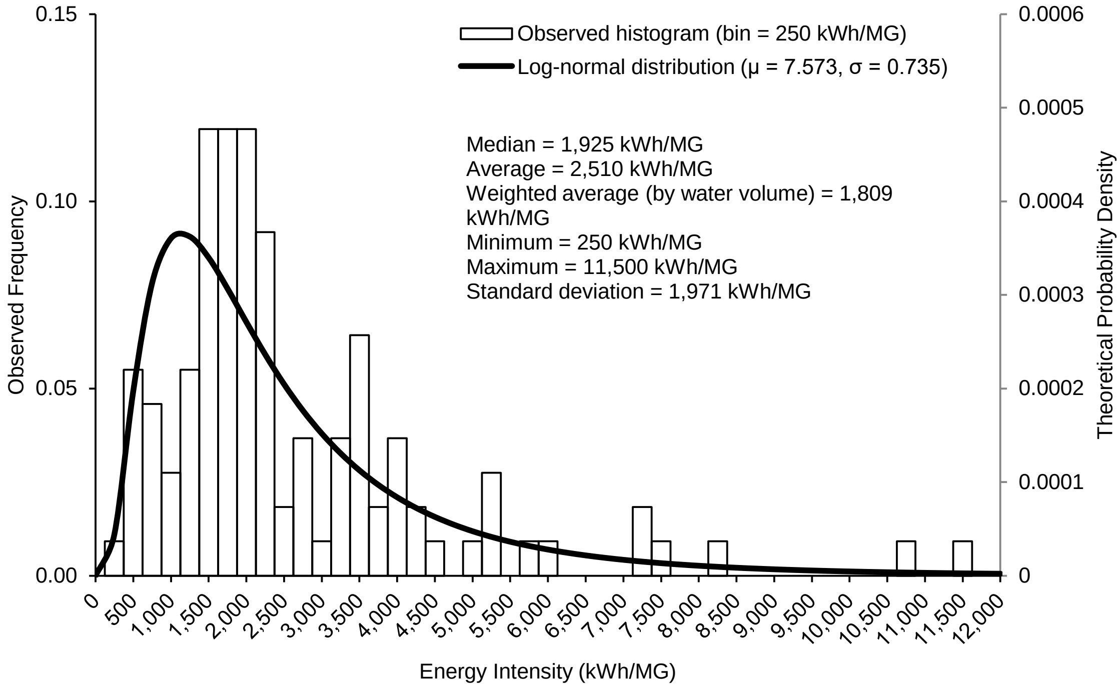

Figure 2.2 Histogram of Energy Intensities for Public Water Supply

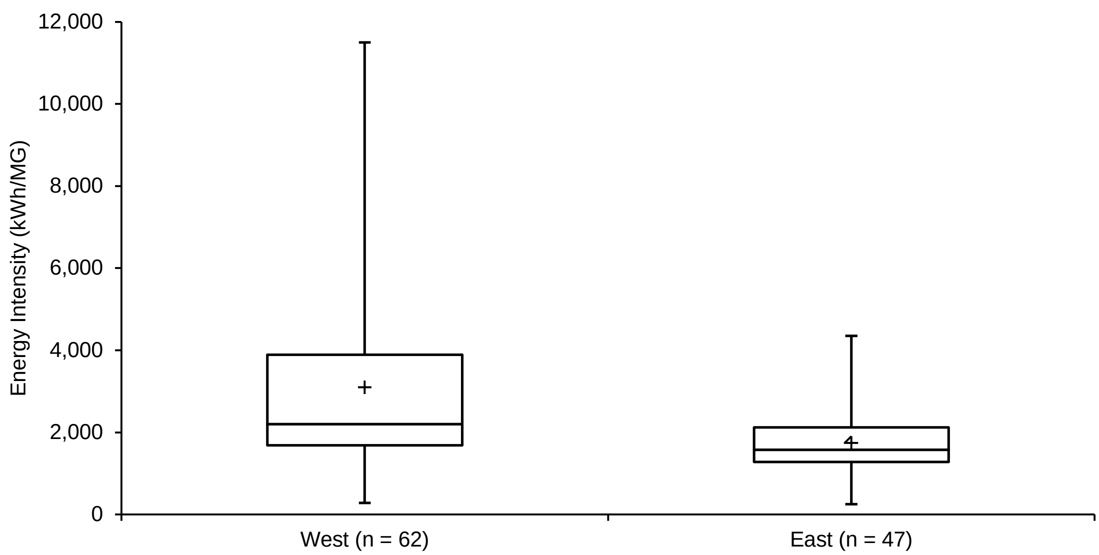

Figure 2.3 Energy Intensity for Public Water Supply by Geographic Region

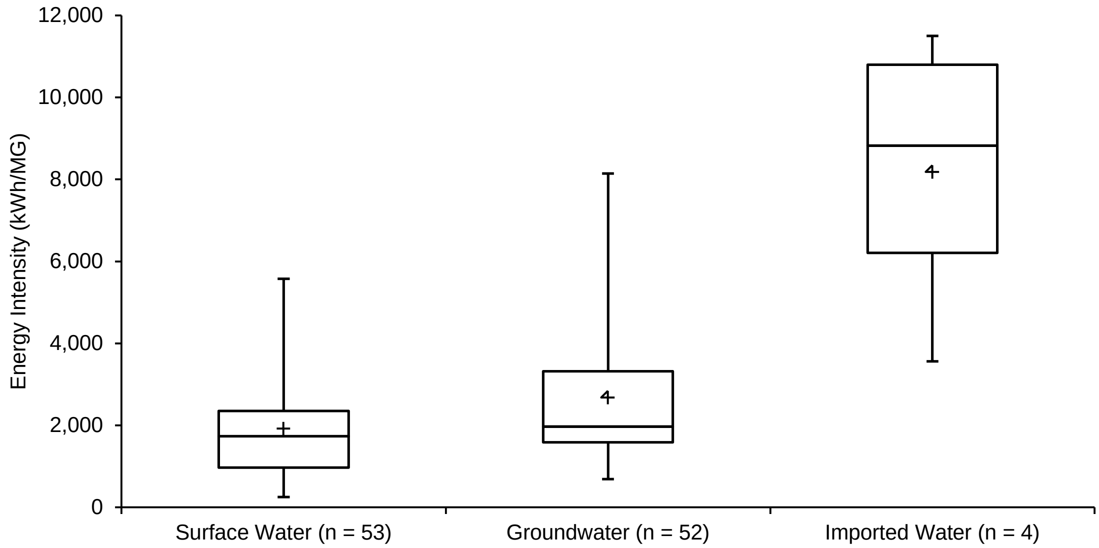

Figure 2.4 Energy Intensity for Public Water Supply by Primary Water Source Type

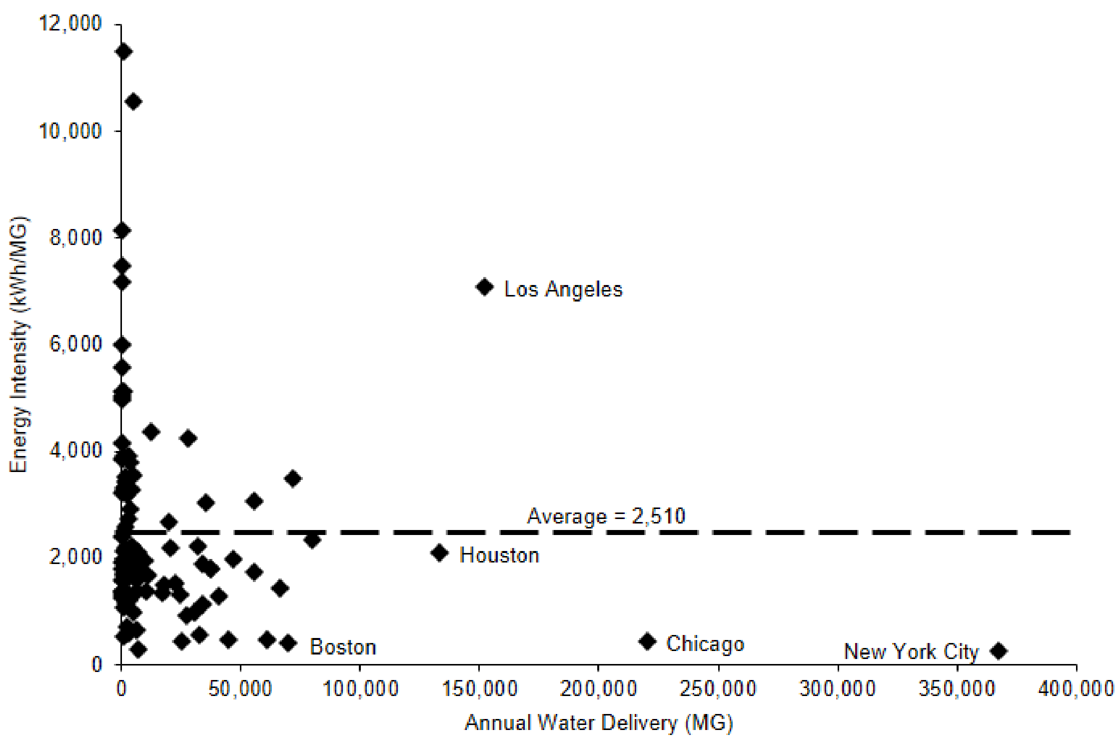

Figure 2.5 Energy Intensity vs. Annual Water Delivery

Table 2.1

Summary Statistics of National Energy Intensity 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%	100%	N/A
Groundwater Supply	Percentage of entity's total supply	33%	50%	46%	0%	100%	N/A
Imported Water Supply	Percentage of entity's total supply	0%	3%	15%	0%	90%	N/A
Other Water Supply	Percentage of entity's total supply	0%	0%	2%	0%	15%	N/A
Annual Energy Expended	Kilowatt-hours (kWh)	6,446,036	35,570,060	111,374,803	12,803	1,075,926,791	3,877,136,587
Annual Water Delivery	Million gallons (MG)	2,920	19,658	46,544	3	367,555	2,142,701
Annual Energy Intensity	Kilowatt-hours per million gallons (kWh/MG)	1,925	2,510	1,971	250	11,500	N/A

source type. Figure 2.5 shows the relationship of energy intensity to water system size, where it should be noted that the largest systems are supplied by surface water. Figure 2.6 shows differences in energy intensity for the same water system for consecutive years. Table 2.1 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 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, since inefficiencies may

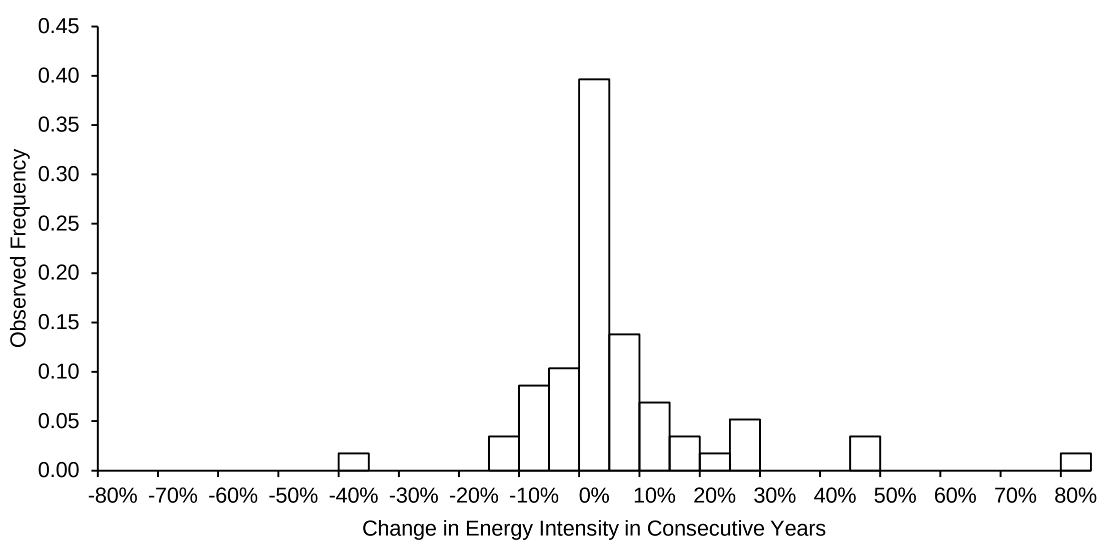

Figure 2.6 Histogram of Differences in Energy Intensity for Public Water Supply. Values compare the energy intensity of the same water system in consecutive years.

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 is associated with the survey responses. Since 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 for acceptable performance. Research by Barfuss et al. (2011) indicates that most water meters are accurate within 5%. Since 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 about 5%.

2.4 Discussion

2.4.1 Variability

The statistics of Figure 2.2 and Table 2.1 depict a wide range of energy intensities among the respondents, from 250 to 11,500 kWh/MG, with an average of 2,510 kWh/MG and a weighted average of 1,809 kWh/MG when weighted by water volume. These averages are consistent with past studies. A U.S. Department of Energy publication (DOE 2014) indicated that in 2011, 0.1 quads of electricity were expended for 44 billion gallons per day of public water supply, which equates to 1,825 kWh/MG—very near the weighted average of 1,809 kWh/MG observed here. Young (2015) reported an average of 2,300 kWh/MG and Twomey and Webber (2011) reported an average of 1,960 kWh/MG, while EPRI (2013) cited weighted averages of 1,400–2,000 kWh/MG. Though the maximum observed in this study was 11,500 kWh/MG, the right-skewed histogram of Figure 2.2 and the fitted log-normal distribution imply that even higher values are possible.

Figure 2.1 illustrates the geographic variability, confirming what others have observed from more limited data. The east–west comparison of Figure 2.3 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 2.4), 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 due to the greater conveyance distance and/or lift.

The energy intensity of a given system may change over time (Figure 2.6). Mixed interannual increases and decreases were observed throughout the panel dataset, but the net change was near zero. The causes of such changes, while 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 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, EPA 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. Since 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 2.2, or apply the constraints described below.

2.4.2 Constraints on Energy Intensity

Past 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 dataset. 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, though a few key constraints are described here.

One constraint is location (Figure 2.1). The dataset itself offers unprecedented spatial detail and captures many major U.S. cities. If the desired water system does not exist in the dataset, energy intensity from a nearby water system in a similar geographic setting, or at least the east–west differences of Figure 2.3, 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 dataset produced by this study enables others to explore related questions.

Another constraint is a water system's source type (Figure 2.4). This is a distinct constraint from location since source type and location are not strongly correlated. Knowledge of the primary water source may further refine an energy intensity estimate, since surface, ground, and imported water vary in intensity.

One key constraint identified in this analysis is a water system's size (Figure 2.5). Though there is considerable scatter throughout the dataset, an economy of scale can be observed, where 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 (DOE 2012b, 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 while 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 above constraints—location, source, and size—offers an alternative to the coarse averages used previously.

2.4.3 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 though the other information may have been readily available. ISAWWA (2012) observed similar behavior in its own study, where nearly a 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 nonwater 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 system-wide data at a minimum.

2.4.4 Applications

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

The U.S. Geological Survey, U.S. Environmental Protection Agency, and U.S. 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 above 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 where 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 dataset 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 constraints described above (location, source type, and size) to estimate a probable range of energy intensities based on system characteristics.

This study confirms that U.S. 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.

2.4.5 Limitations and Further Work

While it represents a significant improvement over previously available information, the dataset 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 dataset 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 above.

This dataset 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 datasets 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.

2.5 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 109 water systems. The resulting dataset 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-U.S. water systems are generally more energy intensive and display a wider range of energy intensities than eastern ones. 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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CHAPTER 3

STATISTICAL MODEL AND BENCHMARKING PROCEDURE FOR ENERGY USE BY PUBLIC WATER SYSTEMS

3.1 Introduction

Modern public water systems require energy to extract, treat, and deliver reliable, high-quality water to built environments. In the United States, this varies from 0.07 to 3.04 kWh/m^3 with an average of 0.48 to 0.53 kWh/m^3 (Sowby and Burian 2017a, 2017b; DOE 2014; Twomey and Webber 2011; EPRI 2013). 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 need to be understood and managed sustainably.

Despite the importance, little work has quantified or analyzed the energy requirements of public water supply, and many research needs are well documented. One recurring theme is the paucity of data, analysis, and models related to the water sector and its energy use (Healy et al. 2015; National Academies 2013; Water in the West 2013; Bazilian et al. 2011; Carlson and Wallburger 2007; Pate et al. 2007). In most cases, utility-level data are being collected but are not publicly accessible since few reporting systems or policies have been established—a curious deficiency in an era of "big data" (Chini and Stillwell 2017). Many of the available data are isolated observations, aggregated averages, or calculations that do not satisfy the resolution and quality needed by data users in government, research, engineering, and professional associations who have repeatedly acknowledged these data gaps. The identification of similar needs by these diverse stakeholders testifies of their broad significance.

This study addresses two specific problems. The first is the difficulty of quantifying water system energy requirements. Unlike water use, energy use is not typically reported by water utilities, so the data must be collected individually, as in Sowby and Burian's (2017a, 2017b) survey. If the data even exist, this primary data collection can be time consuming since most water utilities are unaccustomed to such requests. For these reasons, the literature on this subject has been sparse to date. Past efforts include average or categorized energy intensities as reported by Twomey and Webber (2011), Young (2015), EPRI (2013), DOE (2012), and a more recent survey (Sowby and Burian 2017a, 2017b). Until regular reporting is mandated and the process is streamlined, collecting energy data from a large number of water systems is daunting. A worthy contribution would be the development of an accurate statistical model, based on the observations already available, that could estimate water system energy use as a function of a few key variables and therefore substitute for otherwise infeasible primary data collection.

The second problem is the difficulty of fairly comparing energy use among diverse water systems. Even if a water system's energy use is known, judging its performance and comparing it to other water systems is another matter. Water systems and their energy consumption vary greatly for several reasons, some of which are beyond the systems' control. A small system blessed with clean, abundant surface water will have a markedly different energy footprint than a large system that pumps deep groundwater; comparing the two directly is inappropriate. Even within the same system the energy intensity can change over time, further complicating fair comparisons (Sowby and Burian 2017a). There is, therefore, a need to identify and quantify the factors that influence water systems' energy use. Researchers have supposed that water source type, utility size, conveyance distance, climate, treatment technology, infrastructure age, and topography are important factors, but little research has quantified the relative effects of each of these (Wakeel et al. 2016; Young 2015; Tidwell et al. 2014; Water in the West 2013; Twomey and Webber 2011; Klein 2005). One notable study is that of Carlson and Wallburger (2007), which explored relationships between a water utility's energy use and its water use, pumping horsepower, pipe length, and elevation difference. Once identified, such factors should be developed into a benchmarking tool that enables a more equitable comparison for the water system and its peers.

