
Edward S. Spang  
*University of California, Davis*, ess pang@ucdavis.edu

Andrew J. Holguín  
*University of California, Davis*, ajholguin@ucdavis.edu

Frank J. Loge  
*University of California, Davis*, fjloge@ucdavis.edu

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Edward S. Spang*, Andrew J. Holguin*, and Frank J. Loge*
*Center for Water-Energy Efficiency, University of California, Davis, CA, 95616
(esspang@ucdavis.edu, ajholguin@ucdavis.edu, and fjlope@ucdavis.edu)

Abstract: The water sector demands significant energy inputs to deliver safe and reliable water to urban communities. It follows that water conservation efforts can lead to measurable upstream reductions in energy use, as well as complementary reductions in operational costs and greenhouse gas emissions. However, the complexity of many urban water infrastructure networks produces a high level of seasonal and spatial variability of the energy embedded in the water delivered across the utility service territory. This variability constrains the ability of water agencies to make defensible estimates of the energy savings that may be achieved from water conservation programs. To address this challenge, the Center for Water-Energy Efficiency (CWEE) at UC Davis has developed the WEMap (water-energy mapping) tool. At the core of the tool is the elaboration of a mathematical Directed Acyclical Graph (DAG) model that is informed by the actual layout of the water utility distribution system. Leveraging the open-source R programming language, the web-based tool integrates detailed energy intensity assessments of water utility infrastructure systems with a user-friendly interface to support decision-making to secure linked water-energy savings. More specifically, the program streamlines the estimation of energy savings for a range of water conservation scenarios, including interventions targeted at specific customer types and/or particular geographic areas within the service territory. The software program was tested, refined, and debugged in direct collaboration with the Austin Water utility in Texas—using their infrastructure system as a test simulation for the water-energy analysis and directly incorporating their feedback to advance data visualization and the overall user interface.

Keywords: Water-energy nexus; energy intensity; water conservation; urban water; decision support

1 INTRODUCTION

The water sector demands large amounts of energy. In California, nearly 20% of the electricity and 30% of the non-power-plant natural gas used goes to producing, moving, treating, and heating water (Klein et al. 2005). While managing these integrated systems represents a significant challenge for both water and energy utilities, there is also a great opportunity to design targeted programs that jointly conserve both water and energy (Spang et al. 2018). However, deploying linked water-energy programs in the water sector requires clear, defensible methods for calculating the energy intensity (EI) of water, and reliable, verifiable monitoring of energy and greenhouse gas (GHG) emissions savings. This is no small challenge, since energy use varies significantly depending on where and when it is used within the water infrastructure (Spang and Loge 2015).

The majority of research efforts to estimate the energy intensity of water systems using a “technology portfolio” that sums the energy intensities of the installed technologies in the water infrastructure system, usually by portion of the water supply chain, e.g. extraction, treatment, distribution, wastewater collection, and wastewater treatment (Allen et al. 2010; Bennett et al. 2010; Young 2015). While this approach provides an adequate overview of utility-level energy intensity and allows for comparison between water agencies, it neglects the sub-regional heterogeneity of energy intensity that arises from the actual layout of the water infrastructure system.
To address this gap, the Center for Water-Energy Efficiency (CWEE) at UC Davis has developed a spatially and temporally disaggregated approach to accurately calculate and represent EI by leveraging water flow data from water utilities’ Supervisory Control And Data Acquisition (SCADA) systems and energy consumption data from the associated energy meter for each asset in the infrastructure system (e.g. pumps, treatment systems). Our approach integrates the SCADA and energy meter data streams for calculating site-specific EI estimates within a linked model that explicitly incorporates the infrastructure system’s network layout (Figure 1).

The following paper describes the WEMap tool that CWEE developed to streamline this approach for estimating energy intensity by pressure zone (i.e. sub-regions of the water service territory that share the same water delivery pathway within the broader network), as well as estimate the potential energy savings linked to hypothetical water conservation efforts targeted by customer type and location. The tool was developed using R for model estimation and the Shiny R package for web-based visualization of the results. As components of the model were developed in collaboration with the Austin Water utility in Austin, Texas, we use the Austin Water system as the case example to introduce and explain the application of the tool.

2 METHODOLOGY

The first step of our research process was to collect the required data from the Austin Water utility for the energy intensity analysis, including the water flow data and electricity consumption data for each asset in the system, as well as a complete network schematic of the infrastructure system. For our initial model, we simplified the system boundary of our study by focusing only on the potable water system and did not include the wastewater infrastructure. Once data was collected, we consolidated and aligned the data to estimate energy intensity for each asset over time; linked these estimates across the network to estimate the cumulative energy intensity for each pressure zone; and finally, integrated water consumption data by pressure zone and customer type to enable the estimation of the potential energy savings secured for a range of water conservation scenarios.

