High-Resolution Energy Intensity Modeling to Improve Water Distribution System Performance*

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ABSTRACT

Water distribution systems can improve their sustainability by identifying and implementing the most energy-efficient scheme for water delivery, but this is difficult to determine for complex systems. A method proposed here combines facility-level energy intensity data ("energy maps") with hydraulic models, viewing energy intensity as a conservative general property that is transported with the water. The new approach rapidly quantifies the temporal and spatial variation of energy intensity within a water distribution system and helps evaluate alternative operations and designs that conserve energy. A case study with a real water utility demonstrates the method and validates it through comparison with actual energy savings. The method is an effective analysis technique, mapping the flow of energy through the water distribution system and quantifying the response of local energy intensities to proposed system modifications. The results indicate that water source selection, among other energy management practices, can significantly influence a water system's energy use. Further research applications are recommended.

KEYWORDS

Water; energy; distribution

INTRODUCTION

Water distribution systems require energy to extract, treat, and deliver reliable, high-quality drinking 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 issues include the emissions and ecological impacts associated with generating energy (Ramos et al. 2010; Griffiths-Sattenspiel and Wilson 2009; Stokes and Horvath 2009). On the social side, stakeholders expect water utilities to use energy and other resources wisely while providing 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

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et al. 2012; NYSERDA 2010; EPA 2008). 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 low-energy-intensity water sources
- Prioritizing low-energy-intensity 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 system is unique and requires individual analysis to implement energy management practices. However, the optimum operational scheme is difficult to determine, especially for complex systems with many pressure zones, water sources, and pumping facilities. To improve energy performance, these fluxes should be computed and understood at fine scales within the system, and then tested against alternatives to find, for example, an acceptable operational scheme that minimizes energy use.

This work seeks to answer the following research questions:

- How does energy intensity within a water distribution system respond to operational changes such as water source selection and facility shutdowns, or the other energy management practices listed earlier?
- How can such analysis inform decisions to implement energy management practices and operate more sustainably?

This study addresses a key research gap by proposing, documenting, demonstrating, and validating a high-resolution technique for modeling energy intensity within a water distribution system. 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.

BACKGROUND

The desired modeling method builds on important concepts described below.

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 cubic meter (kWh/m^3) or kilowatt-hours per million gallons (kWh/MG). In this context, energy intensity is for the operational stage only, which makes up most of the life-cycle energy use of water utilities—about 80%, according to one study (Xue et al. 2019). The locations for which energy intensity is computed may be entire systems, as by Sowby and Burian (2017a, 2017b, 2018); pressure zones, as by Saliba and Gan (2006) and Spang and Loge (2013, 2015); or end users, as by Siddiqi and Fletcher (2015). Energy intensity also varies over time at each of these spatial scales (Sowby and Burian 2017a; Spang and Loge 2013, 2015). Wastewater treatment may also be characterized in terms of energy intensity, as others have done (Chini and Stillwell 2018; EPRI 2013; Sanders and Webber 2012;

Twomey and Webber 2011; Carlson and Wallburger 2007), and be combined with drinking water values to complete the energy profile of publicly provided water services.

A few related fields can inspire efforts to model energy intensity for water at fine scales. Studies of "embedded water" or "virtual water" determine the amount of water used to make products like meat, clothing, and lumber by considering each step of the associated supply chain (Hoekstra et al. 2011; Hoekstra 2003; Hoekstra and Hung 2002). Such studies have helped countries and organizations reduce their water impacts. Likewise, community energy mapping combines mildly aggregated energy consumption data with spatial data (Webster et al. 2011; Reul and Michaels 2012; Ea Energy Analyses and GRAS 2012; Gilmour and McNally 2010). By visualizing energy uses in each city block, for example, these maps reveal "energy gushers" and engage communities to act.

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. Saliba and Gan (2006) and Spang and Loge (2013, 2015) studied energy intensity at the pressure-zone level using facility energy data and geographic information systems (GIS). Both enabled energy calculations at finer geographic resolution to prioritize water and energy conservation actions in each pressure zone that would not have emerged from a coarser analysis. The next step, to inform even more site-specific actions, is to model water and energy interactions in the actual water infrastructure with node-and-link resolution.