This study's objective was to produce an empirical model that can estimate water systems' energy use as a function of a few easily obtained, system-specific and geographic variables and to apply the model for energy benchmarking of water systems, thereby advancing the solution of the two aforementioned problems.

3.2 Methods

3.2.1 Definitions

Here, as in Sowby and Burian's (2017a, 2017b) study, a public water system or water utility delivers potable water to the public (more than 25 people). This definition follows that of the Safe Drinking Water Act. The entity may be publicly or privately owned. Most of the systems in this study are municipal drinking water systems.

“Energy” as used here means electricity. Other fuels are occasionally used, but since water utilities consume energy predominantly as electricity (Twomey and Webber 2011; Carlson and Wallburger 2007), the energy data used in this study are limited to electricity.

3.2.2 Data Sources

Annual water and energy use data originated from a survey of 108 U.S. water utilities by Sowby and Burian (2017a, 2017b), which represents water services for about 14% of the U.S. population. The survey also indicated the primary water source type and service population. Literature review, logical suppositions, and a few unique theories informed the selection of additional explanatory variables. To the survey dataset were added the following data, most of which are publicly available:

- Further categorization of water source types into pumped surface water, gravity-fed surface water, groundwater, and imported water based on follow-up inquiries with the survey respondents.
- Average annual precipitation (PRISM 2016a, 2016b).
- Average annual temperature (PRISM 2016a, 2016b).
- Minimum vapor pressure deficit (PRISM 2016a, 2016b).
- The county’s population density (USCB 2012).
- The county’s population growth between the 2000 and 2010 censuses (USCB 2012).
- The state’s average electricity price in 2014 (EIA 2016).
- The water system’s approximate elevation (USGS 2016).
- The standard deviation of elevation within each water system’s estimated

service area, as computed from the National Elevation Dataset (USGS 2016).

- The city's presence on a list of 50 greenest U.S. cities by *Popular Science* (Svoboda 2008).
- Results from the 2012 U.S. presidential general election (Guardian 2012).

For spatial data, values were extracted by water system location; for tabular data, the values were linked directly. Note that the foregoing variables fall into internal (e.g., system-specific) and external (e.g., climate) variables. Table 3.1 presents summary statistics.

3.2.3 Preliminary Investigation

The authors previously attempted three modeling approaches, which ultimately did not meet the study objectives. Since the main dataset was an unbalanced panel (describing water and energy use in the same water systems over multiple years), panel models with fixed and random effects were tried first (Hsaio 2003). The fixed-effects panel model was rejected since it did not consider time-invariant explanatory variables like many of those in Table 3.1. The random-effects panel model was inconsistent since its composite errors were correlated with the explanatory variables (failed Hausman test). A third model, spatial interpolation by kriging, was discarded because the underlying semivariogram was weak, showing little correlation between a water system's energy intensity and that of its neighbors, somewhat defying the first law of geography (Stein 1999; Tobler 1970). These three attempts and further literature review led to the final linear model presented here.

Table 3.1

Summary Statistics of Subject Dataset

Variable	Units	Average	Median	Standard Deviation	Minimum	Maximum
Internal Variables						
Indicator of pumped surface water supply (1 if pumped surface water constitutes >50% of supply; 0 otherwise)		0.37	0	0.49	0	1
Indicator of gravity-fed surface water supply (1 if gravity-fed surface water constitutes >50% of supply; 0 otherwise)		0.11	0	0.32	0	1
Indicator of groundwater supply (1 if groundwater constitutes >50% of supply; 0 otherwise)		0.48	0	0.50	0	1
Indicator of imported water supply (1 if imported water constitutes >50% of supply; 0 otherwise)		0.04	0	0.19	0	1
Service population	People	428,551	74,500	1,071,893	100	8,271,000
Annual energy use	Kilowatt-hours (kWh)	35,884,309	6,828,853	111,845,477	12,803	1,075,926,791
Annual water use	Cubic meters (m^3)	75,057,422	11,242,672	176,865,783	11,356	1,391,345,931
External Variables						
Average annual precipitation, 1981–2010	Centimeters (cm)	60.68	62.05	29.46	12.32	113.28
Average annual temperature, 1981–2010	Degrees Celsius (°C)	11.61	10.81	−13.68	3.02	22.71
Minimum vapor pressure deficit, 1981–2010	Millibars (mbar)	1.81	1.59	1.32	0.25	9.86
County population density, 2010	Persons per square mile	1,384	373	3,882	2	35,369
County population growth, 2000–2010	Fraction	0.14	0.11	0.14	−0.08	0.58
State average price of electricity, 2014	U.S. dollars per kilowatt-hour	0.10	0.09	0.03	0.07	0.16
Elevation	Meters (m) above sea level	606	269	693	4	2905
Standard deviation of elevation within service area	Meters (m)	109	38	145	3	584
Indicator of presence on list of 50 greenest cities (1 if on list; 0 otherwise)		0.16	0	0.37	0	1
Indicator of democratic vote in 2012 U.S. presidential election (1 if democratic vote; 0 otherwise)		0.49	0	0.50	0	1

3.2.4 Data Partitions

The observations were randomly partitioned into a training dataset (80%) and validation dataset (20%). Model development used only the training dataset; the validation dataset was hidden until after the model was developed and then tested against the model. This process helps avoid overstating the accuracy of the predictions and provides an independent measure of error which previous models have not reported.

3.2.5 Transformation

As in Carlson and Wallburger's (2007) work, the range of water utility sizes prompted a logarithmic transformation of both water use and energy use. The transformation produces a strong linear relationship between the two that serves as the basis for further specification. By linearizing the data, the transformation overcomes some of the weaknesses of the attempts described above. Since the relationship is nearly linear, ordinary least squares (OLS) regression was selected for modeling using the cross-section for the most recent year in the panel dataset.

Figure 3.1 shows the transformed datasets of Carlson and Wallburger (2007) and Sowby and Burian (2017a, 2017b) in the same units. The range, slope, intercept, and R^2 are very similar, demonstrating that the two studies, in which all data were self-reported and otherwise could not be verified, corroborate each other.

3.2.6 Model Specification

Specification followed three minimum criteria:

1. The absolute value of all individual test statistics exceeds 2.0. This corresponds to a Type I error probability of about 0.05 or less and follows

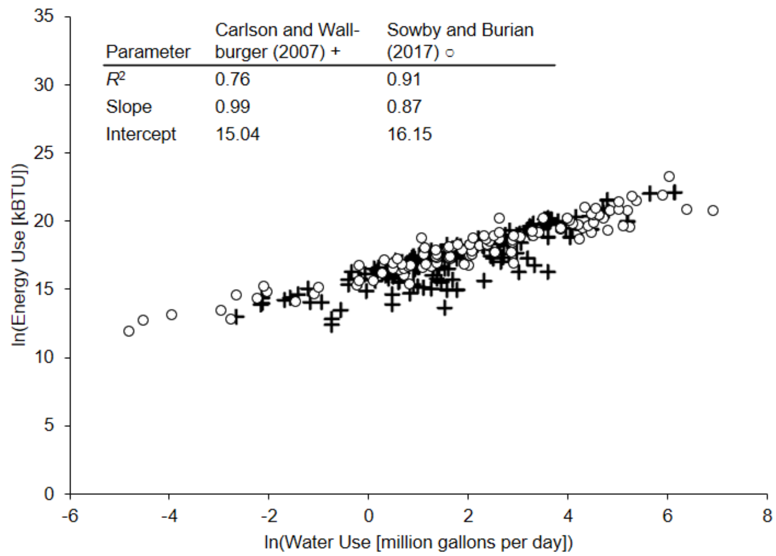


Figure 3.1 Comparison of Two Datasets on Water System Energy Use
(Carlson and Wallburger [2007] figure reprinted with permission. © Water Research Foundation.)

Carlson and Wallburger's (2007) stepwise method.

2. The adjusted R^2 exceeds 0.87, offering an improvement in fit over Carlson and Wallburger's (2007) model. This metric describes the overall fit on a scale from 0 to 1.

3. The model's root mean square error (RMSE) does not exceed 1.79, offering an improvement in accuracy over Carlson and Wallburger's (2007) model (when converted to kilowatt-hour basis). This metric describes the overall accuracy of the predictions relative to the range of observed values.

All model criteria had to be balanced. For example, models without an intercept produced a near-perfect adjusted R^2 (> 0.99) but yielded unacceptably high errors (RMSE > 2.5). A desirable but optional feature was the similarity of RMSE between the training and validation datasets when the model was applied, which would indicate that the model is not prone to overfitting.

3.3 Results and Discussion

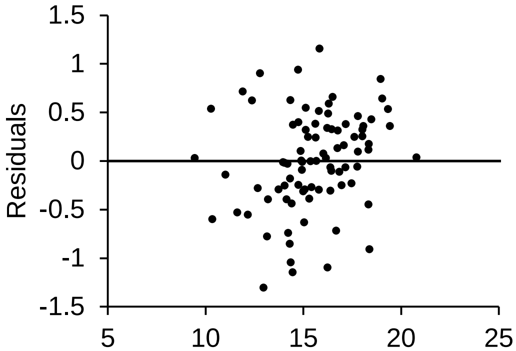
3.3.1 Model Results

The model, presented in Table 3.2, includes five statistically significant variables plus an intercept. All test statistics exceed an absolute value of 2.0, the adjusted R^2 value is 0.9447, and the RMSE is 0.4989, satisfying all three minimum requirements. Figure 3.2 shows model residuals for each variable. Applying the model to the validation dataset yields an RMSE of 0.5183, which closely matches the model dataset's RMSE of 0.4989, demonstrating that the model performs well on an independent sample.

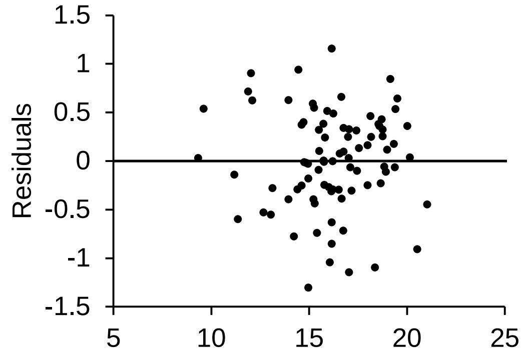
Table 3.2

Model Results for Natural Logarithm of Water System Energy Use

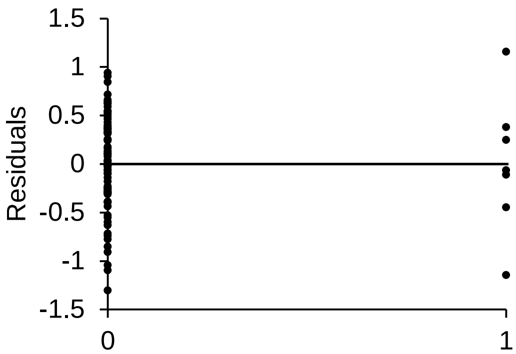
Variable	Coefficient	Standard Error	Test Statistic
Natural logarithm of annual water use in cubic meters	0.8934	0.0287	31.10
Indicator of gravity-fed water supply (>50%)	−0.9494	0.2140	−4.44
Indicator of imported water supply (>50%)	1.2759	0.2726	4.68
Average annual precipitation in centimeters	−0.0054	0.0021	−2.62
Average annual temperature in degrees Celsius	0.0360	0.0164	2.20
Intercept	0.9713	0.3991	36.66
R^2	0.9480		
Adjusted R^2	0.9447		
Root Mean Square Error	0.4989		
Number of Observations	86		



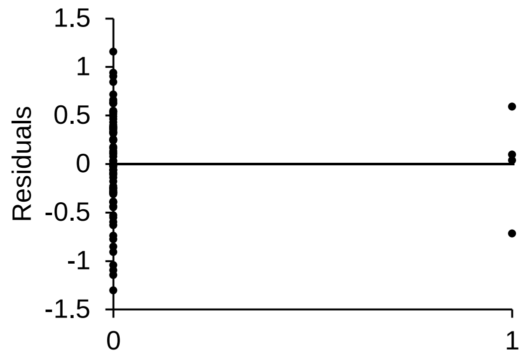
(a) Natural logarithm of annual energy use (kWh)



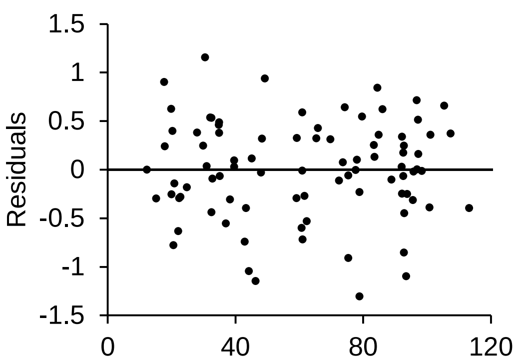
(b) Natural logarithm of annual water use (m^3)



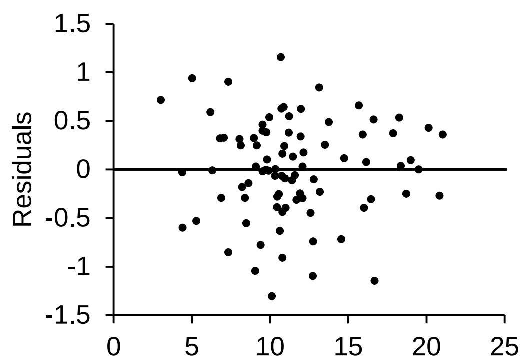
(c) Indicator of gravity-fed surface water



(d) Indicator of imported water



(e) Average annual precipitation (cm)



(f) Average annual temperature (°C)

Figure 3.2 Model Residuals

3.3.2 Magnitudes and Signs of Coefficients

The size of the water system, expressed here as the natural logarithm of its water use, is the most influential factor and correlates positively with energy use. This finding matches that of Carlson and Wallburger (2007). The two extreme water supply types, gravity and imported, have negative and positive coefficients, respectively. Gravity-fed water requires less pumping and therefore less energy, while imported water requires more energy for its conveyance over greater distances and elevations. This variable explains the low energy intensities observed in the water systems of Portland, Denver, New York, and Boston—all which have high-head surface water sources—and the high energy intensities observed in southern California, where water is conveyed hundreds of miles over hundreds of meters of elevation gain before arriving at the point of use.

Precipitation, which shows a negative coefficient, could indicate the wetness of a location and its tendency to have abundant surface water, which is generally more accessible and less energy intensive than groundwater or imported water. Temperature exhibits a positive coefficient, suggesting that warmer regions require more energy for water supply, perhaps because of greater water demand relative to cooler areas and the need for more marginal water sources. Together, these findings support the theories mentioned earlier about what factors influence a water system's energy footprint.

3.3.3 Residuals

The residuals in Figure 3.2 show random, symmetric dispersion without clear correlation to the parameter values, indicating that linear regression is appropriate. While the indicator variables equal to 1 in Figure 3.2(c) and (d) are relatively few, these were nonetheless found to be statistically significant according to the criteria presented earlier.

3.3.4 Fit and Accuracy

The adjusted R^2 value of 0.9447 indicates excellent overall fit. The model predicts the natural logarithm of the water system's energy use within −7% to +10% when using the training dataset, and within −6% to +5% when using the validation dataset. The RMSEs for the training and validation datasets are nearly equal—0.4989 and 0.5183, respectively—demonstrating that the model performs equally well on an independent sample. The measures of adjusted R^2 and RMSE and the provision of an independent error estimate are substantial improvements over previous models.

3.3.5 Limitations and Future Work

Examining the observations that differ most from their predictions tells where the model still does not perform well. The differences tend to decrease with system size, but the correlation is weak. No common characteristics were found that would immediately suggest an additional variable. Future work may refine this model and/or produce new models with greater power and accuracy to explain how much energy a water system consumes. Further, many water systems' energy footprints are shrinking as a result of improved energy management practices (Sowby 2016; see Appendix A), reinforcing the need to continually collect data on this subject.

3.4 Applications

3.4.1 Energy Use Estimation

Since energy data in the water sector are difficult to obtain (Chini and Stillwell 2017; Sowby and Burian 2017a), the model offers an alternative to resource-intensive primary data collection as a means to estimate water system energy footprints. The only multivariable model found in the literature review was that of Carlson and Wallburger (2007), which relied on detailed water system characteristics and/or other obscure data that limit its applicability, especially to studies of numerous systems. The model presented here overcomes these challenges by using only basic water system characteristics and publicly available climate data. It may be used, at least initially, to estimate a water system's energy use until firm data become available.

3.4.2 Energy Benchmarking

As discussed earlier, one of the difficulties in developing energy benchmarks and related sustainability metrics for water systems is the great variability in system characteristics that influence their energy use and complicate fair comparisons. The model overcomes much of this difficulty by quantifying the effects of a few pertinent characteristics that would otherwise render the comparison inappropriate if not impossible.

The natural logarithms of energy use are nearly normally distributed with mean 15.59 and standard deviation 2.16. Figure 3.3 shows the actual observations and a cumulative normal distribution curve. Both are reversed so a low energy use corresponds to a higher percentile. For the purposes of benchmarking, the distribution is considered to be exactly normal.