2.1 Estimating energy intensity by infrastructure asset

Austin Water provided data to the research team in the form of detailed daily reports that included hourly water flows and daily electricity consumption for each of the key assets that we included in the study, including all of the extraction pumps, potable treatment systems, and distribution pumps. These daily reports were provided as individual excel files that the research team stitched together to create continuous time series for each asset in the potable system. Once the data were organized, we calculated the energy intensity (EI) for each asset (i) by dividing daily (j) energy consumption (E) by daily water flow volume (V) as shown (1).

\[
EI_{i,j} = \frac{E_{i,j}}{V_{i,j}}
\]
2.2 Estimation of EI by pressure zone

To estimate the spatial heterogeneity of energy intensity within the service area, the individual-asset energy intensity values are linked to an interconnected model of the water distribution network (Figure A-1), including all the inputs, outputs, and physical assets if the potable water system. The network model is implemented by extending a graph object, as implemented in the R igraph (Csardi and Nepusz 2006) package. The flow of water through the system is then represented in the network as a directed acyclic graph (DAG), where the flow pathways proceed in a single direction between each node, and there are no significant cyclical loops (Jensen and Nielsen 2007). This makes the calculation of cumulative energy intensity straightforward to calculate, by traversing the network and accumulating energy intensity values at each node. This model calculates the cumulative energy added to water as it is distributed throughout the system, which yields the total energy per unit of water required to serve a given location.

The total cumulative EI at each node is equal to the average EI of incoming flows plus the EI added by the asset at that node. If there are no parent nodes in the network then it is just equal to the EI added at that node (2). Since a node may have multiple inputs, a flow-weighted average of the incoming EI values from the parent nodes is used to calculate the total upstream EI (3). Note that the calculation of incoming EI relies on the total EI of the upstream (parent) nodes. This calculation proceeds recursively through each upstream node in the distribution system, fully resolving when it reaches the initial inputs to the system, which have no parent nodes. Structuring the calculation in this manner allows the model to scale easily to large and complicated networks, while remaining relatively simple to implement.

\[
EI_{a,t}^{\text{tot}} = \begin{cases} 
EI_{a,t}^{\text{add}}, & \text{if } P(a) = \emptyset \\
EI_{a,t}^{\text{inc}} + EI_{a,t}^{\text{add}}, & \text{if } P(a) \neq \emptyset
\end{cases}
\] (2)

\[
EI_{a,t}^{\text{inc}} = \sum_{i=1}^{\vert P(a) \vert} \left( EI_{i,t}^{\text{tot}} \times \frac{f_{i,t}}{\sum_{i=1}^{\vert P(a) \vert} f_{i,t}} \right)
\] (3)

Where,
- \( EI_{a,t}^{\text{tot}} \) = total EI at node a for time period t
- \( EI_{a,t}^{\text{add}} \) = EI added by asset at node a for time period t
- \( EI_{a,t}^{\text{inc}} \) = EI of water incoming to node a for time period t
- \( P(a) \) = set of parent nodes (upstream and immediately adjacent to node a)
- \( EI_{i,t}^{\text{tot}} \) = total EI of water at parent node i for time period t
- \( f_{i,t} \) = flow at parent node i for time period t

The main output of the network model is cumulative EI values for every node on the distribution network, which include the sub-regional pressure zones. In the case of Austin Water, we estimated the EI for each of the ten pressure zones in their system.

2.3 Aligning spatial EI estimates with water consumption by customer type

The next step was to incorporate customer consumption data into our analysis to link the spatial distribution of customer types and consumption patterns to our spatially resolved estimates of EI. Given data privacy concerns, we aggregated the raw consumption data by customer type to the pressure zone scale to match the scale of the EI analysis. The ten customer types specified by Austin Water include: Agricultural (AG); Commercial (COM); Government (GOV); Industrial (IN); Medical (MED); Multi-Family (MF); Public Utilities (PU); Residential (RES); Unassigned (UA); and City Streets (CS). This mesoscale aggregation of the customer data provided enough information to produce spatially disaggregated assessments while preserving the privacy of individual customers.

Aligning the water consumption and customer type data with the EI data allows for the estimation of hypothetical energy savings (and GHG reductions) from proposed water conservation scenarios. For example, a user might consider a 20% reduction in residential water use as a potential scenario. This 20% reduction (S) could be distributed across the service territory by pressure zone since we know the
average amount of water being consumed by residential customers in each pressure zone. Water savings (WS) by customer type (c) by pressure zone (p) can then be converted into energy savings (ES) using the EI estimates derived above; subsequently, GHG emissions reductions (GS) can be estimated using the emissions factor (EF) of the regional electricity utility (e). See (4-6) below.

\[ WS_{cp} = S \times WC_{cp} \] (4)

\[ ES_{cp} = WS_{cp} \times EI_p \] (5)

\[ GS_{cp} = ES_{cp} \times EF_e \] (6)

For the application of the WEMap tool to the Austin context we use the estimated emissions factor for the Austin Energy generation mix of 1.1 lbs CO2e/kWh (Austin Water 2016). Since the Austin Water utility has chosen to fully offset their GHG emissions by purchasing credits from wind generation, this estimate of GHG savings from water conservation could be used to estimate the associated value of reduced offset purchases (Austin Water 2016).

The resource savings can be converted to cost savings for the water utility by multiplying the total estimated water and electricity resource savings by the marginal cost of providing additional water and procuring additional electricity, respectively. For the Austin Water case, reduced water consumption was valued at $490/MG and electricity savings was valued at $0.07/kWh (Austin Water 2016).