Water and energy demands are generally well understood in isolation, but the processes that "convert" energy to water (i.e., use energy to supply 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 triggers an operational scheme (one of many potential operational schemes), which triggers an energy demand (reacting to the system's needs); in turn, energy provision enables system operation, which enables water delivery (Fig. 1). This framework outlines 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.

In a water distribution system, 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, energy intensity accumulates with each step in the water supply chain. 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. Since energy has no physical signature, it cannot be observed in a water sample. The energy intensity can be determined only by modeling. One must therefore know the water's history: its origins and paths and the associated energy intensities associated.

METHOD

The combination of two existing tools and the concept of "conservation of a general property" bridges this gap.

First, for individual water systems, an "energy map" quantifies each water facility's energy requirements, thereby mathematically linking the facilities 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 (Sowby et al. 2017; Jones and Sowby 2014). Second, extended-period hydraulic models, e.g., EPANET (Rossman 2000), simulate water system behavior and mathematically link a water system's facilities to individual water demands. As such, they are important for considering the system's constraints (e.g., adequacy of water quality, quantity, pressure, and storage) 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 (Fig. 1). Combined, the two tools offer a framework for modeling energy-for-water interactions and a novel way that tracks 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 (described below) completes the picture of modeling interactions along both hydraulic and energetic pathways. (Incidentally, 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 fluxes be modeled at the same resolution as hydraulics. For this reason, the authors propose that energy intensity be considered a "conservative general property" (Lansey and Boulos 2005). 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 but only external additions.

With energy intensity (or even energy cost) treated as a conservative general property, the approach leverages existing modeling technology and streamlines energy analysis in complex water distribution systems. Since the hydraulic model already computes the hydraulics for transport and mixing, one 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 as described below.

Modeling Requirements

Considering 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 (Rossman 2000). Terminology and procedures may differ among other packages.

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. 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 dynamic head and wire-to-water efficiency are known, as from a pump curve, the expected energy intensity may be computed (see Appendix). 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.

Table 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 the Appendix.

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 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 Fig. 2 for examples.

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/m^3) 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 that accumulates through the water delivery process, this option applies to all energy nodes and represents the continuous “dosing” of energy intensity into the system.

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.

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. The modeler must interpret the concentrations according to the units in which they were defined (e.g., kWh/m^3). 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 work.

CASE STUDY

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 elevated 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 0.41 m^3/s (6,500 gallons per minute). Fig. 3 shows the system as defined in the model.

Energy Analysis Preparation

The hydraulic model had already been calibrated and used specifically for energy analysis, so its application to this research is appropriate. 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 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 1, using the design heads and efficiencies from their respective pump curves. Table 2 shows the results. (Incidentally, these limitations in obtaining facility-level energy data echo those described more fully by Sowby et al. [2019a]).

Table 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 2 are represented as pumps in the model, the energy nodes were chosen as the first nodes downstream of the pumps. At each of these locations the source quality was set using the energy intensity values in Table 2 with the type option set to flow-paced booster, which adds a fixed concentration to the existing concentration. No time pattern was specified since an average 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 reach a stable repeating pattern—a common practice in water quality modeling (Haestad Methods et al. 2003). Results of the final 24 hours (hours 120–144) are reported.

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 amount of energy. Since the water distribution system offers many hydraulic and 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 (or at least less than the existing scenario). One possible path to the node is from the wholesale connection and Booster 1, a path with a total energy intensity of 0.644 kWh/m^3 (2,434 kWh/MG); another is Well 3 via Booster 1, with a total energy intensity of 0.934 kWh/m^3 (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 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.

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 questions for this water distribution system. The prioritized water source scheme was selected iteratively based on the energy map of Table 2. The model controls were modified manually 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 21 m during peak instantaneous demand and minimum 28 m 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. The scenarios were developed manually using copies of the base model. The proposed model was modified manually until the pressure criteria mentioned above were satisfied.

Model Analysis and Discussion

Figs. 4 and 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, 2015). 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 as energy intensity at every point in the system.

In Fig. 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 (perhaps because of deeper groundwater). Comparison of historical water production versus capacity showed that the other water sources in the same pressure zone are underutilized—only about 60% of their capacity is used—and could replace much of Well 2's production. Hydraulic modeling confirmed that shifting water production away from Well 2 does adversely affect the level of service for pressure mentioned above and is therefore feasible. The other water sources would be prioritized and Well 2 would stand by for occasional use.