Consider a water system of given characteristics and an observed energy use whose natural logarithm is y. Given these characteristics, the model will predict the natural logarithm of energy use for a theoretical water system with the same characteristics, called $\hat{y}$. The ratio $y/\hat{y}$ indicates how much higher or lower the actual

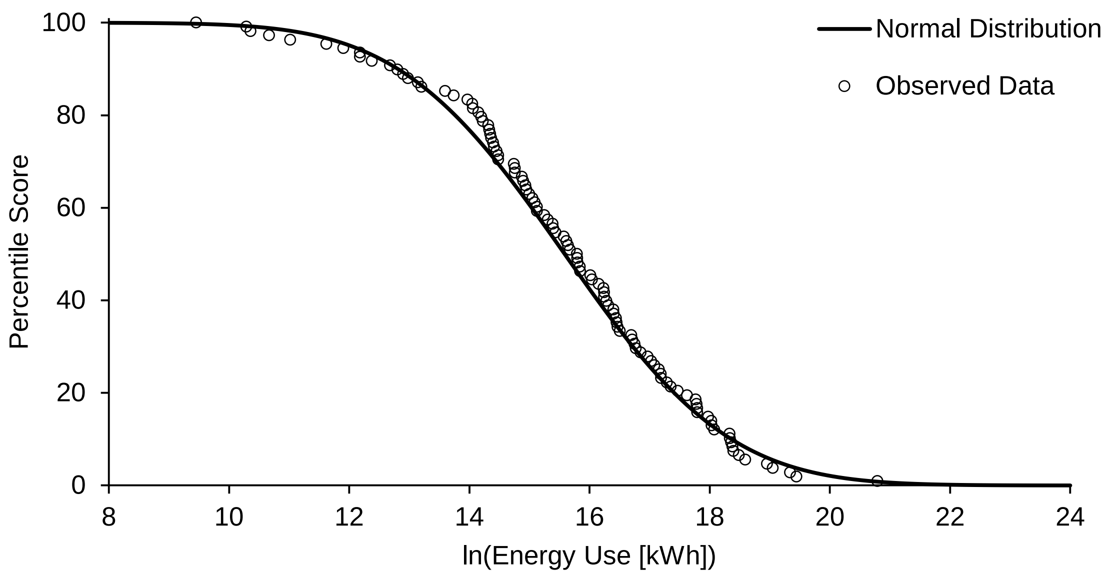


Figure 3.3 Water System Energy Use Distribution

energy use is relative to the predicted value. There also exists a sample mean, $\hat{y}_{\text{mean}}$, which may be used to scale the ratio to the sample.

Using these three numbers, one may compare the water system to its theoretical peers:

$$E_{\text{adj}} = \hat{y}_{\text{mean}} \frac{y}{\hat{y}} \tag{3.1}$$

where E_{adj} is the natural logarithm of adjusted energy use, $\hat{y}_{\text{mean}}$ is the sample mean (here, 15.59), y is the natural logarithm of the observed energy use, and $\hat{y}$ is the natural logarithm of the predicted energy use (or, more precisely, the expected energy use of a theoretical water system with the same characteristics). The value of E_{adj} corresponds to a percentile ranking on the curve of Figure 3.3, assuming that the normal distribution applies to the theoretical peers as well as to the overall sample. This method follows that of Carlson and Wallburger (2007).

As an example, consider the water system described in Table 3.3 that delivered 102,865,000 m^3 of water in one year. The natural logarithm of its observed energy use (20,379,000 kWh) is 16.83. Using the same characteristics, the model predicts a value of 17.21. The ratio of these two is 0.9779, indicating that the observed energy use is somewhat less than predicted. Multiplying by the sample mean 15.59, the adjusted natural logarithm of energy use is 15.25. On the curve of Figure 3.4, this value corresponds to the 57th percentile, or a score of 57 out of 100 among its peers, slightly above average.

Applying the benchmark procedure to Sowby and Burian’s (2017b) dataset, several dissimilar water utilities actually have the same score. For example, the water systems serving Boise, Denver, and Tampa—although they differ in size, topography, water supply, and climate—all score 55. Likewise, water systems serving Houston,

Table 3.3

Water System Energy Benchmarking Example

Variable	Value	Coefficient	Product
Natural logarithm of annual water use in cubic meters	18.45	0.8934	16.4828
Indicator of gravity-fed water supply	1	−0.9494	−0.9494
Indicator of imported water supply	0	1.2759	0.0000
Average annual precipitation in centimeters	18.29	−0.0054	−0.0985
Average annual temperature in degrees Celsius	22.3	0.0360	0.8039
Intercept	1	0.9713	0.9713
			Sum = 17.21
Natural logarithm of observed energy use (y)	16.83		
Natural logarithm of predicted energy use ($\hat{y}$)	17.21		
Sample mean ($\hat{y}_{\text{mean}}$)	15.59		
Natural logarithm of adjusted energy use (E_{adj})	15.25		
Percentile score	57/100		

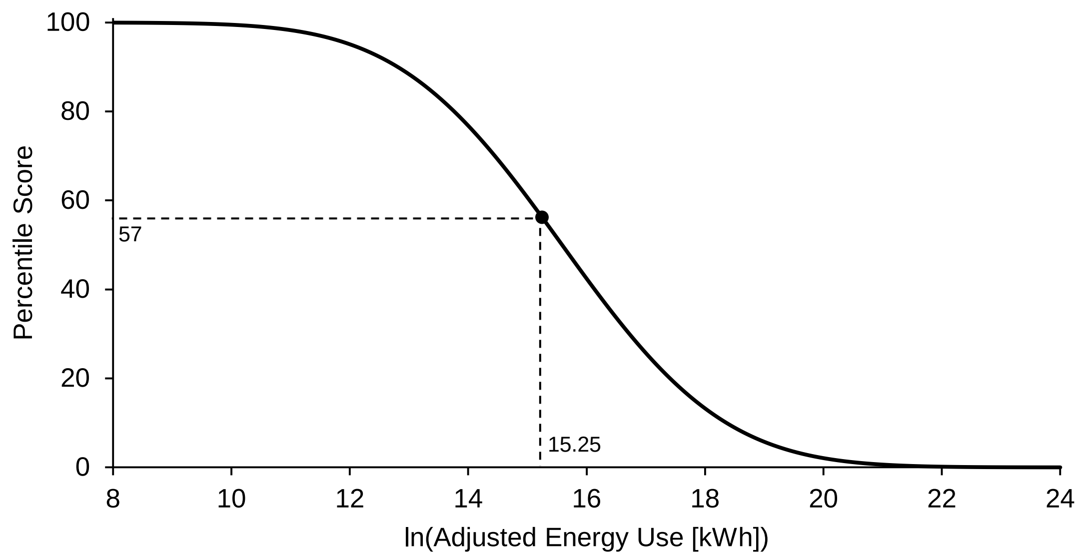


Figure 3.4 Benchmark Application Example

Milwaukee, and St. Louis all score 46. Both cases demonstrate how the model normalizes great differences and identifies groups of similar performers.

This method can also be used to evaluate what magnitude of energy reductions are needed to achieve a higher score (thus defining an energy savings goal) or what impact proposed energy management projects will have. The water system may then pursue the energy savings using power company programs, qualified consultants, and/or published energy management guidance (AWWA 2016; Jones and Sowby 2014; UDDW 2014; Liu et al. 2012; NYSERDA 2010; EPA 2008). Energy management in the water sector is a major sustainability opportunity, and many water systems have already achieved significant energy savings (Sowby 2016; see Appendix A), while new research and resources will continue to promote energy reductions.

Jordan Valley Water Conservancy District, for example, serves the greater Salt Lake City area. Using this benchmarking procedure and data provided by the District

(Todd Schultz, pers. comm.), its 2013 score would have been 37. In 2014 the District began an energy management program that delivered verified energy savings (Sowby et al., forthcoming). The District's 2014 and 2015 scores increased to 41 and 42, respectively, illustrating the incremental improvement likely attributed to the program.

3.5 Summary and Conclusions

Based on a recent survey and public datasets, a model of water system energy use was developed that offers improvements in accuracy and applicability over previous models. While more sophisticated methods and more exact models may follow, this study identified a few important internal and external characteristics—water use, water source type, precipitation, and temperature—that are easily obtained. The model can provide reasonable estimates of energy use where primary data collection is infeasible. Since it explains much of the variation in energy use among water systems, the model is conducive to energy benchmarking, peer comparisons, and energy management planning.

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CHAPTER 4

HIGH-RESOLUTION ENERGY INTENSITY MODELING TO IMPROVE WATER DISTRIBUTION SYSTEM PERFORMANCE

4.1 Introduction

Water distribution systems require energy to extract, treat, and deliver reliable, high-quality water. This energy use has financial, environmental, and social impacts that suggest a need to manage it sustainably. Energy can consume up to 40% of a water utility's operating budget; this proportion is expected to increase with scarcer water supplies and stricter water quality standards (EPA 2016). Environmental impacts include the emissions and ecological considerations associated with generating power for water services (Lane et al. 2015; Ramos et al. 2010; Griffiths-Sattenspiel and Wilson 2009; Stokes and Horvath 2009). On the social side, stakeholders 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 2009).

Water utilities can improve their sustainability by identifying and implementing the most energy-efficient scheme for water delivery that still satisfies the prescribed level of service and water quality (Jones and Sowby 2014). The motivation for water utilities to reduce their energy use is clear and much guidance has appeared in recent years (AWWA 2016; UDDW 2014; Liu et al. 2012; NYSERDA 2010; EPA 2008). Some of the most common practices include:

- Determining baseline energy intensity and monitoring regularly
- Auditing water and energy use simultaneously
- Upgrading aged or improperly designed equipment
- Prioritizing efficient water sources
- Prioritizing efficient conveyance paths
- Increasing storage utilization to balance loads
- Adjusting pressure-reducing valves to minimize unnecessary flow
- Eliminating redundant pumping
- Shutting down nonessential facilities (permanently or seasonally)
- Controlling water loss

While this general guidance is helpful, each water distribution system is unique and still requires individual attention and analysis to identify and implement energy management practices. However, the optimum scheme is difficult to determine, especially for complex systems with many pressure zones, water sources, and pumping facilities; it is not always clear how water uses correspond to energy inputs. For the purposes of improving energy performance, these fluxes should be computed and understood, and then tested against alternatives to find, for example, an acceptable operational scheme that minimizes energy use. Water system energy management efforts "require clear, defensible calculations of the energy embedded" and "must account for energy inputs at all stages of the water life cycle" in order to be justified (Spang and Loge 2015). Beyond the practical application to water utilities, several research spaces could benefit from this capability, such as those involving water/energy optimization, system dynamics models, life cycle assessment, electric grid reliability, water supply reliability, and the broader water–energy nexus.

The concept of energy intensity is central to understanding this problem. In Wilkinson's (2000) words, "Energy intensity is the total amount of energy … required for the use of a given amount of water in a specific location." It is an energy footprint specific to water. Also called embedded energy or specific energy, it is the ratio of energy inputs to water volume, often expressed in kilowatt-hours per million gallons (kWh/MG). The locations for which energy intensity is computed may be entire water distribution systems, as by Sowby and Burian (2017a, 2017b); pressure zones, as by Saliba and Gan (2006) and Spang and Loge (2013, 2015); or individual end users, as by Siddiqi and Fletcher (2015). There is also a temporal dimension where energy intensity varies over time at each of these spatial scales (Sowby and Burian 2017a; Spang and Loge 2013, 2015). Note that "energy intensity" should not be confused with "energy grade line" or similar energy-related terms used in hydraulic engineering.

Studies of "embedded water" or "virtual water" employ a related approach to determine the amount of water used to make common products like meat, clothing, and lumber by considering each step of the associated supply chain (Hoekstra 2011; Hoekstra 2003; Hoekstra and Hung 2002). The concept was first developed to quantify and map international water dependencies and to understand how water-scarce countries could provide water-intensive goods to their inhabitants and has been the foundation of recommendations for private, public, and nonprofit organizations to reduce their water impacts.

Similarly, mapping energy intensity in water distribution systems—where the product of interest is drinking water and the embedded resource is energy—could inform recommendations to improve performance and reduce energy impacts, as well as to better understand system behavior. However, looking at the product (water delivered to the user) does not tell the whole story. The embedment is to be determined spatially and temporally across an entire water distribution system by computing each energetic path from beginning to end. For a simple system with only one pressure zone and one water source, the determination is almost trivial, but for large systems with many sources, facilities, and pressure zones where waters of differing energy intensity move and mix, the determination is resource intensive. For this reason, there is an "absence of studies capturing the spatial aspect of the [water–energy] nexus problem" (Vakilifard et al. 2017) and almost all previous studies of the subject stop short of linking energy impacts to site-specific water use (Spang and Loge 2015).

The difficulty of computing energy intensity increases with both system complexity and level of spatial and temporal detail for three reasons. First, the degree of hydraulic and energetic connectivity increases from the national scale to the water utility scale. Second, each step in the process adds energy intensity to the same volume of water, so the energy intensity accumulates along the water supply chain from source to use. This is a one-way operation, and energy intensity cannot be subtracted (except in the rare case of energy recovery). Finally, as the water moves through the system, it may mix with other waters of differing energy intensity, losing any uniqueness carried from a given source. At a service connection, for example, the energy is embedded before the water arrives, and since energy has no physical signature, unlike mass constituents, it cannot be observed in a water sample. Given flow and pressure, one may calculate the theoretical energy required, but nothing in the calculation indicates whether the supply is gravity fed (with an energy intensity near zero) or pumped several times to arrive there. The accumulated energy intensity can be determined *only* by modeling. One must therefore know the water's history: its origins and paths and the energy intensities associated with them.

To illustrate the complexity, consider a parcel of deep, brackish groundwater. A well extracts the parcel, adding energy in the process. The parcel then undergoes treatment, which adds more energy. A pump station then adds energy to pressurize it for service. The parcel is the same size, but energy has been added three times already. After pumping, the parcel travels through the distribution system where it encounters another parcel from a different water source with a different energy intensity, and the two blend instantly. Farther on, a third parcel blends in. The resulting parcel, equal in volume to the original one, is delivered to and consumed at a commercial property. How much energy was embedded in the consumed parcel? In other words, how much energy was expended to deliver that parcel of water to the commercial property? Since the parcel's history is known, one may determine its energy intensity by analyzing the energy inputs along each of the three paths. This exercise does not work in reverse: nothing about the consumed parcel itself informs the determination. The question is only answerable when the hydraulic pathways and the associated energy inputs are known.

This is different from the basic energy calculations built into most hydraulic modeling software, which compute pump energy intensities from user inputs and report overall system energy consumption from pump runtimes. These calculations only give the energy intensity of pumps and do not provide energy intensities for other processes (like treatment) or indicate how much energy is required for water delivery at points within the system. Beyond these basic features, a more insightful method is needed to model energy intensity everywhere in the system over time and produce useful data and visualizations. Once the energy intensity of water delivery at a particular point and its variation over time are understood, a modeler may begin exploring alternatives by which to conserve energy.

Some inspiration may be drawn from the field of energy density maps or community energy mapping. This tool combines disaggregated or mildly aggregated energy consumption data with spatial data and, in the past few years, has become a useful tool for community energy planning and sustainability engagement (Webster et al. 2011; Reul and Michaels 2012; Ea Energy Analyses and GRAS 2012; Gilmour and McNally 2010). Reul and Michaels (2012) observed that energy mapping reveals “energy gushers” where a large potential exists for energy savings. Gilmour and McNally (2010) stressed the importance of visual techniques for understanding the impacts.

Saliba and Gan (2006) and Spang and Loge (2013, 2015) applied similar concepts to study energy intensity differences within an individual water distribution system at the pressure-zone level using facility energy data and geographic information systems (GIS). Both enabled energy calculations at finer geographic resolution to prioritize site-specific water and energy conservation actions that would not have emerged from a lumped, system-wide analysis that obscures significant temporal and spatial effects. However, their spatial analyses did not penetrate to individual nodes and links and did not capture energy intensity changes over time. Currently there is no mechanism to model energy intensities at fine scales in water distribution systems. Such a mechanism must consider the entire supply chain from energy demand to water delivery, a chain that becomes increasingly interconnected at finer scales.

Water and energy demands are generally well understood when considered in isolation, but the processes that “convert” energy to water (i.e., use energy to provide water) are not. The main gap here is understanding what occurs in the black box between energy demand and water delivery: the operation of the water system’s facilities. Water demand, assumed to be fixed for a given scenario, triggers an operational scheme (one of many potential operational schemes), which triggers energy demand (reacting to the system’s needs); in turn, energy provision enables system operation, which enables water delivery. This framework explains the service chain from energy demand to water demand, but there is as yet no mechanism to model it or determine how energy is translated through the system and ultimately reappears as embedded energy during water delivery.

One specific research question to be answered is, how does energy intensity within the water distribution system respond to operational changes such as water source selection and facility shutdowns, or the other energy management practices listed earlier? Another is, how can such analysis inform decisions to implement energy management practices and operate more sustainably? This study builds on past efforts and addresses a key research gap by proposing, documenting, demonstrating, and validating a high-resolution technique for modeling energy intensity within a water distribution system.

4.2 Methods

One gap noted above is the lack of a mechanism to model the exact paths by which energy is embedded in water via the system, between energy demand and water delivery. The combination of two existing tools and the concept of “conservation of a general property” bridges this gap. For individual water systems, tools called “energy maps” quantify each water facility’s energy requirements and have been effective in informing operational decisions to reduce energy use (McWilliams et al. 2017; Sowby et al. 2017; Jones and Sowby 2014). An energy map characterizes water facilities by their energy use and thereby links them to the electric grid. Equipped with an energy map, a water system may make data-driven decisions about prioritizing the least-energy-intensive water sources and other facilities in a given demand scenario, or add energy considerations to existing operational criteria for water quality, water rights, seasonal availability, and other constraints. It is much like currency exchange, where each facility in the system has a different exchange rate: kilowatt-hours may be traded for gallons anywhere in the system, but certain locations may offer a better deal. Going the other direction, extended-period hydraulic models, e.g., EPANET (Rossman 2000), simulate water system behavior and link a water system’s facilities to individual water demands. As such, they are important for considering the system’s constraints when testing alternatives.

The important common component between the energy map and the hydraulic model is the operation of water system facilities, being the means by which energy inputs are exchanged for water outputs (Figure 4.1). Combined, the two tools offer a framework for modeling energy-for-water interactions and a novel way to track energy from its origin in the grid, through its embedment into water via operation of the water system, and to its fate among water users. Using the energy map inside the hydraulic model completes the picture of modeling interactions along both hydraulic and energetic

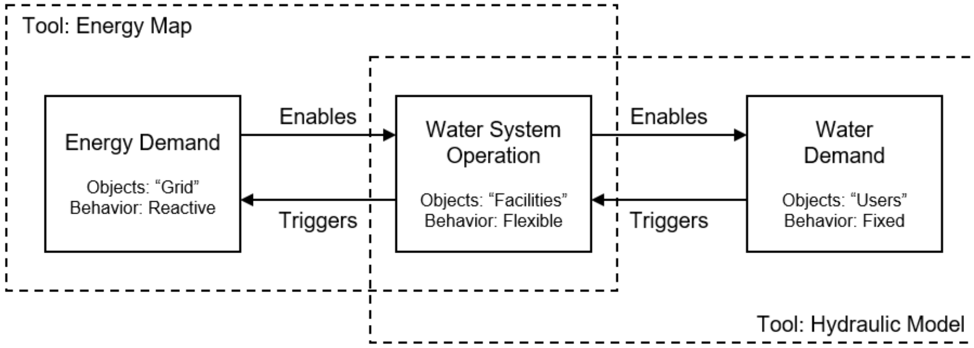

Figure 4.1 Energy-for-Water Framework

pathways. A corresponding framework could be developed for the opposite side of the nexus, water-for-energy.

Since energy becomes embedded with the water, the method requires that energy flows be modeled at the same resolution as hydraulics. For this reason, the authors propose that energy intensity be considered a conservative general property. This idea rests on two assumptions: 1) that energy intensity is a property concentration of energy per volume, analogous to a chemical concentration of mass per volume; and 2) that energy intensity is conservative, with no internal growth or decay. These assumptions are discussed in Appendix D.

With energy intensity treated as a conservative general property, the approach leverages existing modeling technology and significantly streamlines energy analysis in complex systems. Since the hydraulic model already computes the hydraulics for transport and mixing, the modeler may develop an energy intensity simulation by specifying energy intensities instead of chemical concentrations and by setting the proper reaction terms, initial conditions, and boundary conditions. The energy intensity of each energy-using element in the model must be known and defined. This requires selecting an energy node and specifying the source quality for each as described below.

4.2.1 Modeling Requirements

With energy intensity as a conservative general property, it follows that the same principles govern its transport, mixing, and fate in the system. Modeling this behavior requires that the energy intensities input into the model match the model element, whether it is a single pump or an entire facility or process; the absolute scale is not important.

The method requires an extended-period simulation (EPS) hydraulic model of the system whose completeness, calibration, and accuracy are satisfactory. Unlike water quality, additional calibration of energy intensity results is impossible since the quantities cannot be determined by sampling and since any conservative constituent has, by definition, no reaction and therefore no reaction coefficients to adjust (Clark 2012). The results can be determined only by modeling and depend entirely on the energy inputs and the underlying hydraulics, so both must be sound. The results may, however, be confirmed by observing energy performance before and after implementing changes identified from the modeling.

The method proposed here is compatible with major hydraulic modeling software packages. For simplicity, this study uses EPANET, a free computer program developed by the U.S. Environmental Protection Agency (Rossman 2000). Terminology and procedures may differ among other packages, but the same concepts apply.

4.2.2 Energy Intensity Determination

In a water distribution system, each energy-using element—a pump station, a well, or a treatment facility, for example—has an energy intensity. The energy intensities of any energy-using elements must be determined for input as “source quality” in the model. This exercise is straightforward, and three methods are common.

First, where water and energy records are available for the same time period, the element's average energy intensity for that time period may be calculated as the ratio of energy usage to water volume and input directly. This is the preferred method since it captures observed behavior. Second, if the total head and wire-to-water efficiency are known, as from a pump curve, the expected energy intensity may be computed from first principles (see Appendix D). A third method, applicable to water treatment plants, is to look up energy intensities in a library of plant features published by EPRI (2013). In any case, an element's energy intensity may change over time depending on equipment, operations, and other conditions (Spang and Loge 2013), so the value(s) chosen for model input should correspond to the time period(s) being studied.

Since energy intensities, and not energy grade lines, are of interest here, it is not appropriate to include "losses" in the hydraulic sense. Energy intensity refers to the one-way embedment of energy inputs into the water system, not the hydraulic behavior. Energy losses in the hydraulic sense are not subtracted from the energy intensity. The total energy intensity should already include these losses, much like a pump design should anticipate dynamic head losses.

Table 4.1 summarizes the options for determining energy intensity inputs for modeling. A selection of typical energy intensities for common facilities based on EPRI (2013) is found in Appendix D.

4.2.3 Energy Nodes

For each energy-using element, the modeler must select a node at which to "inject" the energy intensity. This will be called the energy node. As a consistent

Table 4.1

Methods for Determining Energy Intensities for Water Supply

	Pump	Plant	Custom
Direct Input (use observed data)		1. Select control volume (facility of interest) 2. Select period of interest 3. Observe energy use and water volume processed in control volume during period of interest 4. Compute: $EI = \frac{\Sigma E}{\Sigma V}$	
Calculation (use equations)	1. Determine total dynamic head in feet (h) 2. Determine typical efficiency as decimal (η) 3. Compute: $EI = \frac{3.14h}{\eta}$ (see Appendix)	Not applicable	Not applicable
Library Lookup (use literature)	Not applicable	1. Determine average plant flow rate 2. Determine unit processes 3. Look up in EPRI (2013) Table 4-2	Not applicable

Notes:
1. Units: Energy assumed to be in kilowatt-hours (kWh), water assumed to be in million gallons (MG), and energy intensity assumed to be kilowatt-hours per million gallons (kWh/MG).
2. Observations of energy use will likely include nonhydraulic loads like lighting, heating, cooling, and controls.
3. Calculations do not include the extraneous energy uses in Note 2, which must be added for complete energy intensity.

practice, it is recommended that the energy node be at or immediately downstream of any location where energy is added to the system. This applies whether the element adds energy and produces water (e.g., a well) or only adds energy (e.g., a pump station between pressure zones). See Figure 4.2 for examples.

4.2.4 Energy Intensity Entry

After identifying energy nodes, the modeler must specify each one's energy intensity as the source quality. This is a set of nodal properties that define the concentration, behavior, and time pattern. Energy intensity (kWh/MG) is entered in place of the concentration. This value must correspond to the energy intensity of the element being modeled and will be constant in the simulation unless an optional time pattern (a user-defined set of multipliers) is specified. The source type should be specified such that it adds a fixed concentration to the resulting inflow concentration at the node; in EPANET this is a flow-paced booster (Rossman 2000). Since energy intensity is a property concentration and is cumulative through the water delivery process, this option applies to all energy nodes and represents the continuous "dosing" of energy intensity into the system.

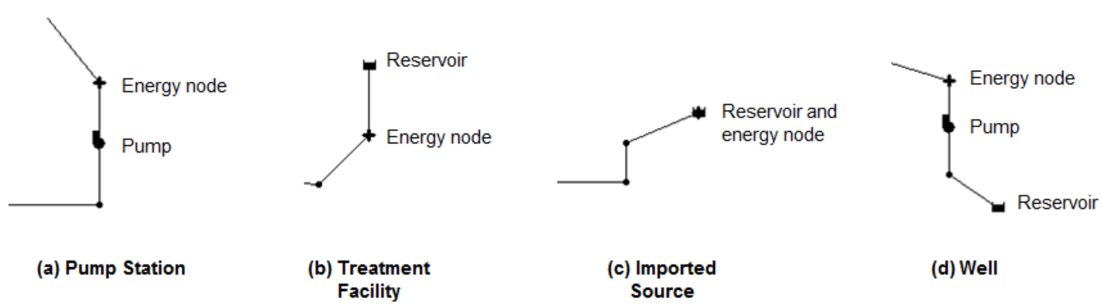

Figure 4.2 Energy Node Examples

4.2.5 Simulation Setup

Once the foregoing steps are complete and energy nodes and source qualities are defined, the modeler may set up the energy intensity simulation. Since energy intensity is modeled as a conservative constituent, only the bulk and wall coefficients (which would otherwise govern in-pipe chemical reactions) are of interest, and both are zero because there are no reactions. The reaction order and the limiting concentration are irrelevant but should be set to zero to avoid confusion. These are the same values one would specify for a nonreactive tracer as suggested by Rossman (2000) and Clark (2012). No reaction is occurring in the fluid; the energy intensity is merely being transported and mixed in the network.

The simulation's total duration should be long enough, usually several days, to allow energy intensities to stabilize or reach a repeating pattern. Especially in extensive systems and/or those with significant storage volumes, the simulation must be long enough for water produced during the simulation to reach all points of the system. The user must interpret the concentrations according to the units in which they were defined (e.g., kWh/MG).

4.2.6 Visualization and Interpretation

Once the simulation is run, the modeler may display the results in the network map with user-defined colors and value ranges. This produces system-wide maps of energy intensity at every time step, thereby illustrating the temporal and spatial variation of energy intensity within a water distribution system with node-and-link resolution. The data may be exported to a geographic information system (GIS) for further analytical and cartographic options. Only basic visualizations are used here, and more advanced ones are reserved for future research.

4.3 Case Study

4.3.1 Study Model

A case study with an actual water distribution system will demonstrate the modeling method and its value in answering the research questions for a specific water distribution system, with generalizable applications to others.

The study subject is the water distribution system of Eagle Mountain City, Utah, USA. The system provides water for indoor and outdoor uses to a population of 29,000 in residential and rural settings. The system is laid out in three pressure zones (nos. 1–3, from lowest to highest). Four wells (nos. 1, 2, 3, and 5) and one wholesale connection (which must be pumped) supply all water to Zone 2. Two boosters move water from Zone 2 to Zone 3; pressure-reducing valves (PRVs) allow water to descend from Zone 2 to Zone 1. Five water tanks provide equalization storage. The City provided a calibrated EPANET hydraulic model, flow records, and energy use data during a recent project with engineering consultant Hansen, Allen & Luce (2016) and subsequently authorized their use in this research. The hydraulic model contains about 1,300 links and 1,000 nodes, and its average water demand is 6,500 gpm. Figure 4.3 shows the system as defined in the model.

4.3.2 Energy Analysis Preparation

The hydraulic model had already been calibrated and used specifically for energy analysis, so its application to this research is appropriate. Following a sensitivity analysis described in Appendix D, the authors judged the model to be adequate for understanding

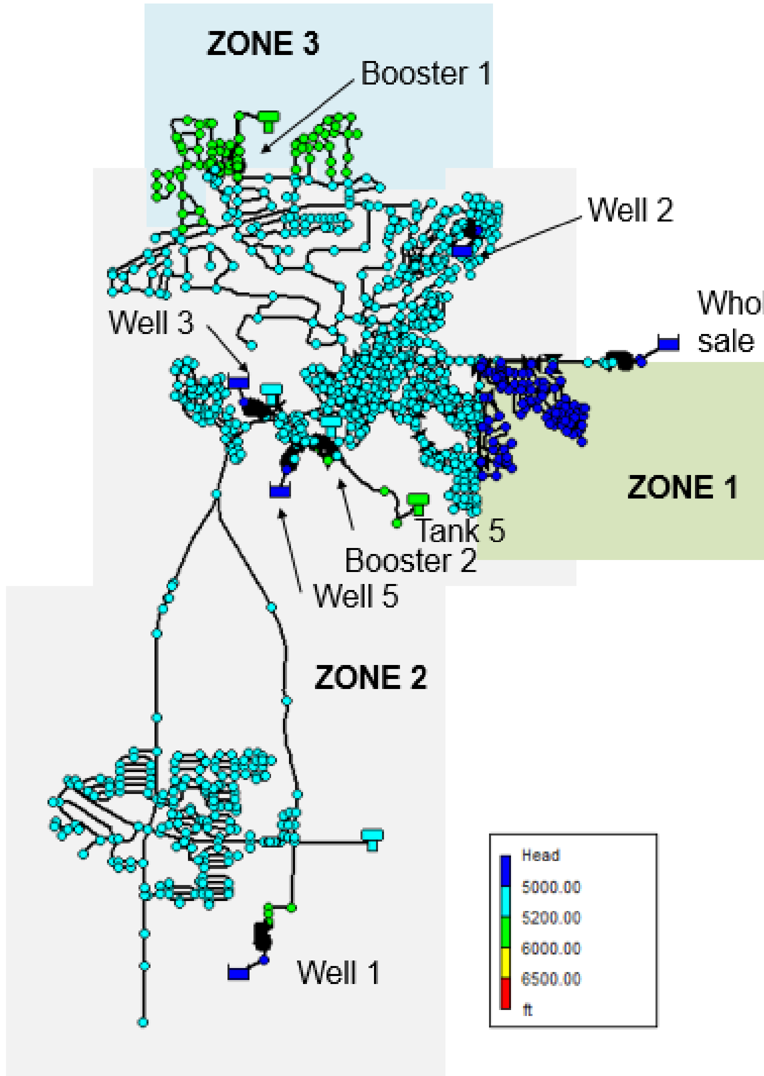

Figure 4.3 Eagle Mountain Water System Model

the proposed technique. Energy intensity inputs were found to be the most influential parameters, with a linear effect that underscores the importance of accurate determination.

The first step was therefore to determine the energy intensities of all relevant facilities—the energy map. For wells, the energy intensities were determined by Method A, Direct Input, in Table 4.1. The average energy intensity for each facility was calculated from historic records by dividing its total energy use by its total water use over a one-year period. Monthly data were available, but billing periods between water and electricity could not be matched exactly for an accurate ratio, so the annual average was chosen as a representative value. For boosters, in which flows were not metered, the energy intensities were determined by Method B, Calculation, in Table 4.1, using the design heads and efficiencies from their respective pump curves. Table 4.2 shows the results.

Table 4.2 indicates that Well 1 is the least-energy intensive well; the wholesale connection is comparable. The next-best is Well 3, which requires about 30% more energy for the same amount of water. Just having this energy map—a normalized quantification of each facility's energy use—is immensely valuable. This case study goes one step further by using this information inside the hydraulic model, which enables calculation and visualization of energy intensities throughout the distribution network.

Since the energy-using facilities of Table 4.2 are represented as pumps in the model, the energy nodes were chosen as the first nodes downstream of the pumps. At

Table 4.2

Water Facility Energy Intensities

Facility	Pressure Zone Served	Average Energy Intensity (kWh/MG)
Well 1	Zone 2	1,692
Well 2	Zone 2	2,844
Well 3	Zone 2	2,712
Well 5	Zone 2	2,487
Wholesale	Zone 2	1,618
Booster 1	Zone 3	820
Booster 2	Zone 3	816

each of these locations the source quality was set using the energy intensity values in Table 4.2 with the type option set to flow-paced booster. No time pattern was specified since an average (static) energy intensity is to be used. The bulk and wall reaction orders, their coefficients, and the limiting concentration were set to zero as for a conservative constituent or as placeholders for irrelevant parameters. After a few preliminary runs, a simulation duration of 144 hours was chosen to allow sufficient time for results to stabilize—a common practice in water quality modeling (Haestad Methods et al. 2003).

To illustrate how the method can help optimize energy use within the system, consider a node in Zone 3 where the objective is to meet its water demand using the least possible amount of energy. Since the water distribution system offers many hydraulic and energetic paths by which water could arrive at the node at any given time, modeling is required to determine the actual paths and how much energy is expended along them from source to delivery. Each hydraulic path has a corresponding energetic path; the objective is to find the one with the lowest total energy intensity. One possible path to the node is from the wholesale connection and Booster 1, a path with a total energy intensity of 2,434 kWh/MG; another is Well 3 via Booster 1, with a total energy intensity of 3,532 kWh/MG. The result may be a combination of several paths over time. The potential for multiple paths of significantly different energy intensity, combined with the fact that the paths are not known before modeling, suggests an opportunity to reduce energy use by choosing a more efficient path.

Hydraulic modeling helps determine the source of the water arriving at the node at each time step and, consequently, the energy intensity carried with it. It is the time-averaged energy intensity which is to be reduced, representing a decrease in energy use while delivering the same amount of water. In this example, the reduction may be accomplished by prioritizing the path of lowest energy intensity from among the possible choices in Table 4.2. The “best” path minimizes the sum of energy intensities along the water supply chain within the system’s constraints defined in the model as well as external factors like water rights and seasonal availability.

Two major opportunities previously identified by Hansen, Allen & Luce (2016) and implemented by the City (Cascade Energy 2017)—a prioritized water source scheme and the shutdown of nonessential facilities (listed earlier among other energy management practices)—were selected to illustrate the method, validate the method, and answer the research question for this water distribution system. The prioritized water source scheme was selected iteratively based on the energy map of Table 4.2. The model controls were modified such that less-energy-intensive sources were activated before more-energy-intensive sources. The acceptability of each iteration was assessed by checking pressures at all nodes. If the resulting pressures did not satisfy the City’s level of service (minimum 30 psi during peak instantaneous demand and minimum 40 psi during peak day demand), the scheme was rejected. This process continued until an acceptable alternative scheme was found that balanced the prioritized sources with the system’s level of service. The shutdown of the nonessential facilities (a booster station and tank) was modeled by permanently closing the pump and pipe that represents it and removing all controls that would trigger its operation.

Two scenarios were prepared—existing and proposed—to study how energy intensity in Eagle Mountain’s system responds to these operational changes.

4.3.3 Model Analysis and Discussion

Figures 4.4 and 4.5 show the energy intensity of water passing each node and link in Eagle Mountain's water system under existing and proposed conditions, respectively, at 144 hours. The figures highlight the spatial variation of energy intensity within a water distribution system at even finer levels than those studied by Saliba and Gan (2006) and Spang and Loge (2013). Similar figures may be produced for any time step. The figures illustrate how electricity originating in the grid is translated through the operation of the water system and reappears embedded as energy intensity at every point in the system.

In Figure 4.4, patches of energy-intensive water appear in the northern and eastern portions of the system. This is a combination of the water supply from Well 2 (the most energy-intensive water source) and the boosting operations into Zone 3 (which add energy intensity to water produced in Zone 2). Although Well 2 is the *nearest* water source to this part of the system and would logically be the best choice, it requires more energy than any other. Modeling shows that the other water sources are underutilized and could replace much of Well 2's production.