Another opportunity is associated with Tank 5, which is hydraulically located in Zone 3 but serves no connections yet. A land developer constructed the tank years ago, but no homes have been built. Water is pumped to Tank 5 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, 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 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. While this is a large example, it suggests further opportunities to save energy by turning off other unnecessary, even smaller, assets such as heaters and lights. It also highlights the importance of energy analysis during the design of new facilities, which could help avoid wasting energy from the very beginning.

These two opportunities—prioritizing low-energy-intensity water sources and shutting down unnecessary facilities—were modeled in the proposed scenario presented in Fig. 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 Fig. 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, Figs. 4 and 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).

Fig. 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. The area between the curves represents energy intensity savings which, if integrated over the water demand at the node, yield a total energy savings for the node. Similar graphs could be produced for every node in the model.

For existing conditions in Fig. 6, the energy intensity at the node averages 0.723 kWh/m^3 (2,735 kWh/MG) and varies between 0.645 kWh/m^3 (2,443 kWh/MG) and 0.751 kWh/m^3 (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 2, when weighted by these percentages, 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 Fig. 6, the energy intensity at the node averages 0.537 kWh/m^3 (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 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 2 does not guarantee that the path is hydraulically feasible or that it will satisfy demands and pressures—criteria that must 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% over the entire system. 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 head fluctuation (the difference in maximum and minimum head during the simulation period) across all nodes in the existing scenario is 20.4 m; in the proposed scenario, it is only 8.4 m, 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. Turnover in equalization storage (the volume of water stored in or released from tanks during the day) increased by 12%, from 7,680 m^3 to 8,590 m^3 systemwide in the existing and proposed conditions, respectively, even with one tank offline. 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 non-capital 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.

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 technique. It 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 questions 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. This is a specific result in this case, but has been documented elsewhere (Sowby et al. 2019b; Sowby et al. 2017; Jones and Sowby 2014). If nothing else, asking energy questions helps one understand how the system works and leads to insights for improvements elsewhere.

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.

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. 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.

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 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.

FURTHER WORK

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 better still, 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 the Appendix, 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 liter. 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. A notable study by Spang et al. (2018) estimated energy and emissions reductions associated with water conservation in California; the high-resolution method presented here could help prioritize conservation in specific areas where water provision is particularly energy intensive.

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, energy policies (Sowby 2018), system dynamics models, the broader water–energy nexus, and related research areas should also be explored.

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 a 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 technique 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.

DATA AVAILABILITY

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions. The case study hydraulic models, energy use data, water use data, and related data are the property of Eagle Mountain City, Utah, and may be provided through the corresponding author with the City's permission.

ACKNOWLEDGMENTS

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APPENDIX

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 direct measurements are not available and the energy intensity must be estimated.

The pump equation is

$$P = \frac{\gamma Q h}{\eta} \tag{1}$$

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, dividing by volume, and converting units, the equation ultimately becomes

$$Y = \frac{0.00272h}{\eta} \tag{2}$$

where Y is the energy intensity (kWh/m^3) of the element, h is the total dynamic head (m) which is applied to the water, and η is the overall efficiency (fraction) which is less than 1. This expression means that for every meter of head in a perfectly efficient system, one would expect an energy intensity of 0.00272 kWh/m^3 (3.14 kWh/MG).

Typical Energy Intensities

Table 3 gives energy intensities for common water facilities. These may be used as approximations when actual data are not available.