Another opportunity is associated with Tank 5, which is hydraulically located in Zone 3 but serves no connections yet. Water is pumped there via Booster 2 and then returns through PRVs into Zone 2, effectively being pumped in circles. (Note that while *energy* in the form of pressure is released through the valves, the *energy intensity* from pumping remains embedded in the water.) Citing a need for storage capacity during peak demand that could only be provided by pumping to Tank 5, the City had been operating this way for some time. Further modeling, both here and by the consultant, indicated that other tanks could provide adequate storage, that this extra pumping was not necessary,

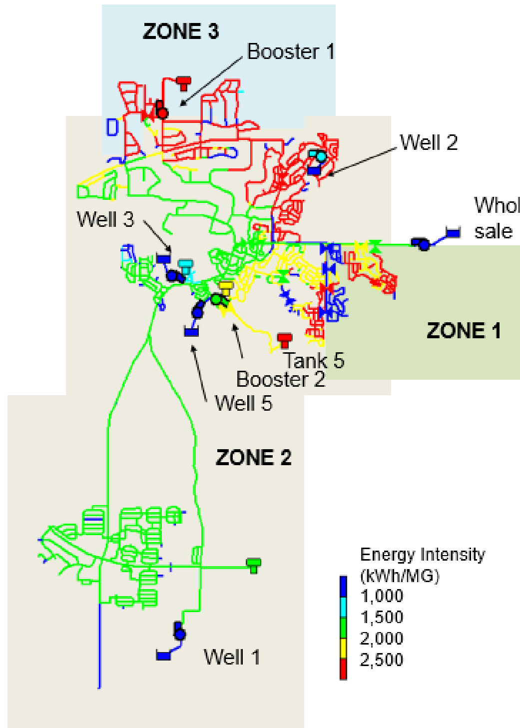

Figure 4.4 Energy Intensity under Existing Conditions

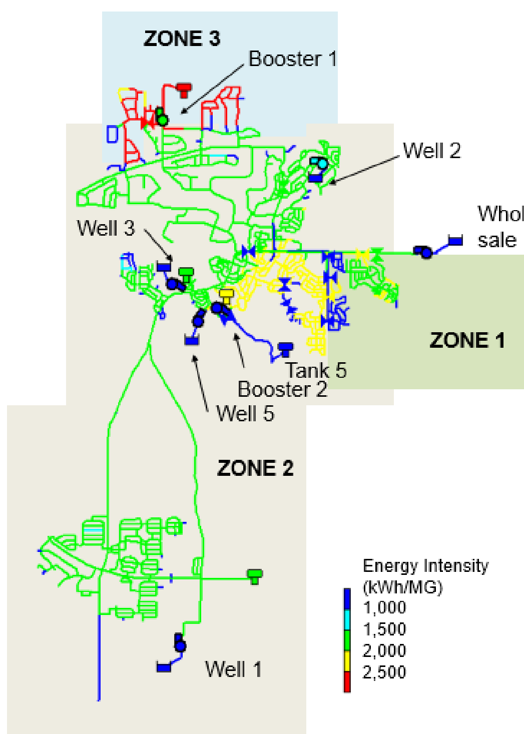

Figure 4.5 Energy Intensity under Proposed Conditions

and that Tank 5 and Booster 2 could be shut down until they are truly needed. The shutdown of these two facilities is, admittedly, an unsophisticated solution and a reversal of the City's previous engineering efforts to establish them. Still, it represents an opportunity to discontinue an unnecessary energy use, and such elimination of waste should be commended.

These two opportunities—prioritizing low-energy-intensity water sources and shutting down unnecessary facilities—were modeled in the proposed scenario presented in Figure 4.5. Well 2 was demoted and other sources, particularly Well 1, were favored. The model runs such that the wells are dispatched in order of increasing energy intensity. Further, Booster 2 and Tank 5 were closed so the other tanks could provide the needed equalization storage. In Figure 4.5, the area of high-energy-intensity water which was so extensive in the existing scenario is now confined to Zone 3. Even without Well 2 and Tank 5, the same amount of water is delivered with adequate pressure throughout the system. Having based this simulation on an existing acceptable model, one can be confident that the proposed operation is feasible.

As in detailed community energy mapping, Figures 4.4 and 4.5 exemplify how such an approach can expose local behavior not otherwise apparent (Reul and Michaels 2012) and how "the ability to illustrate the results … offers a powerful way to understand the impacts" (Gilmour and McNally 2010).

Figure 4.6 shows the energy intensity of water arriving at a node in Zone 2 that is particularly affected by the changes. As discussed earlier, time series analysis of energy intensity is rare. This example illustrates how it can vary over time at small scales and how scenarios may be compared at specific locations. Integrating energy intensity over

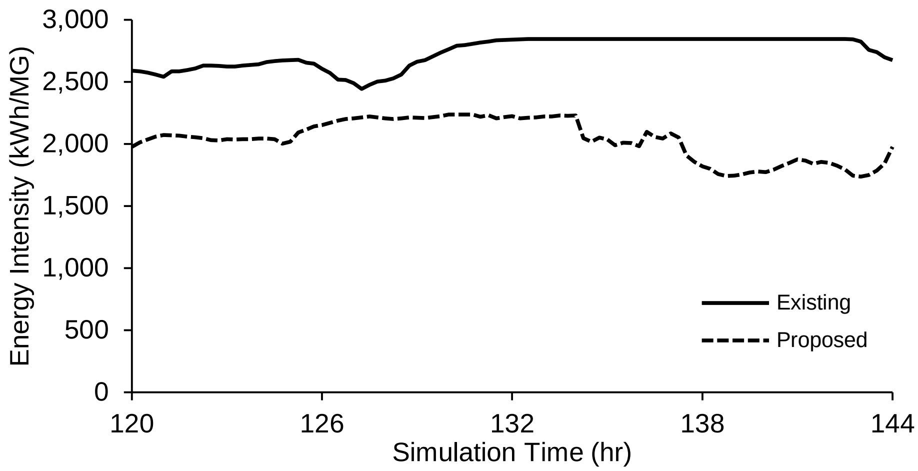

Figure 4.6 Energy Intensity at Node in Zone 2

time yields a total energy use (the area under each curve of Figure 4.6); the area between the curves represents energy savings.

For existing conditions in Figure 4.6, the energy intensity at the node averages 2,735 kWh/MG and varies between 2,443 kWh/MG and 2,844 kWh/MG. The variation is attributed to the contributions of different water sources at different times; the upper limit equals the energy intensity of Well 2 and corresponds to times when all water reaching the node originates from Well 2. Trace simulations confirm this and further indicate that on average, Well 1 contributes 2% of the node's supply; Well 2, 91%; Well 3, 0%; Well 5, 0%; and wholesale, 7%. Note that the energy intensities of Table 4.2, when weighted by these percentages as in Eq. D.11, approximate the average result; using energy intensity in the place of water quality reduces the calculations to one simulation without requiring traces from each potential source.

For proposed conditions in Figure 4.6, the energy intensity at the node averages 2,036 kWh/MG. This constitutes a 26% reduction from existing conditions while still satisfying demand and pressure requirements. This is accomplished by fully utilizing

Well 1 and the wholesale supply—baseloading the least-energy-intensive water sources—and activating additional facilities only when necessary.

This option could have been chosen without modeling using only the energy map of Table 4.2, but hydraulic modeling adds two important features. First, the *benefit* of the path (the energy savings) cannot be determined without first modeling existing conditions and comparing the difference in energy intensity with the proposed operation. Second, merely selecting a path from Table 4.2 does not guarantee that the path is hydraulically feasible or that it will satisfy demands and pressures—criteria that need to be evaluated with the hydraulic model. Integrating the energy map with the available hydraulic model overcomes these two challenges.

The model's built-in energy calculations report an average daily energy use of 3,350 kWh for the existing scenario and 2,977 kWh for the proposed scenario, a reduction of 11%. The model's calculations are based on user-defined pump characteristics (in this case, the actual pump curves) and are separate from the energy intensity simulation. These calculations confirm that the difference in energy intensities between the two extended-period scenarios translates into energy savings reported by other means.

The proposed operation provides more than just energy benefits. Average pressure fluctuation (the difference in maximum and minimum pressure during the simulation period) across all nodes in the existing scenario is 29 psi; in the proposed scenario, it is 12 psi, indicating that the changes allow water to be delivered with shorter paths, larger pipes, less friction loss, and/or lower velocities and facilitate better system-wide hydraulic performance. Average water age at the end of the 144-hour simulation period is 33 hours in the existing scenario; in the proposed scenario, it is 30 hours, suggesting that the changes slightly improve water quality. This is yet one more demonstration that energy efficiency, hydraulic performance, and water quality can exhibit the positive synergistic effects described by Jones and Sowby (2014), rather than being competing goals.

Hansen, Allen & Luce's (2016) review of Eagle Mountain's water system did not use this energy intensity modeling approach, but the approach identifies, visualizes, and quantifies many of the same findings. Eagle Mountain ultimately implemented most of the consultant's recommendations, including the two major opportunities to prioritize low-energy-intensity water sources and to shut down Booster 2 and Tank 5. As a result, over a one-year period following implementation of these noncapital improvements, the system observed a 7% reduction in energy use (454,000 kWh) relative to the baseline condition (Cascade Energy 2017). By comparison, the energy reduction predicted by this modeling method was 11%. This analysis was specific to daily summer operations, so the comparison to a yearlong energy management program is not direct; still, it validates the approach since the same changes resulted in energy reductions quantified by both modeling and measurement.

4.4 Results and Discussion

By showing energy intensities at all locations and multiple time steps, the case study with the new method helps visualize, justify, and quantify two opportunities identified from a previous study. Further, it successfully predicts energy savings similar to those actually achieved when the recommendations were implemented.

These findings suggest that the method, which combines an energy map with a hydraulic model and treats energy intensity as a conservative general property, is an effective analysis tool. The technique effectively models energy intensity interactions and their response to changing operational schemes and designs. As such, it can inform energy management decisions at the facility level where they are most relevant by offering modeling and insight at finer scales than previously available.

The case study revealed several generalizable insights about energy use in water distribution systems. Returning to the research question posed earlier, the selection of water sources and the shutdown of nonessential facilities significantly impacts a water system's energy profile for the given demand scenario. While this has been observed generally elsewhere, the new modeling technique exposes the previously hidden local impacts of these actions in a specific system. Each facility has its own energy intensity characteristics, which, when coupled with its hydraulic characteristics, influence the acceptability of the overall water supply scheme and the associated energy loads. Improving this scheme reduces energy use and has the potential to improve water quality and hydraulic performance concurrently. Due to the highly interconnected nature of water distribution networks, the transport and fate of energy intensity are complex phenomena—even in a medium-sized water distribution system with just a few sources and pressure zones—and require the same level of modeling as water quality simulations to fully describe the impacts of system operations on energy use, especially when investigating proposed changes. The linkage of facility operation to energy use is not always direct, local, or isolated but can influence even distant parts of the system and the operation of other facilities. These interactions are not apparent in coarser models. As in Spang and Loge's (2013, 2015) and Thayer's (2015) work, the case study shows a clear pattern of increasing energy intensity in successively higher pressure zones. The findings confirm that because of the unique hydraulics and topology of each water distribution system—and even within its individual pressure zones— “no one-size-fits-all energy intensity can be given to a gallon of water” (Spang and Loge 2015). Like water quality, in most cases the results cannot be figured by mere intuition, even with intimate knowledge of the system (AWWA 2012). The method illuminated energy intensity behavior in one system with sufficient accuracy to support recommendations that resulted in verified energy savings.

Just as hydraulic modeling has developed to sufficient levels of detail and has become an indispensable tool for designing, planning, and operating water distribution systems for adequate pressure and water quality, the proposed method of modeling energy intensity could become a valuable complement to evaluate and improve energy performance of the same systems. While the technique is novel, it promises value in several research and practice areas similar to the advances of extended-period hydraulic modeling and water quality simulations.

As in Spang and Loge’s (2013, 2015) analysis, the new method offers “a way to represent the spatially and temporally dynamic characteristics of water system energy intensity,” but with even higher resolution made possible by the use of hydraulic modeling. It connects energy intensity to water use and maps the flow of energy through the actual water infrastructure, not just the lumped system or pressure zone. This provides a more detailed characterization of energy use in a water distribution system that can inform site-specific energy management and water conservation measures that consider timing, topography, hydraulic behavior, and system constraints.

Several research gaps remain to be filled. Being limited to a specific system and a specific demand scenario, the case study did not capture all potential energy management opportunities, system operations, or analysis cases. The method should be applied to other systems and the energy performance results should be documented to further validate the method and its value in informing specific energy-savings measures, as well as to develop examples of the many insights the method can provide in other situations. Of the many possible operational schemes that could meet the water demand, the case study found *one* that was better, in terms of energy use, than the existing scenario. Many others could exist that may be even better than this one, and the search for the best scheme then becomes an optimization problem. While full-scale optimization was not attempted here, the modeling technique could be linked to algorithms that optimize energy intensity at specific points or times, or even over an entire water distribution system or among several systems in a regional water supply. One particular question to test is whether, for a given water demand scenario, there is at least one water supply scheme with the minimum energy requirement. The case study did not consider the impact of peak power demand, an important operational constraint for power utilities and an expensive line item for water utilities. Studies optimizing both energy reduction and power reduction are recommended. This case study used static, average energy intensities from aggregated annual data, admittedly the lowest-resolution parameter. Future work might explore the value of more explicit and time-sensitive ways to define energy intensity inputs—for example, by linking to system telemetry/SCADA as done by Spang and Loge (2013, 2015). The results of the sensitivity analysis in Appendix D, in which energy intensity inputs were the most influential parameters, support this recommendation. Water cost and other conservative properties associated with individual processes and facilities may be modeled by the same principles if they can be reasonably normalized by water volume and expressed as a concentration, e.g., dollars per gallon. Used this way, the method could inform water conservation or water loss control activities with greater spatial sensitivity to save water, energy, and money where they matter most. This study used only very basic visualizations; investigating the value and application of more advanced visualization techniques, perhaps involving time series, heat maps, and spatial interpolation, is recommended. The method's applications to aging infrastructure analysis, water and energy system reliability, life cycle assessment of water and wastewater systems (Lundie et al. 2004; Sahey and Kennedy 2007; Mahgoub et al. 2010; Venkatesh and Brattebø 2011), system dynamics models, the broader water–energy nexus, and related research areas should also be explored.

4.5 Summary and Conclusions

This research introduced a method for modeling energy intensity as a conservative general property in water distribution systems. The method leverages water quality simulations built into existing hydraulic modeling software to streamline the computation and visualization of energy intensities with previously unavailable detail. The approach informs energy management decisions at relevant scales to improve overall water system sustainability.

A case study with a real water distribution system demonstrated the method's value by highlighting two particular energy management opportunities previously recommended by a consultant and implemented by the water utility. Both modeling and implementation predicted energy reductions, validating the modeling technique used here. The rapid computation of system-wide energy results facilitated the testing of an alternative operational scheme and confirmed its feasibility by quantifying local reductions in energy intensity resulting from the proposed changes. The model also indicated simultaneous improvements in hydraulic performance and water quality. From these results, the authors conclude that the method is an effective analysis tool for targeted energy management in water distribution systems.

Further applications of network-scale energy intensity modeling are recommended to further develop the technique, explore the insights it can produce, and apply these insights to improve water distribution systems' energy performance and overall sustainability, as well as to link them to other research areas.

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CHAPTER 5

GENERAL CONCLUSION

5.1 Summary

This research program produced useful data, models, and analysis on public water systems and their energy use. The work was driven by a lack of such resources in both scholarly literature and engineering practice, representing research needs widely acknowledged by diverse stakeholders. The products of this research program will inform the planning, design, and operation of sustainable public water systems from an energy perspective.

5.2 Conclusions

Filling a critical data gap, the survey of Chapter 2 collected data to define the energy requirements of 109 U.S. public water systems. The results show that their energy intensities range from 250 to 11,500 kWh/MG, with a volume-weighted average of 1,809 kWh/MG. These energy intensities are approximately log-normally distributed. Significant geographic differences were found, with fundamentally higher energy intensities in the western United States than the eastern United States proven by a statistical test. Systems supplied by surface water are the least energy intensive, while those supplied by groundwater or imported water require more energy to deliver the same amount of water. This finding validates, on a national scale, what others have observed from more limited observations about the relative energy intensity of different water source types. The analysis found that energy intensity tends to decrease with water system size, showing an economy of scale consistent with those already observed in water and wastewater treatment processes. The survey revealed mixed interannual variations in energy intensity that need to be investigated further. The geographic and temporal variability of water system energy intensities should be considered in future modeling and research. One nontechnical finding was that the energy data were difficult to obtain, even when water data were plentiful, underscoring the need to better integrate water and energy data in the future to overcome a significant data gap. Providing a consistent characterization of energy-for-water demands, the dataset will find uses in water system planning, national water and energy evaluations, and national security applications. The data are publicly available on GitHub and Zenodo at http://doi.org/10.5281/zenodo.1048275.

From this set of empirical data, the statistical model in Chapter 3 was developed to estimate a water utility's energy use as a function of a few readily accessible variables. The most important factors influencing the energy use were found to be water system size, water source type, average precipitation, and average temperature, constituting a combination of both internal and external variables. Past studies have theorized that these factors may be influential, but this is the first quantitative substantiation of such claims. The statistical model is more accurate than previous models and has the added benefit that the variables it uses are more accessible, facilitating its application, especially to studies of many water systems. By considering such variables, the model overcomes much of the difficulty heretofore encountered in energy benchmarking of water systems, where comparisons are otherwise unfair and inappropriate. A benchmarking application was described as a planning tool for energy management in water systems.

Having produced a strong dataset and statistical model, the research extended these analyses to the subsystem scale where water–energy interactions are complex and require spatially and temporally sensitive modeling. The method described in Chapter 4 combines two existing tools—energy maps and hydraulic models—in a new application to describe the entire energy-for-water service chain. Treating energy intensity as a conservative water quality constituent—a property concentration of energy input per unit of water—enables the application of extended-period hydraulic models to simulate its behavior in a given water distribution system, a necessary step given the complexity and interconnectivity of water distribution networks. The method produces visualizations and data that can inform energy management decisions at relevant scales, and since the results are coupled with an established hydraulic model, one may also test alternatives and be confident in how the system will respond to a potential change. In a case study with a real water utility, the method effectively illuminated several inefficiencies (and their solutions) that would not have emerged in a lumped system-wide analysis. The model indicated a reduction in energy use concurrently with improvements in water quality and hydraulic performance, exemplifying the positive synergy of the three parameters. The model identified energy savings similar to those actually achieved in the same water utility during a yearlong energy management program, thereby validating the method and its value for providing specific and actionable energy management insights.

5.3 Applications

Since the energy intensity data presented in Chapter 2 represent empirical energy-for-water linkages and their statistical properties are well defined, researchers may input them into models of the water–energy–food nexus, life cycle assessments of water utilities, critical infrastructure evaluations, and similar studies requiring such factors relating water use to energy use. Policymakers and regulators may use the data to plan energy conservation and grant programs targeting the water sector, as well as to develop further guidance and best practices. Power companies—which as monopolies are mandated to implement energy efficiency programs and use the least-cost resource—will recognize in these data the significant electric loads associated with water services and can deploy demand-side management programs targeting the most energy intensive and/or largest water systems. They may also find value in the site-specific observations and statistical characterizations when preparing demand projections specific to the water industry. Likewise, water managers may estimate their future energy demands and/or costs according to water use projections, or use the data as a baseline for energy management activities.

The statistical model documented in Chapter 3 enables researchers to more accurately estimate a water utility's energy use with a few accessible variables. Like the survey dataset, it may find a place in many types of studies, especially those of national scale with a large number of water utilities that would otherwise be characterized without considering important internal or external factors. The model and benchmarking procedure may be adopted by policymakers and regulators to monitor water systems' performance and prescribe certain energy management practices. This could become part of state and federal reporting requirements, which would also serve to collect additional data. The tool may also interest power companies and their demand-side management programs serving water systems so the power companies can direct their efforts at the most fruitful opportunities. Individual water utilities may use the tool to benchmark their current energy performance, set a specific goal to improve, quantify the energy reduction needed to reach the goal, and monitor their performance over time. Such activities may be done in cohorts of several water systems—especially small ones with limited resources—to provide peer support and accountability. The benchmark score could be an important metric for demonstrating progress toward sustainability goals when reporting to boards and the public, reported annually to match the time scale for which the model was designed.

The tools and methods of Chapter 4 are most valuable to individual water systems since the outcomes are, by design, system-specific. Water utilities and their engineers may incorporate this new type of analysis aimed at energy management into their existing engineering, planning, and modeling practices. Hydraulic modelers, who are already familiar with a system's operation and its hydraulic model, are the best suited to implement this method and may be supported by operators and senior staff to ensure accuracy of the outcomes and feasibility of the alternatives. This is most effective for extended-period models calibrated to common operational schemes, e.g., summer or winter. Coupled with monthly energy and water observations to compute energy intensity for each facility, the hydraulic model becomes a vehicle to display and quantify energy use in great detail, leading to informed decisions about deliberate energy management, whether through operational adjustments or capital projects. Power companies may be interested in this tool as part of broader demand-side management and incentive programs that already serve water utilities as a means to generate further ideas for energy savings or peak load reductions.

5.4 Limitations and Further Work

While the energy intensity survey of Chapter 2 produced the largest known dataset of its kind, it misses a large portion of U.S. water suppliers. The survey compiled data from over 100 public water systems, but many tens of thousands exist in the United States alone. The dataset should be expanded through the collection of additional city-scale data, especially for small systems, which constitute a large portion of the remainder. Understanding of how water systems' energy intensities vary over time is also weak. Most of the available data, including those presented here, are static and do not describe potentially important seasonal or interannual differences and, where time series do exist, they lack context and metadata sufficient to investigate the causes of such changes. For these reasons, specific study of time-series energy intensity is recommended. With the existing dataset, there may be opportunities to uncover further spatial patterns by combining energy intensity with or normalizing it by population, elevation, distance to water source, or water system age. The size relationship, in which larger water systems have lower energy intensities, should be examined to determine particular causes, whether technological (e.g., economy of scale through larger infrastructure), financial (e.g., ability to select better equipment and engineering services), or organizational (e.g., greater availability of employee resources to manage energy). Energy intensity on its own does not describe the cost, source, or emissions of the energy used. Studies of such topics must therefore consider additional factors such as cost per kilowatt-hour depending on local rates and carbon emissions per kilowatt-hour depending on fuel type, which, when coupled with energy intensity, further characterize the nature of the energy being used for public water supply. This is an important step for evaluating the climate impacts associated with public water supply and the potential for reducing emissions through water conservation. City-specific data on energy-for-water intensities outside the United States are even more sparse, presenting an opportunity for global efforts to quantify these uses and help water systems operate efficiently, especially in developing countries where water and power services are limited.

The statistical model and benchmarking tool presented in Chapter 3 offer substantial improvements over previous resources, in terms of both accuracy and usability, but could still be refined. For a lack of time series data, they do not include time-sensitive variables that could influence energy intensity. The model currently uses an annual basis, which may be too long to observe progress toward goals, so future work should seek to define benchmarks at monthly scales for more prompt feedback. Through additional variables or more advanced statistical techniques, further refinement of empirical models relating water and energy is recommended, as well as broader implementation of energy benchmarking tools to help water systems conserve energy. Such models may also be integrated with system dynamics models and other meta-models of water and energy systems. Additional variables to consider are hydraulic head (between the natural water source and its end uses), raw-water quality (which dictates the level of treatment required), and aging infrastructure.

The area ripest for further work is the method of high-resolution energy intensity modeling described in Chapter 4. The case study was limited to two proposed actions in a single water system and did not capture all potential energy management actions. Further, it was limited by the annual resolution of the energy intensity inputs. Future work should explore the value of using higher-resolution energy intensity data (minimum monthly scale, with potential for near-real-time SCADA linkages), the potential for optimization problems, advanced visualization techniques, and more explicit financial comparisons that consider peak power demand and other energy pricing schemes. The technique could also inform more spatially sensitive analysis of water conservation potential, recognizing energy use and cost as important general properties conveyed with the water, to aim conservation activities at the areas where the associated energy or cost are the greatest. The technique may also apply to evaluations of a water system's physical condition and the corresponding effect on energy use. The development of this new high-resolution technique suggests research applications in life cycle assessment, water system reliability, and the broader water–energy nexus. Additional system-specific studies are recommended to build the body of knowledge about energy flows through water systems, explore energy management opportunities, and apply the technique to improve water system sustainability.

Most of all, the literature review and this entire research program confirmed that a lack of adequate data is one of the primary barriers to further scientific study in this field and that integrated water and energy data reporting is needed at both state and federal levels. In Utah, this would require coordination among the Division of Water Rights, which has the legal authority to collect water use data; the Division of Water Resources, which evaluates and reports these data; the Division of Drinking Water, which regulates public water systems and promotes their efficient use of energy through a specific program; and the Governor's Office of Energy Development, which supports policies for energy efficiency and conservation. In this scheme, policies would originate from the latter, supported by the three water divisions and the legislature. The Division of Water Rights would request annual (monthly if possible) energy use along with water use in its annual data collection effort (as is done voluntarily in California). Since water utilities often struggle to find their energy use data, local power providers like Rocky Mountain Power may facilitate the process by offering, with permission, energy use data for each water system they serve. The Division of Water Resources would maintain the data, and the Division of Drinking Water would analyze, interpret, and use the data to support its energy efficiency program and make the data available to local practitioners. (Incidentally, this theoretical multiparty process further underscores the fragmentation of management and data surrounding water and energy discussed earlier). Similar data collection programs would need to be developed in other states. A federal agency, perhaps the U.S. Environmental Protection Agency, Department of Energy, or Geological Survey, could then compile the data nationwide, similar to the U.S. Geological Survey's National Water Use Information Program. The growing dataset would become a resource for exploring further energy-for-water relationships and answering the associated management, policy, and engineering questions.

APPENDIX A

REVIEW OF POTENTIAL AND ACTUAL ENERGY MANAGEMENT RESULTS IN PUBLIC WATER SYSTEMS[1]

A.1 Introduction

The water–energy nexus has received considerable attention in the past 10 years. Much of the work has focused on the water intensity of energy generation, local studies of energy intensity for water services, and the research needs in this emerging field. Less work has addressed energy efficiency in the water sector.

Water services are a substantial component of a state's or country's energy consumption. Public water and wastewater utilities consume 2% of all U.S. energy, or about 2 quadrillion BTU annually (Sanders and Webber 2012). Utah, the country's second-driest state, expends about 7% of its energy on water supply (Larsen and Burian 2012; UDWR 2012). In California, water consumes 19% of the state's electricity and 30% of its natural gas, underscoring the significance of the water sector's role in energy consumption, especially amid California's current multiyear drought (Klein 2005; Navigant Consulting 2006).

Water is a significant energy demand. As the challenge of managing water and

[1] Adapted, with permission, from Robert B. Sowby, "Energy management in the water sector: A major sustainability opportunity," 1st International Electronic Conference on Water Sciences, Nov. 15–29, 2016.

energy resources continues to grow, energy efficiency in the water sector is a ripe sustainability opportunity.

A.2 Background

Historically, water suppliers have focused on providing reliable, high-quality water without necessarily considering energy requirements. Many have viewed a water system's energy footprint as fixed; several technical, financial, social, and political obstacles have dissuaded water utilities from pursuing energy efficiency (Barry 2007). Now, with increasing population, stricter water-quality standards, and rising energy costs, energy efficiency in the water sector is emerging as an optimal solution.

Indeed, "planning by drinking and wastewater utilities is increasingly considering issues of energy use," mostly for financial reasons (Tidwell et al. 2014). According to the U.S. Environmental Protection Agency (EPA), energy for water and wastewater services is the largest single cost for municipal governments and private utilities, accounting for over 40% of operating expenses; for small cities, the cost can exceed 80% (EPA 2008). The World Bank likewise acknowledged that "improving energy efficiency is at the core of measures to reduce operational cost at water and wastewater utilities" (Liu et al. 2012).

Looking beyond cost savings, the Department of Energy identified the optimization of water management, treatment, and distribution systems as one of its six strategic pillars in the water–energy nexus (DOE 2014). Water in the West concluded that "the energy deployed in water treatment and distribution is a principal target for reducing the embedded energy in the nation's water supplies" (Water in the West 2013). The EPA realized that "improved energy efficiency … will help ensure the long-term sustainability of our nation's water and wastewater infrastructure" (EPA 2008).

A.3 Energy Management as a Solution

Efficiency is the most immediate, affordable, and environmentally beneficial solution to resource shortages. For power providers, energy management is a least-cost resource; its levelized cost is two to three times less than conventional energy generation (Hoffman et al. 2015; Milina 2014). Though power providers are aware of this difference and have targeted residential and commercial energy efficiency, potential savings in the water sector have been largely overlooked until recently. For water utilities, energy efficiency offers reduces their operation costs, shrinks their energy footprints, and improves public acceptance.

A.4 Theoretical Savings

Potential and theoretical energy efficiency savings for water utilities have been studied extensively, and most estimates indicate that savings of 10%–30% are possible through combinations of operational (no-cost) and capital measures. An EPA Region 9 pilot study found an average of 17% energy savings potential and 26% cost savings potential, regardless of a utility's size (Horne et al. 2014); a Massachusetts pilot study identified an average 33% potential savings at 14 water facilities (MassDEP 2016). According to the EPA, water facilities can achieve up to 30% percent reduction in energy use through energy efficiency upgrades and operational measures (EPA 2013). The Alliance to Save Energy claimed that 25% savings are possible in most water systems worldwide (Alliance to Save Energy 2016). The World Bank found that 10%–30% energy savings are common, with relatively short payback periods of one to five years (Liu et al. 2012). The U.S. Department of Energy (DOE) observed that "energy usage in delivering water services represents a nontrivial portion of U.S. electricity consumption and may present significant opportunities for both efficiency and renewable generation" (DOE 2014).

A.5 Actual Savings

Beyond theory, significant energy savings have been achieved throughout the United States as water utilities and engineers translate theory into action. See Table A.1.

In Utah, Jordan Valley Water saved 3.9 million kilowatt-hours (kWh) with operational changes (UDEQ 2015). North Salt Lake's water system saved 32% through no-cost operational changes and Spanish Fork's water system saved 29% after a capital project (Hansen, Allen & Luce, unpublished data). Logan, Utah, reduced its water system's energy use by 32% and also observed a 17% decrease in water use and a 40% decrease in mainline breaks, demonstrating that energy efficiency has a synergistic effect that can support rather than oppose improvements in other areas (Jones et al. 2015). A large pump station of Nashville's Metro Water Services used 30% less energy after an efficiency upgrade (Yarosz and Ashford 2015). Equipment upgrades and operational changes saved significant energy at several Arizona water utilities (Mundt and Dodenhoff 2015). Energy efficiency in wastewater treatment, though not discussed here, is likewise effective. These cases show that energy savings are not only possible but also catalyze other improvements. Several best practices and resources to help water utilities save energy are available (EPA 2008; DOE 2014; Martin and Ries 2014; UDDW 2014; Jones and Sowby 2014; NYSERDA 2010; Moran and Barron 2009; DEC 2016).

Table A.1

Water System Energy Efficiency Results

Water Utility	Location	Annual Energy Savings	Source
City of Yuma	Yuma, Ariz., USA	6,500,000 kWh	Mundt and Dodenhoff 2015
City of Flagstaff	Flagstaff, Ariz., USA	5,800,000 kWh	Mundt and Dodenhoff 2015
Jordan Valley Water Conservancy District	West Jordan, Utah, USA	3,900,000 kWh (10%)	UDEQ 2015
Dublin San Ramon Services District	San Francisco, Calif., USA	2,232,000 kWh	EPA 2013
City of North Salt Lake	North Salt Lake, Utah, USA	1,800,000 kWh (32%)	Hansen, Allen & Luce, unpublished data
City of Holbrook	Holbrook, Ariz., USA	1,750,000 kWh	Mundt and Dodenhoff 2015
Spanish Fork City	Spanish Fork, Utah, USA	1,100,000 kWh (29%)	Hansen, Allen & Luce, unpublished data
Logan City Water	Logan, Utah, USA	900,000 kWh (32%)	Jones et al. 2015
Carefree Water Company	Carefree, Ariz., USA	425,000 kWh	Mundt and Dodenhoff 2015
Metro Water Services	Nashville, Tenn., USA	30% (facility)	Yarosz and Ashford 2015

A.6 Discussion

To date, most of the literature and practice has focused on equipment energy efficiency at water facilities. While those advances are welcome, there many opportunities beyond the facility. A typical water system is a collection of water sources, treatment plants, pump stations, storage tanks, and other facilities that function not as discrete elements but as an interdependent system. Many potential water delivery paths exist, each with different energy requirements. The underlying assumption in the value of facility-specific equipment upgrades is that the facility lies along the most energy-efficient water delivery path. This is not always true, since in many cases there is a better way to deliver water by thinking “outside the box”—that is, thinking outside the facility—on a system level. For example, Jordan Valley Water saved energy by prioritizing its most efficient water sources, and North Salt Lake saved energy by adjusting pressure-reducing valves to keep water in the intended pressure zone without excessive pumping. Rather than undertake capital projects to upgrade certain facilities, both water utilities found a more efficient water delivery path that leverages their existing efficient facilities and avoids inefficient ones. The practice of water system optimization considers such system-wide possibilities and aligns energy efficiency with water quality and level of service, the three main constrains of public water supply (Jones and Sowby 2014).

The next level of optimization is thinking outside the system—forging mutually beneficial partnerships among neighboring water suppliers to give and take water in ways that lower the overall energy requirements. Several water utilities in the Salt Lake Valley area are negotiating such agreements, which may be the first of their kind.

A.7 Conclusions

Energy efficiency in the water sector is an untapped sustainability opportunity. Research and case studies demonstrate that energy reductions of 10% to 30% are typical for water utilities that pursue efficiency. Such solutions are cost-effective, prompt, and synergistic.

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APPENDIX B

ENERGY INTENSITY SURVEY RESULTS[1]

Table B.1 lists the results of the primary survey carried out from 2015 to 2017 to collect water system energy intensity data and related information.

[1] Sowby, R. B., and Burian, S. J. (2017). "Energy Intensity Data for Public Water Supply in the United States (v1.0.0)" [dataset]. Zenodo. http://doi.org/10.5281/zenodo.1048275. CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0/).

Table B.1

Energy Intensity Survey Results

ID	Water System Name	City	State	Service Population	Surface Water Source	Ground-water Source	Imported Water Source	Other Water Source	Observation Year	Energy Use (kWh)	Water Delivery (MG)	Energy Intensity (kWh/MG)
1	New York City	New York City	NY	8,271,000	100%	0%	0%	0%	2009	91,888,750	367,555	250
2	Chicago Department of Water Management	Chicago	IL	5,300,000	100%	0%	0%	0%	2015	97,622,129	219,985	444
3	Los Angeles Department of Water and Power	Los Angeles	CA	3,900,000	24%	12%	63%	1%	2009	1,075,926,791	151,791	7,088
4	Houston Public Works	Houston	TX	2,331,000	70%	30%	0%	0%	2015	279,016,219	133,211	2,095
5	Massachusetts Water Resources Authority	Boston	MA	2,200,000	100%	0%	0%	0%	2014	28,248,980	69,971	404
6	Cleveland Water	Cleveland	OH	1,500,000	100%	0%	0%	0%	2013	187,971,133	79,967	2,351
7	Missouri American Water	Jefferson City	MO	1,500,000	78%	22%	0%	0%	2015	170,698,539	55,654	3,067
8	Denver Water	Denver	CO	1,400,000	100%	0%	0%	0%	2014	29,118,267	61,185	476
9	East Bay Municipal Utility District	Oakland	CA	1,400,000	90%	10%	0%	0%	2015	92,432,000	46,780	1,976
10	Seattle Public Utilities	Seattle	WA	1,300,000	100%	0%	0%	0%	2006	20,822,053	44,454	468
11	Columbus Department of Public Utilities	Columbus	OH	1,160,000	85%	15%	0%	0%	2015	52,233,772	40,908	1,277
12	Fort Worth Water Department	Fort Worth	TX	1,159,000	100%	0%	0%	0%	2015	96,392,443	55,529	1,736
13	Austin Water	Austin	TX	983,000	100%	0%	0%	0%	2015	107,237,600	35,479	3,023
14	Portland Water Bureau	Portland	OR	958,000	99%	1%	0%	0%	2013	18,173,351	32,500	559
15	Milwaukee Water Works	Milwaukee	WI	865,000	100%	0%	0%	0%	2015	68,046,950	37,595	1,810
16	Inland Empire Utility Agency	Ontario	CA	830,000	16%	52%	17%	15%	2009	250,780,849	71,866	3,490
17	Charlotte Water	Charlotte	NC	818,000	100%	0%	0%	0%	2015	70,856,041	32,075	2,209
18	Anonymous			800,000	90%	10%	0%	0%	2012	94,350,000	66,135	1,427