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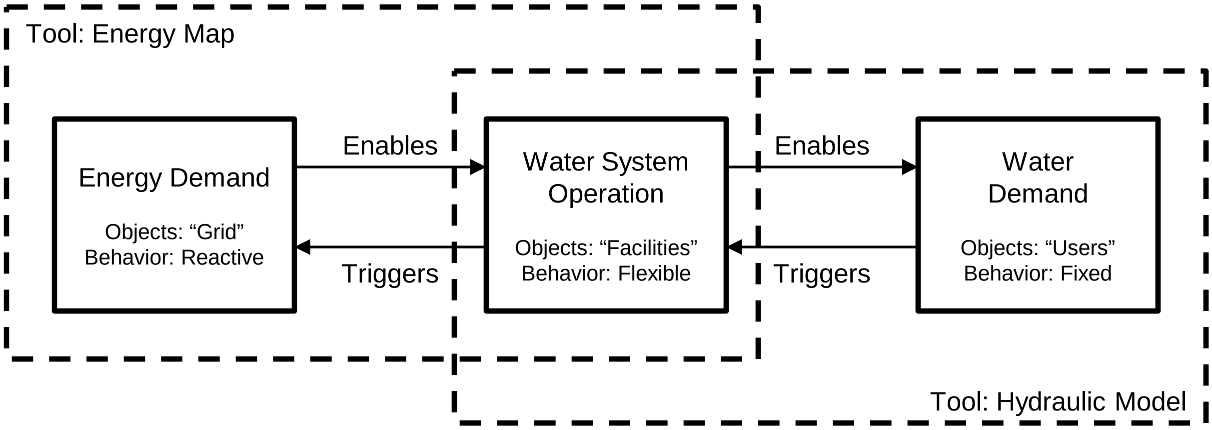