Table B.1 continued

ID	Water System Name	City	State	Service Population	Surface Water Source	Ground-water Source	Imported Water Source	Other Water Source	Observation Year	Energy Use (kWh)	Water Delivery (MG)	Energy Intensity (kWh/MG)
19	Kansas City	Kansas City	MO	770,000	87%	13%	0%	0%	2015	38,690,878	33,961	1,139
20	Jordan Valley Water Conservancy District	West Jordan	UT	630,000	90%	10%	0%	0%	2014	29,340,283	30,282	969
21	Tampa Water Department	Tampa	FL	599,000	100%	0%	0%	0%	2015	34,384,041	22,362	1,538
22	Albuquerque Bernalillo County Water Utility Authority	Albuquerque	NM	566,000	57%	43%	0%	0%	2015	118,922,772	28,100	4,232
23	City of Tulsa Water and Sewer Department	Tulsa	OK	500,000	100%	0%	0%	0%	2015	64,296,000	33,931	1,895
24	Kentucky American Water	Lexington-Fayette	KY	490,000	100%	0%	0%	0%	2015	52,891,512	12,151	4,353
25	Colorado Springs Utilities	Colorado Springs	CO	470,000	100%	0%	0%	0%	2015	53,493,415	19,972	2,678
26	Mesa Water Resources Department	Mesa	AZ	461,000	90%	10%	0%	0%	2015	24,817,829	27,208	912
27	St. Louis Water Division	St. Louis	MO	319,000	100%	0%	0%	0%	2015	67,723,215	37,435	1,809
28	Anonymous			270,000	30%	70%	0%	0%	2012	26,300,000	17,491	1,504
29	Madison Water Utility	Madison	WI	250,000	0%	100%	0%	0%	2015	19,276,380	9,855	1,956
30	Anonymous			250,000	0%	100%	0%	0%	2012	32,362,000	24,601	1,315
31	Anonymous			239,000	100%	0%	0%	0%	2012	11,395,000	25,300	450
32	Spokane Water Department	Spokane	WA	228,000	0%	100%	0%	0%	2015	45,203,060	20,700	2,184
33	Portland Water District	Portland	ME	200,000	100%	0%	0%	0%	2015	4,210,274	6,402	658
34	Santa Rosa Water	Santa Rosa	CA	173,000	0%	10%	90%	0%	2015	17,919,500	5,034	3,560
35	Cherokee County Water & Sewerage Authority	Canton	GA	170,000	100%	0%	0%	0%	2015	14,738,125	4,514	3,265
36	Anonymous			166,000	92%	8%	0%	0%	2012	18,900,000	11,190	1,689
37	Greenville Utilities Commission	Greenville	NC	134,000	100%	0%	0%	0%	2015	7,624,800	3,957	1,927
38	Roseville Environmental Utilities	Roseville	CA	129,000	99%	1%	0%	0%	2015	1,897,395	6,679	284
39	City of Bloomington Utilities	Bloomington	IN	120,000	100%	0%	0%	0%	2010	11,231,780	5,110	2,198

Table B.1 continued

ID	Water System Name	City	State	Service Population	Surface Water Source	Ground-water Source	Imported Water Source	Other Water Source	Observation Year	Energy Use (kWh)	Water Delivery (MG)	Energy Intensity (kWh/MG)
40	Norman	Norman	OK	118,000	66%	33%	1%	0%	2015	9,262,898	4,172	2,220
41	Provo City	Provo	UT	116,300	8%	92%	0%	0%	2014	13,237,560	7,210	1,836
42	Charleston Water System	Charleston	SC	113,000	100%	0%	0%	0%	2014	23,467,001	17,383	1,350
43	Anonymous			110,000	100%	0%	0%	0%	2012	5,047,000	2,402	2,101
44	Anonymous			109,000	100%	0%	0%	0%	2012	13,865,000	10,064	1,378
45	Green Bay Water Utility	Green Bay	WI	105,000	100%	0%	0%	0%	2015	14,201,559	6,753	2,103
46	California American Water - Los Angeles County	San Marino	CA	103,000	0%	10%	90%	0%	2015	53,685,302	5,083	10,562
47	California American Water - Sacramento	Sacramento	CA	101,000	0%	94%	6%	0%	2015	13,316,749	7,691	1,732
48	California American Water - Monterey Peninsula	Monterey	CA	101,000	3%	95%	2%	0%	2015	11,805,094	3,019	3,910
49	New Bedford	New Bedford	MA	93,000	100%	0%	0%	0%	2007	4,461,000	4,599	970
50	Orem City	Orem	UT	92,000	67%	33%	0%	0%	2014	7,589,401	2,775	2,735
51	Anonymous			92,000	0%	100%	0%	0%	2012	10,391,000	6,582	1,579
52	Kennewick	Kennewick	WA	87,000	40%	60%	0%	0%	2015	7,250,333	3,987	1,818
53	Anonymous			84,000	0%	100%	0%	0%	2014	3,444,866	2,797	1,231
54	Fayetteville	Fayetteville	AR	81,000	100%	0%	0%	0%	2015	13,988,296	3,705	3,776
55	Eau Claire Municipal Water Utility	Eau Claire	WI	68,000	0%	100%	0%	0%	2015	7,211,670	3,376	2,136
56	Anonymous			52,000	100%	0%	0%	0%	2015	4,886,780	1,425	3,428
57	Anonymous			50,000	100%	0%	0%	0%	2012	9,057,000	6,556	1,381
58	Mishawaka City Utilities	Mishawaka	IN	48,000	0%	100%	0%	0%	2010	4,826,760	2,920	1,653
59	Anonymous			46,000	0%	100%	0%	0%	2015	11,341,000	3,875	2,927
60	Anonymous			40,000	0%	100%	0%	0%	2012	3,715,000	1,121	3,313

Table B.1 continued

ID	Water System Name	City	State	Service Population	Surface Water Source	Ground-water Source	Imported Water Source	Other Water Source	Observation Year	Energy Use (kWh)	Water Delivery (MG)	Energy Intensity (kWh/MG)
61	Laramie	Laramie	WY	36,000	70%	30%	0%	0%	2014	1,953,894	1,459	1,339
62	Pleasant Grove	Pleasant Grove	UT	35,000	0%	100%	0%	0%	2014	1,816,237	1,162	1,563
63	Valparaiso City Utilities	Valparaiso	IN	35,000	0%	100%	0%	0%	2010	2,892,260	1,460	1,981
64	Anonymous			33,000	0%	100%	0%	0%	2012	3,261,000	2,739	1,190
65	South Tahoe Public Utility District	South Lake Tahoe	CA	32,000	0%	100%	0%	0%	2015	3,716,165	1,435	2,590
66	Springville City	Springville	UT	31,000	0%	100%	0%	0%	2014	3,065,061	1,409	2,176
67	Anonymous			27,000	75%	25%	0%	0%	2012	2,574,000	1,897	1,357
68	Aberdeen Water Works	Aberdeen	SD	26,000	64%	31%	0%	5%	2015	5,805,647	1,133	5,123
69	Eagle Mountain City	Eagle Mountain	UT	25,000	0%	85%	15%	0%	2015	6,052,487	1,807	3,349
70	Oxford Public Works	Oxford	MS	25,000	0%	100%	0%	0%	2015	1,403,040	1,092	1,285
71	Easton Water Division	Easton	MA	25,000	0%	100%	0%	0%	2007	1,171,842	683	1,716
72	Wenatchee	Wenatchee	WA	24,000	0%	100%	0%	0%	2015	6,229,502	1,963	3,174
73	City of Griffin	Griffin	GA	23,000	100%	0%	0%	0%	2015	7,293,614	2,219	3,287
74	Eagle	Eagle	ID	6,000	0%	100%	0%	0%	2014	321,610	134	2,400
75	Virgin Valley Water District	Mesquite	NV	20,000	0%	100%	0%	0%	2015	6,446,036	1,826	3,531
76	Anonymous			20,000	100%	0%	0%	0%	2012	1,656,000	2,759	600
77	Anonymous			19,500	0%	100%	0%	0%	2012	2,954,000	1,835	1,609
78	Dodge City	Dodge City	KS	18,000	0%	100%	0%	0%	2015	1,514,400	1,307	1,159
79	Highland City	Highland	UT	17,000	0%	100%	0%	0%	2014	1,731,306	2,500	693
80	Anonymous			17,000	100%	0%	0%	0%	2012	3,586,000	2,903	1,235
81	Kuna	Kuna	ID	17,000	0%	100%	0%	0%	2015	1,277,440	596	2,143

Table B.1 continued

ID	Water System Name	City	State	Service Population	Surface Water Source	Ground-water Source	Imported Water Source	Other Water Source	Observation Year	Energy Use (kWh)	Water Delivery (MG)	Energy Intensity (kWh/MG)
82	Town of Ashland	Ashland	MA	16,000	0%	100%	0%	0%	2007	1,264,176	748	1,690
83	Mammoth Community Water District	Mammoth Lakes	CA	16,000	40%	60%	0%	0%	2015	2,532,432	504	5,027
84	Anonymous			14,000	0%	100%	0%	0%	2012	1,788,000	714	2,504
85	Anonymous			14,000	0%	100%	0%	0%	2015	1,681,400	846	1,989
86	Minden	Minden	LA	13,000	0%	100%	0%	0%	2015	1,948,781	599	3,254
87	Woods Cross	Woods Cross	UT	11,000	0%	91%	9%	0%	2014	544,390	304	1,790
88	Jerome	Jerome	ID	11,000	0%	100%	0%	0%	2015	2,569,560	656	3,920
89	California American Water - Toro	Sierra Village	CA	1,500	0%	100%	0%	0%	2015	238,361	48	4,979
90	Anonymous			8,500	0%	45%	55%	0%	2014	12,155,500	1,057	11,500
91	Anonymous			8,000	0%	100%	0%	0%	2015	806,261	745	1,082
92	Anonymous			7,000	100%	0%	0%	0%	2012	434,000	840	517
93	Eagle	Eagle	CO	6,600	100%	0%	0%	0%	2015	1,631,200	394	4,145
94	Mountain Regional Water Special Service District	Park City	UT	6,400	0%	100%	0%	0%	2014	3,121,663	1,874	1,666
95	Fruitland	Fruitland	ID	4,800	100%	0%	0%	0%	2014	1,710,000	307	5,577
96	Anonymous			4,400	0%	100%	0%	0%	2015	929,605	483	1,925
97	Morgan City	Morgan	UT	3,900	0%	100%	0%	0%	2014	195,564	123	1,590
98	Anonymous			3,400	0%	100%	0%	0%	2015	512,761	405	1,266
99	Anonymous			2,700	0%	100%	0%	0%	2012	1,468,000	823	1,783
100	Hayward	Hayward	WI	2,300	0%	100%	0%	0%	2015	111,955	85	1,321
101	Town of Lee	Lee	MA	2,100	100%	0%	0%	0%	2007	400,968	292	1,373
102	Eagle River Light and Water Department	Eagle River	WI	1,400	0%	100%	0%	0%	2015	31,667	23	1,380

Table B.1 continued

ID	Water System Name	City	State	Service Population	Surface Water Source	Ground-water Source	Imported Water Source	Other Water Source	Observation Year	Energy Use (kWh)	Water Delivery (MG)	Energy Intensity (kWh/MG)
103	Hazelton	Hazelton	ID	800	0%	100%	0%	0%	2014	195,000	26	7,488
104	Manila City	Manila	UT	400	0%	100%	0%	0%	2015	363,817	45	8,143
105	Salt Lake County Service Area No. 3	Alta	UT	400	0%	100%	0%	0%	2014	148,200	39	3,840
106	Anonymous			400	0%	100%	0%	0%	2015	61,033	19	3,215
107	Chelan Ridge	Manson	WA	100	0%	100%	0%	0%	2015	43,098	7	5,986
108	Dryden	Dryden	WA	100	0%	100%	0%	0%	2015	29,456	4	7,184
109	Ollala Canyon	Cashmere	WA	100	0%	100%	0%	0%	2015	12,803	3	5,121

APPENDIX C

COMPARISON OF ENERGY FOOTPRINTS IN PUBLICLY AND PRIVATELY OWNED WATER UTILITIES

C.1 Introduction

One point of interest in utilities policy and management research is the comparison of efficiency or performance between public and private utilities, particularly in the water industry. In the United States, most water suppliers are publicly owned (e.g., by a municipal government), while private water utilities (e.g., those owned and/or operated by a private company) serve about one quarter of the population (EPA 2017a; NAWC n.d.).

In the economic sense, an organization's efficiency is determined by the amount of output produced by a given level of input (Renzetti and Dupont 2003). Economic theory predicts that private ownership will yield greater efficiency than public ownership (Renzetti and Dupont 2003; Megginson and Netter 2001; Brubaker 1998; Millward 1982). These claims assume that private utilities are better managed, have more advanced technology, and can access more capital. Further, a private utility's for-profit mission would motivate measures to reduce costs and improve efficiency (Romano and Guerrini 2014). However, no conclusive empirical evidence shows that private water utilities are more efficient than public ones (Peda et al. 2013; Kallis et al. 2010; Renzetti and Dupont

2003; Seppälä et al. 2001; Lobina et al. 1999), while some evidence suggests just the opposite (Bhattacharyya et al. 1994; Pescatrice and Trapani 1980).

The quantity of resources water utilities consume directly impacts the efficiency of these organizations and the critical services they provide. Water utilities' consumption of one resource in particular has not been well quantified until recently: energy. Water utilities require energy to extract, treat, pump, and deliver water to end users, transforming natural waters that would otherwise be unsuitable for human consumption into a reliable, high-quality product consumed by every person every day. Water utilities' energy footprints carry financial, environmental, and social impacts that need to be understood and managed sustainably (Sowby and Burian 2017a).

Among the ongoing discussions about the benefits and drawbacks of privatization in the water industry, the question then arises as to whether there is any difference in energy use between public and private water utilities. If the same theories and assumptions that predict greater efficiency in private enterprises apply to their energy use, one would expect private water utilities to have smaller energy footprints than their public counterparts. Further, with energy being one of the largest operational expenses in water supply (EPA 2017b), profit-driven private water utilities might naturally seek cost savings through strategic energy management and therefore require less energy than comparable public ones. This study compares energy intensities of both types of water utilities to determine if a statistically significant difference exists.

C.2 Method

Data for this research originated in a new primary survey of 109 U.S. water utilities by Sowby and Burian (2017a, 2017b). While water usage and financial data are readily available, water utilities generally do not report or publish their energy use. This information is difficult to find, especially for large numbers of water utilities. This longstanding data gap is what motivated Sowby and Burian's (2017) primary survey, which appears to be the largest available dataset on this subject. The data include annual energy intensities, or energy footprints, defined as the ratio of energy input to water deliveries (revenue water only) on an annual basis. (Water deliveries were used instead of total production because using all water in the denominator, including losses, would reduce the energy intensity unfairly, e.g., in two otherwise identical systems, the one with more water loss would have a lower energy intensity, which is inaccurate. Only the revenue water should be counted as the utility's "product.")

Energy intensity, being a ratio of inputs to outputs, is like the reciprocal of the efficiency metric described earlier. It describes how much energy is required to deliver a unit of water to a certain place at a certain time (Wilkinson 2000), and is expressed here in units of kilowatt-hours per million gallons of water delivered (kWh/MG). Normalizing by water volume eliminates all effects of water demand and enables comparison solely in terms of energy. The survey results range from 250 to 11,500 kWh/MG with an average of 2,510 kWh/MG and a weighted average of 1,809 kWh/MG when weighted by water volume. While not yet fully understood, the range of values is attributed to local variations in utility size, water availability, topography, climate, and operational practices.

In this analysis, complete control over the water system's operation (and therefore its energy use) was deemed important for comparing energy intensities by ownership type. Of the 109 systems, 10 were excluded from this analysis because they relied on water imported from other water utilities and were therefore not responsible for a portion of their energy footprint. Of the remaining 99 water utilities with total operational control, 79 were publicly owned and 20 were privately owned. Both groups contain large and small water systems.

The relationship between ownership type and energy intensity was tested through an ordinary least squares (OLS) regression. One potentially complicating factor was acknowledged to be the water utility's size, since larger water systems tend to have lower energy intensities and an economy of scale (Sowby and Burian 2017a). To control for size, energy intensity was regressed on both size (in terms of water delivery volume) and ownership type. The regression then expressed results for each variable individually. The null hypothesis was that ownership type is not related to energy intensity; the alternative hypothesis was that it is. A 95% confidence level was selected (significance level α = 0.05). If the test statistic's probability, p, for ownership type was below 0.05, the null hypothesis would be rejected and the alternative hypothesis accepted.

C.3 Results

Figure C.1 shows statistics for the two groups and Table C.1 shows the regression results. The average energy intensity of private water utilities (1,877 kWh/MG) is less than that of public water utilities (2,365 kWh/MG) and the regression model indicates a negative coefficient for private ownership. The range of energy intensities is also narrower than that of public water utilities. However, the difference is not statistically significant. The regression model yielded a result of $p = 0.1427$ for ownership type, meaning that the null hypothesis cannot be rejected. The difference in energy intensities

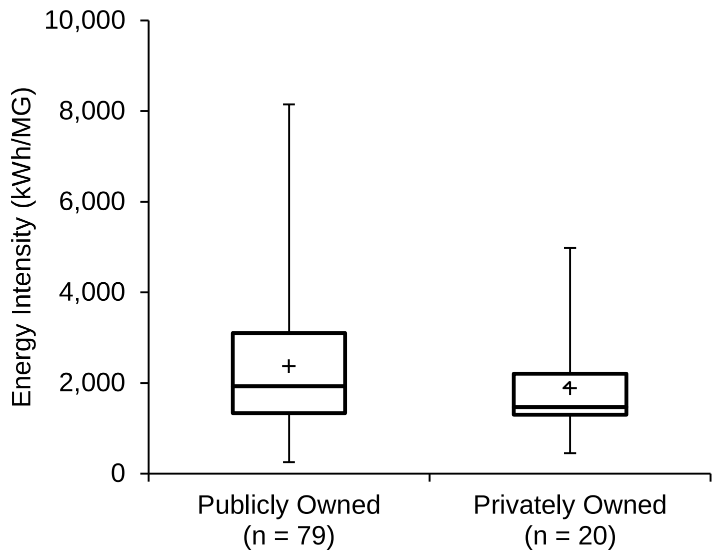

Figure C.1 Energy Intensities of Public and Private Water Utilities

Table C.1

Regression Model Results

	Coefficient	Std. Error	t	p
Intercept	2,555	183.4	13.93	0.0000
Indicator of private ownership (1 if private, 0 otherwise)	−561.1	379.6	−1.478	0.1427
Size (million gallons of water delivered)	−0.009128	0.003296	−2.769	0.006749

between public and private water utilities cannot be conclusively attributed to their ownership structure.

C.4 Discussion

The consensus from the literature is that private water utilities are not necessarily more efficient, in the economic sense, than public ones. This work's finding, namely that the energy intensities of public and private water utilities do not differ with any statistical significance, supports the consensus in the energetic sense.

Further, this means that neither public nor private water utilities enjoy any inherent energy performance advantage by virtue of their ownership. The ownership type alone, therefore, should not excuse a water utility from being subject to, or dissuade them from adopting, policies concerning its energy use or from implementing energy management practices. Both implications are discussed below.

First, since neither has the upper hand, policies concerning energy use in the water industry should apply equally to public and private water utilities. Considerable research has recommended such policies for the integrated management of water and energy resources (Bazilian et al. 2008; Scott et al. 2011; Hellegers et al. 2008). While no broad policies on water utility energy management have been adopted in the United States, the finding suggests that proposed and future policies, especially by state and federal regulators, should address both public and private water utilities.