Fig. 1. Energy-for-water framework

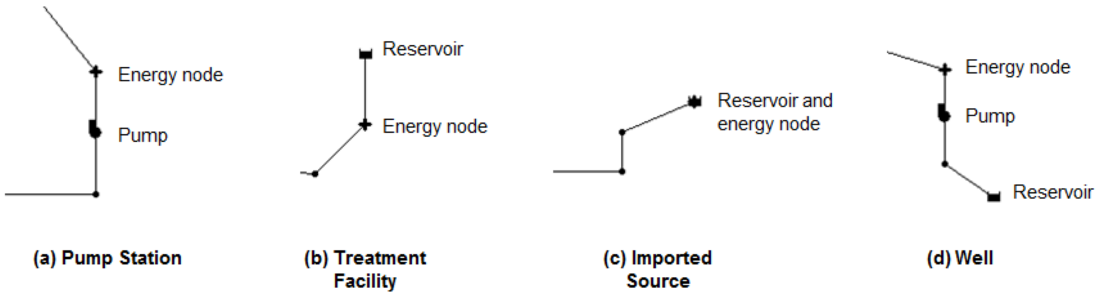

Fig. 2. Energy node examples

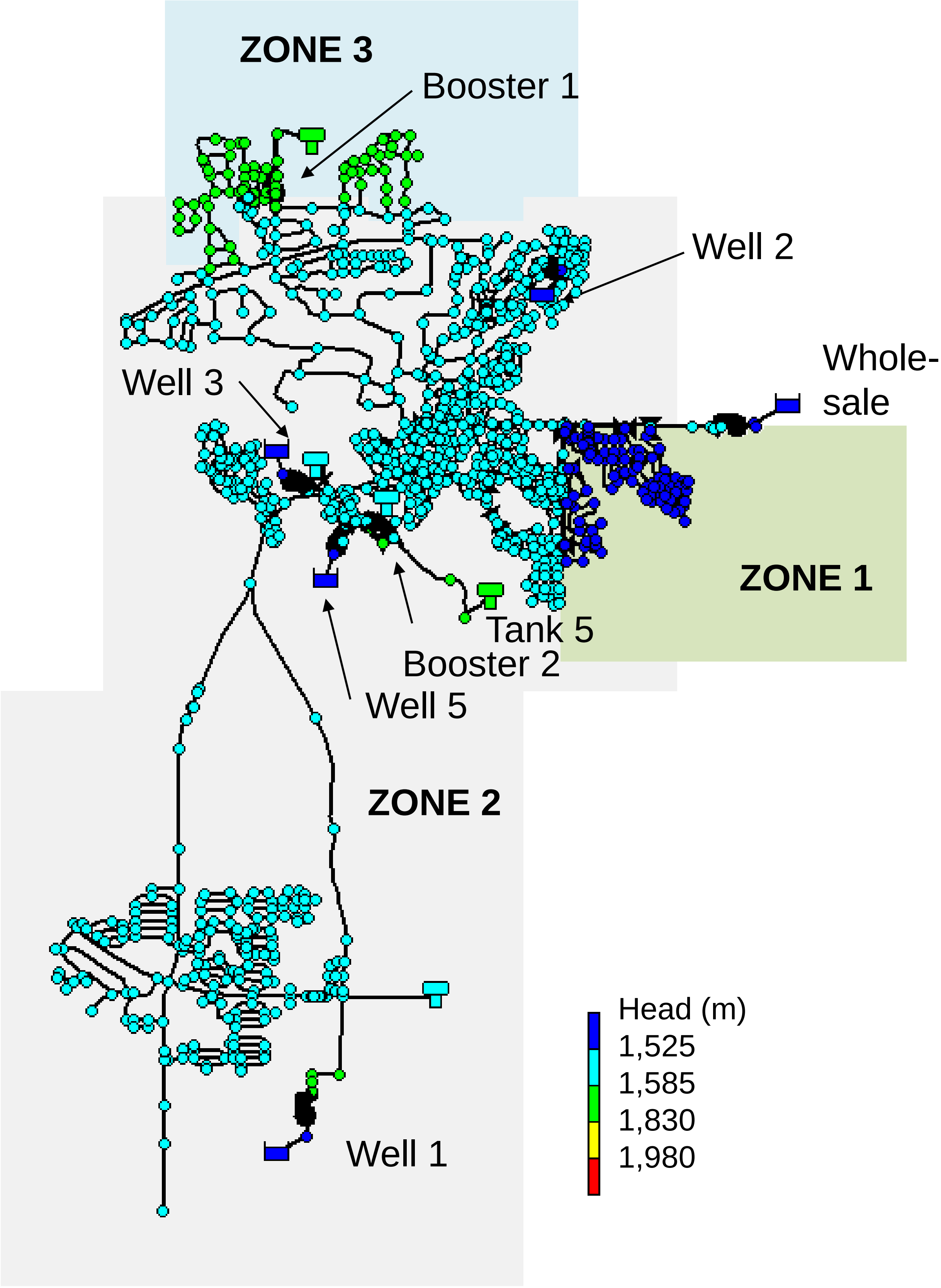

Fig. 3. Eagle Mountain water system model

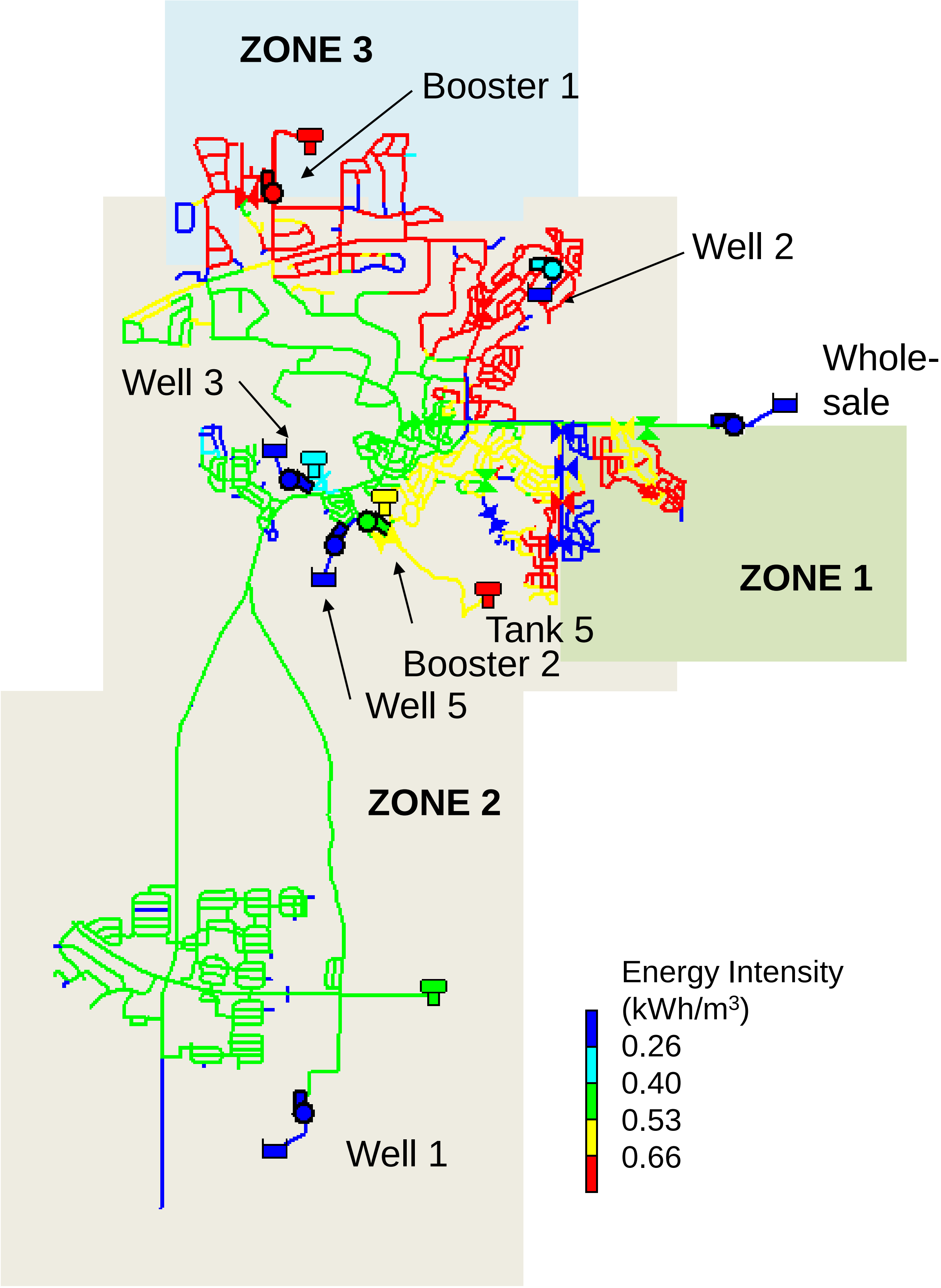

Fig. 4. Energy intensity under existing conditions

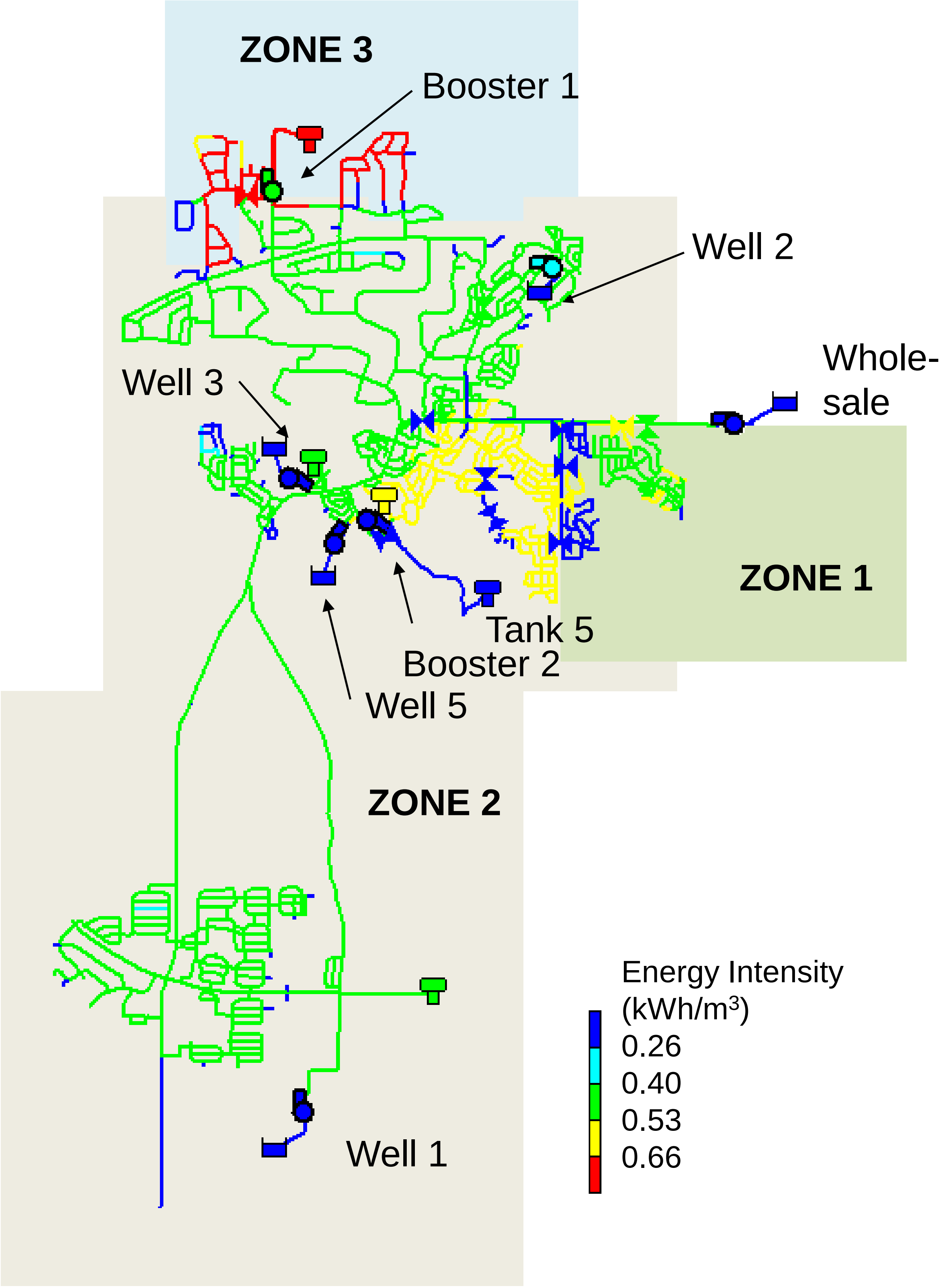

Fig. 5. Energy intensity under proposed conditions

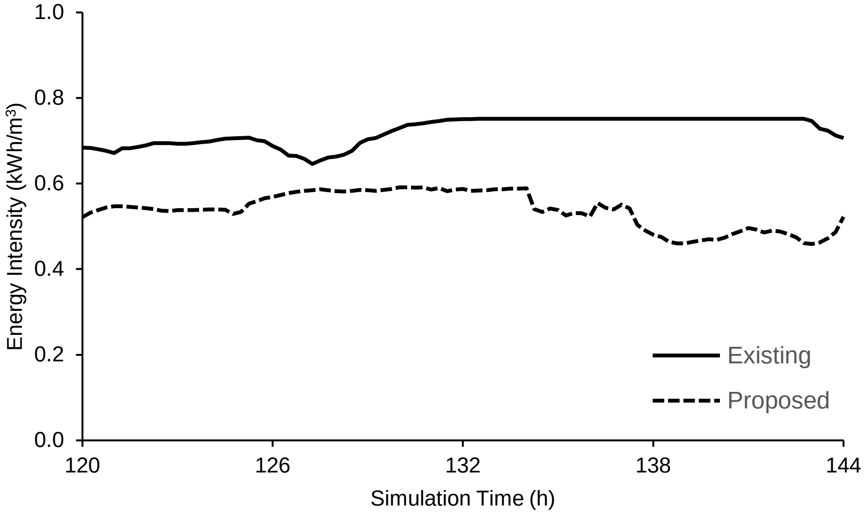

Fig. 6. Energy intensity at node in Zone 2

Table 1. Methods for Determining Energy Intensities for Water Supply

	Pump	Plant	Custom
A: 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: $EI = \frac{\Sigma E}{\Sigma V}$		
B: Calculation (use equations)	1. Determine total dynamic head in meters (*h*) 2. Determine typical efficiency as decimal (*η*) 3. Compute: $EI = \frac{0.00272h}{\eta}$ (see Appendix)	Not applicable	Not applicable
C: 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 cubic meters (m^3), and energy intensity assumed to be kilowatt-hours per cubic meter (kWh/ m^3).
2. Observations of energy use will likely include non-hydraulic 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.

Table 2. Water Facility Energy Intensities

Facility	Pressure Zone Served	Average Energy Intensity (kWh/m^3)
Well 1	Zone 2	0.447
Well 2	Zone 2	0.751
Well 3	Zone 2	0.717
Well 5	Zone 2	0.657
Wholesale	Zone 2	0.427
Booster 1	Zone 3	0.217
Booster 2	Zone 3	0.216

Table 3. Typical Energy Intensities for Common Water Facilities

Facility	Energy Intensity (kWh/m^3)
Well[1,2], 100 m TDH	0.36
Well[1,2], 200 m TDH	0.73
Raw surface water pump[3]	0.04
Surface water treatment plant[3], 4,550 m^3/d	0.18
Surface water treatment plant[3], 455,000 m^3/d	0.12
Reverse osmosis plant (seawater)[3]	3.25
Finished water pump[3]	0.26
Booster pump, one pressure zone[1,2], 60 m TDH	0.22

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