Second, both public and private water utilities have opportunities to reduce their energy footprints through deliberate energy management. Regardless of size, location, energy intensity, or ownership, most water utilities can decrease their energy use by 10% to 30% through cost-effective actions, according to estimates by the U.S. Environmental Protection Agency (EPA 2017b; Horne et al. 2014; EPA 2013; EPA 2008), the World Bank (Liu et al. 2012), and the Alliance to Save Energy (2016). In recent years many water utilities, both public and private, have undertaken focused energy management programs and successfully reduced their energy use by these same amounts while still providing adequate hydraulic performance and water quality (Sowby et al. 2017; Sowby 2016; Jones et al. 2015; Jones and Sowby 2014). With scarcer water resources and stricter water quality standards, energy use in the water industry is expected to increase, making energy management a higher priority for water suppliers (EPA 2008). Both public and private water utilities stand to benefit from efforts to reduce their energy footprints and operate more sustainably.

As the motivation and movement for water utilities to proactively manage energy use continues to swell, public and private ones may respond in different ways, so this analysis should be revisited when additional data become available. Further, more water utilities are adopting their own energy management policies or plans, and when a sufficient sample exists, the effect of these voluntary policies on energy intensity should be analyzed.

C.5 Conclusion

This study compared the energy footprints of public and private water utilities and found no statistically significant difference. This finding echoes that of other efficiency comparisons in the literature and contributes to the ongoing discussion about the value of privatization in general and its effect on energy use in the water industry in particular. Since no defensible difference in energy intensity was found, policies concerning energy management should cover public and private water utilities alike and both should pursue energy management practices to operate more sustainably.

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APPENDIX D

SUPPLEMENTAL MATERIAL TO CHAPTER 4

D.1 Energy Intensity as a Conservative General Property

The idea that enables in-model simulation of energy intensity rests on two assumptions: 1) that energy intensity is a property concentration of energy per volume, analogous to a chemical concentration of mass per volume; and 2) that energy intensity is conservative, with no internal growth or decay. These are discussed below.

First, in chemistry, a mass concentration is the mass of a constituent, m, divided by the volume of the mixture (constituent plus water), V:

$$C = \frac{m}{V} \tag{D.1}$$

In water resources, chemical concentrations are often expressed in milligrams per liter (mg/L). Keeping volume in the denominator, one can express nonmass quantities as "property" concentrations: kilowatt-hours per million gallons, for example, which is the energy intensity described earlier:

$$Y = \frac{E}{V} \tag{D.2}$$

It behaves like a physical concentration in that it travels with the water throughout the system.

There is some precedent for this concept. Lansey and Boulos (2005) generalized the law of conservation of mass to develop a law of "conservation of a general property" to describe the behavior of nonmass fluid properties. Specifically, they state that the conservation of a general property B is

$$\dot{B}_{in} - \dot{B}_{out} + \frac{dB_{sys}}{dt} = \frac{dB_{CV}}{dt} \tag{D.3}$$

where $\dot{B}_{in}$ and $\dot{B}_{out}$ are the rates of the property entering and leaving a control volume, respectively, and $(dB_{CV})/dt$ is the rate of change of B in the control volume. So far, these terms are analogous to conservation of mass. The remaining term, $(dB_{sys})/dt$, is the addition of the property to the control volume by means external to the fluid (i.e., by the system). In conservation of mass this term is zero, but for other properties it may be nonzero, as when the property is added or removed without changing the fluid mass. While not necessarily addressing energy intensity, Lansey and Boulos (2005) suggested that this describes, among other phenomena, a pot of water heated on a stove—energy added to a closed fluid system.

Second, having shown that energy intensity may be treated like a chemical concentration in a water distribution system, its transport and fate must be further characterized. Clark (2012), AWWA (2012), and Rossman (2000) state that the change in concentration in a pipe by advection is given by the following differential equation:

$$\frac{\partial C_i}{\partial t} = -u_i \frac{\partial C_i}{\partial x} + r(C_i) \tag{D.4}$$

where C_i is the mass concentration (mass per volume) in pipe i at distance x and time t, u_i is the flow velocity (length per time) in pipe i, and r is the reaction rate (mass per volume per time) within the pipe as a function of concentration. Substituting energy intensity for mass concentration the equation becomes

$$\frac{\partial Y_i}{\partial t} = -u_i \frac{\partial Y_i}{\partial x} + r(Y_i) \tag{D.5}$$

where Y_i is the energy intensity (energy per volume) in pipe *i* at distance *x* and time *t* and other variables are as described above. Rossman (2000) further defines the reaction rate with *n*-th order kinetics:

$$r(Y_i) = K_b Y_i^n \tag{D.6}$$

where K_b is the bulk-flow reaction rate coefficient and *n* is the reaction order (0, 1, 2, etc.). Unlike a chemical, energy intensity has no physical presence in the pipe and cannot “react” with anything; it cannot be added or removed internally, so the term $r(Y_i)$ is always zero:

$$r(Y_i) = K_b Y_i^n = 0 \tag{D.7}$$

One of the factors must be zero in order to make the product zero. Since Y_i is not always zero and the exponent *n* is at least zero, K_b must be zero:

$$K_b = 0 \tag{D.8}$$

Rossman (2000) states that K_b is zero when there is no reaction; that is, when the constituent is conservative. Energy intensity, therefore, is analogous to a conservative constituent.

With the reaction rate $r(Y_i)$ being zero, the remaining terms are then

$$\frac{\partial Y_i}{\partial t} = -u_i \frac{\partial Y_i}{\partial x} \tag{D.9}$$

This equation describes that the rate at which energy intensity changes within the pipe equals the difference in energy flow into and out of the pipe. The modeler must specify boundary conditions (Y_i at $x = 0$ for all times) and initial conditions (Y_i at $t = 0$ for all locations). The hydraulic model will compute the flow velocity u_i in each pipe at each time step.

While not a physical concentration of mass per volume, energy intensity is a property concentration of energy per volume. Further, energy intensity is conservative; it is a fluid property that does not decay or grow by any internal reaction. It may be added externally, as by a pumping facility, but it is never removed from the system. With this perspective, the modeling of energy intensity within a water distribution system may follow the same principles and techniques as water quality modeling in extended-period simulations described by others (Lansey and Boulos 2005; Clark 2012).

For example, the nodal mixing of energy intensities could be modeled as

$$Y_j = \frac{\sum_{i \in IN_j} Q_i Y_i + Y_{sys}}{\sum_{i \in OUT_j} Q_i} \quad \text{(D.10)}$$

where Y_j is the resulting energy intensity at node j, IN_j is the set of pipes entering the node, OUT_j is the set of pipes leaving the node, Q_i is the flow rate entering the node from pipe I, Y_i is the energy intensity of the water entering the node from pipe I, and Y_{sys} is the energy intensity added by the system at node j (as by a pump). This equation follows the same form as mixing of any water quality constituent and is performed for each node in the network (Haestad Methods et al. 2003; Clark 2012). In the absence of any external addition, the equation degrades to

$$B_j = \frac{\sum_{i \in IN_j} Q_i B_i}{\sum_{i \in OUT_j} Q_i} \quad \text{(D.11)}$$

which states that the resulting energy intensity at a node is equivalent to the flow-weighted average of the incoming energy intensities. Similar equations can be derived for tanks and pipes.

D.2 Pump Equation and Energy Intensity

Modifying the pump equation leads to an expression for energy intensity in terms of hydraulic head and overall efficiency. This is useful when data needed to compute an element's observed energy intensity are not available and the energy intensity must be estimated.

The pump equation is

$$P = \frac{\gamma Q h}{\eta} \tag{D.12}$$

where, in any consistent set of units, P is the power applied to the fluid, γ is the fluid density, Q is the mass flow rate, h is the total dynamic head, and η is the pump efficiency. Multiplying by time, t, the equation becomes

$$Pt = \frac{\gamma Q h}{\eta} t \tag{D.13}$$

Since the product of power and time is energy and the product of flow and time is volume, this becomes

$$E = \frac{\gamma V h}{\eta} \tag{D.14}$$

where E is the energy applied to the fluid and V is the fluid volume. Dividing by volume, the expression becomes

$$\frac{E}{V} = \frac{\gamma h}{\eta} \tag{D.15}$$

Energy intensity, as defined earlier, is the ratio of energy to water volume, which is the left-hand side of the above equation. When energy intensity (Y) replaces this term, the equation becomes

$$Y = \frac{\gamma h}{\eta} \tag{D.16}$$

For English units, a standard water density of 62.4 lb/ft^3 and energy intensity units of kilowatt-hours per million gallons (kWh/MG) are assumed. With some unit conversions the equation becomes

$$Y = \left[\frac{\left(62.4\,\frac{\text{lb}}{\text{ft}^3}\right)h}{\eta}\right]\left[\left(3.776 \times 10^{-7}\,\frac{\text{kWh}}{\text{ft}\cdot\text{lb}}\right)\left(133{,}680\,\frac{\text{ft}^3}{\text{MG}}\right)\right] \tag{D.17}$$

$$Y = \frac{3.14h}{\eta} \tag{D.18}$$

where *Y* is the energy intensity (kWh/MG) of the element, *h* is the total dynamic head (ft) which is applied to the water, and *η* is the overall efficiency (fraction) which is less than 1. This expression means that for every foot of head in a perfectly efficient system, one would expect an energy intensity of 3.14 kWh/MG.

D.3 Typical Energy Intensities

Table D.1 gives energy intensities for common water facilities. These may be used as approximations when actual data are not available.

D.4 Examples of Energy Intensity Behavior

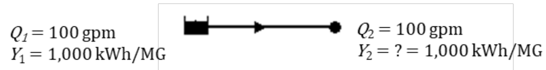
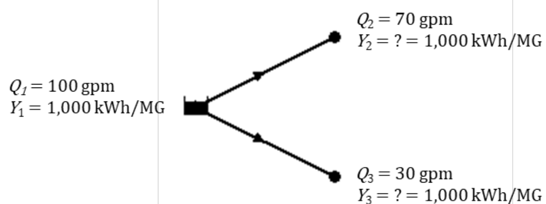
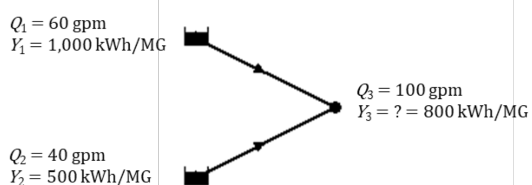
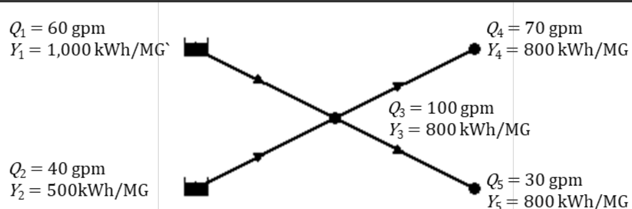
To illustrate how energy intensity behaves as a conservative general property within a water distribution system, a few examples of commonly occurring configurations are presented in Figure D.1. In each case, all pipes are equal diameter and equal length and the given demands and energy intensities are arbitrary. Both model results and manual calculations are included, along with comments on the behavior of energy intensity in each configuration.

Table D.1

Typical Energy Intensities for Common Water Facilities

Facility	Energy Intensity (kWh/MG)
Well, 400 ft TDH[1,2]	1,680
Well, 800 ft TDH[1,2]	3,350
Raw surface water pump[3]	150
Surface water treatment plant, 1 MGD[3]	675
Surface water treatment plant, 100 MGD[3]	470
Reverse osmosis plant (seawater)[3]	12,300
Finished water pump[3]	1,000
Booster pump, one pressure zone, 200 ft TDH[1,2]	840

Notes:
1. See Table 4.1
2. Assumes 75% wire-to-water pump efficiency
3. See Table 4-2 in EPRI (2013)

Case	Schematic and Model Results	Manual Calculation	Comments
(a) Segment		By conservation of mass, $Q_1 = Q_2$ By conservation of general property, $Q_1Y_1 = Q_2Y_2$ Combining, $Y_2 = \frac{Q_1Y_1}{Q_2} = \frac{(100\text{ gpm})\left(1{,}000\frac{\text{kWh}}{\text{MG}}\right)}{100\text{ gpm}} = 1{,}000\text{ kWh/MG}$	Energy intensity is conserved with flow.
(b) Branch		By conservation of mass, $Q_1 = Q_2 + Q_3$ By conservation of general property, $Q_1Y_1 = Q_2Y_2 + Q_3Y_3$ Assuming complete instantaneous mixing at node, $Y_1 = Y_2 = Y_3 = 1{,}000\text{ kWh/MG}$	Branches do not affect energy intensity from a single source, regardless of how flow is split.
(c) Confluence		By conservation of mass, $Q_1 + Q_2 = Q_3$ By conservation of general property, $Q_1Y_1 + Q_2Y_2 = Q_3Y_3$ Assuming complete instantaneous mixing at node, $Y_3 = \frac{Q_1Y_1 + Q_2Y_2}{Q_1 + Q_2}$ $= \frac{(60\text{ gpm})\left(1{,}000\frac{\text{kWh}}{\text{MG}}\right) + (40\text{ gpm})\left(500\frac{\text{kWh}}{\text{MG}}\right)}{(60\text{ gpm}) + (40\text{ gpm})}$ $= 800\text{ kWh/MG}$	Energy intensity at confluence node is flow-weighted average of incoming energy intensities.
(d) Cross		By conservation of mass, $Q_1 + Q_2 = Q_3 = Q_4 + Q_5$ By conservation of general property, $Q_1Y_1 + Q_2Y_2 = Q_3Y_3 = Q_4Y_4 + Q_5Y_5$ Assuming complete instantaneous mixing at central node, $Y_3 = \frac{Q_1Y_1 + Q_2Y_2}{Q_1 + Q_2}$ $= \frac{(60\text{ gpm})\left(1{,}000\frac{\text{kWh}}{\text{MG}}\right) + (40\text{ gpm})\left(500\frac{\text{kWh}}{\text{MG}}\right)}{(60\text{ gpm}) + (40\text{ gpm})}$ $= 800\text{ kWh/MG}$ and outgoing links carry the same energy intensity to the end nodes.	Combination of confluence and branch. Energy intensity of central node is flow-weighted average of incoming energy intensities. Outgoing links carry same energy intensity as central node, regardless of flow. Loop is opposite configuration (branch followed by confluence).

Notes:

1. All pipes = 12 in. diameter, 1,000 ft length. Given demands and energy intensities are arbitrary.
2. Q = flow rate or demand, Y = energy intensity.
3. Equations assume at least one nonzero flow rate.

Figure D.1 Examples of Energy Intensity Behavior

D.5 Sensitivity Analysis

Because of uncertainty associated with the many input parameters, sensitivity analysis is an important aspect of responsible use of computerized models (Hall et al. 2009). This research relied on energy intensity results obtained from a particular model and was subjected to a sensitivity analysis to determine how the results respond to incremental changes in certain input parameters.

This analysis examined the effects of six parameters: pipe diameter, pipe roughness (Hazen-Williams *C* factor), pipe length, water demand, pumping head, and source energy intensity on the energy intensity results, defined here as the energy intensity at simulation time 144 hours averaged across all nodes in the system. These input parameters are attributes of the most basic components of the system—pipes, nodes, and pumps—and encompass combinations of hydraulic, energetic, and geometric characteristics. Source energy intensity affects the energy intensity results directly; the other parameters influence the underlying network hydraulics and thereby change the path by which water is delivered and the corresponding energy intensity associated with the path.

To quantify the effects, the value of each parameter was changed by positive and negative increments of 10% around its original value, up to 50% each way, while holding the other parameters constant. While certain values in the test may fall outside the reasonable range for a given parameter, Lenhart et al. (2002) showed that sensitive parameters can be identified independent of the chosen range. Further, since EPANET is a demand-driven model, each model run may produce unacceptable or infeasible hydraulic conditions (such as low or negative pressures), but these are ignored since the purpose of the sensitivity analysis was to quantify each parameter's effect on energy intensity results. While not as comprehensive as other approaches, this "one-at-a-time" approach is a finite-difference estimation of the dependent variable's partial derivative with respect to each parameter and is well accepted in many fields (Lenhart 2002; Hamby 1994) and has been applied specifically to hydraulic models of water distribution networks (Lee et al. 2017; Filion et al. 2004).

Figure D.2 shows the results. Of the parameters selected, source energy intensity is the most influential. Considered as a conservative general property, its effect on the resulting nodal energy intensity is exactly linear. Other parameters are much less influential at every increment, yielding relatively small effects even when changed by as much as 50%. This suggests that accurately determining source energy intensity is a critical step in this type of energy analysis for water distribution systems and is where data quality efforts should focus.

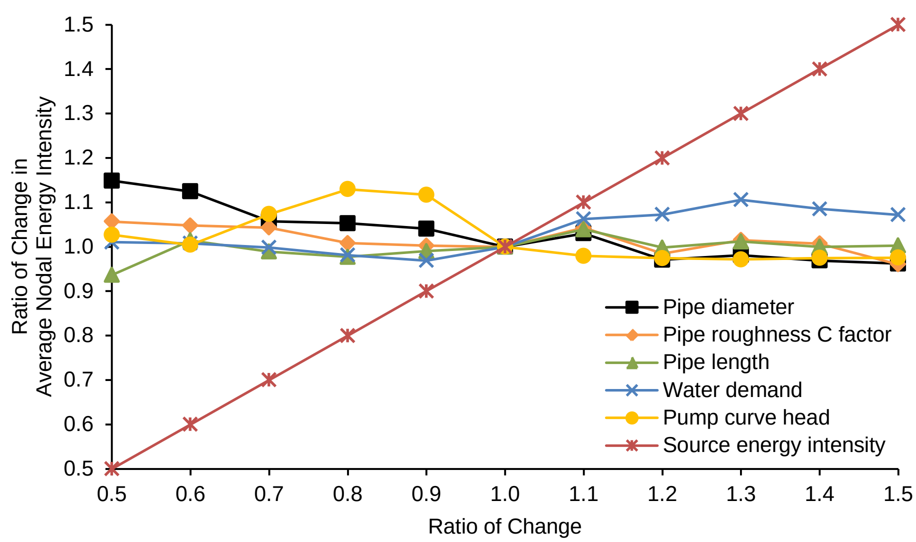


Figure D.2 Sensitivity Analysis Results

D.6 References

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