2.4 Creating a web-based tool for data exploration and visualization

The final step of this effort was to embed the entirety of our analysis into a web-based tool, so that participating water utilities could gain dynamic access to the complete set of underlying data, the EI estimates by node and network, and the scenario-based water conservation, energy savings, and GHG reduction calculator. In this case, “dynamic” refers to the user’s ability to explore and visualize the data, as well as define and compare proposed water conservation scenarios.

![Figure 3. Diagram of data flow and web application architecture.](image-url)
web application is organized into several modules, which encapsulate related functionality, including the server code and user interface (UI) components. These modules are designed to use EI model outputs directly, with minimal modifications. They are also used to facilitate re-use of code, for example the “EI Map Module” is used once in a full-page display, and again in the “Conservation Scenarios Page”, where it displays a small map of the targeted pressure zones. In general, data flow between the modules is limited to node IDs, or data subsets, which tie together the different components.

The interactive application was built using the Shiny web development framework, which facilitates the creation of interactive data-intensive applications using the R programming language. Since Shiny applications are linked to an R session running on the host web server, it is easy to take data processing and analytical functionality created during model development and integrate it into a user-oriented web application. This model of development allows for rapid integration of new and updated results, with minimal replication of development effort between tasks.

3 RESULTS AND DISCUSSION

By integrating disparate data from across the Austin water network (i.e. pump flow data, pump energy consumption data, consumption data by customer type and pressure zone, and the infrastructure layout schematic), we produced high-resolution estimates of energy intensity for the utility system. By high-resolution, we refer to EI estimates that are disaggregated and accessible by time period (both daily and monthly); individual infrastructure asset; and geographically by pressure zone. These results were then linked to water consumption data (disaggregated by customer type and pressure zone) for improved estimation of water-energy-GHG savings resultant from proposed water conservation programs. All of the analysis and results were consolidated in the web-based WEMap tool, which was built using the R-based Shiny package.

3.1 Results of EI analysis

An important component of the WEMap tool is the web-based accessibility of the EI analytics, so that water utilities can have dynamic access into the EI estimates. In this case, “dynamic” refers to the user’s ability to select EI results for specific assets (or specific sets of assets) by month and year. For example, Figure 4 is a screenshot of the software platform where the user can compare flow, energy consumption, and EI for single or multiple assets to identify trends over time as well as make cross-comparisons between assets.

![Figure 4. Comparison of time series flow, energy, and energy intensity for multiple pumps](image-url)
We produced similar capabilities to the user for exploring the spatial components of the EI analysis. We calculated the cumulative EI by pressure zone for Austin Water and presented the results as a network graphic (Figure A-1) as well as in map form (detailed map is included in Appendix A as Figure A-2 while thumbnail version is visible in Figure 5 below) within the web portal. The user selects the timeframe for their desired results, and the interface then updates the graphic and the map to present the average EI (kWh) for each of the pressure zones in the study.

3.2 Scenario-based estimation of water, energy, and GHG savings

The scenario-based water-energy-GHG conservation analysis is embedded as a dashboard within the WEMap tool, a portion of which is shown in Figure 5 below. The section on the right shows the system pressure zones (shaded by energy intensity value). The figure on the left shows the water consumption amount (size of bubble) by customer type (different colors) by pressure zone (different bubbles within each customer type) relative to energy intensity of each pressure zone (y-axis). Each of these exact values is presented to the user when they hover their cursor over the bubble of interest. The black dots represent the average energy intensity for each customer type, and the black line represents the overall energy intensity for the entire service territory. By integrating all of this data together in a single visualization, the user can quickly assess the variation in water consumption across these multiple variables.

![Figure 5. Portion of WEMap Tool showing relative water consumption by customer type, pressure zone and EI estimate (left) and the energy intensity map of the Austin Water system (right)](image)

This consolidated set of data provides the core information for the water conservation scenario analysis. Figure 6 demonstrates the user interface for leveraging these tools. The data entry fields on the left allow the user to input specific percentage water savings by customer type. (Similar targeting can be achieved by pressure zone by clicking on the “PZ” tab above the conservation input fields). The bar charts at bottom show total water consumption by customer type and estimated water savings, electricity savings, GHG emissions reduction, and water-electricity cost savings, respectively. The example provided in Figure 6 shows the results of modeling a 20% reduction in both commercial (“COM”) and residential (“RES”) customer types.

Additional information produced from the scenario runs are rendered in the top middle graphic. The size of the water consumption bubbles is reduced proportionally to the savings achieved in each pressure zone; the red dots highlight the average energy intensity of the water conserved; and the system-wide energy intensity estimate (black line) automatically updates to reflect the new post-program value for the entire infrastructure system.
Figure 6. Full Water Conservation Dashboard with Results from 20% Commercial and Residential Water Reduction Scenario

Figure 7 below shows an additional scenario where the user targets 20% reduction in the same customer groups, but this time, the conservation program is targeted at the 5 most energy intensive pressure zones (using “Pressure Zone Filter” slider at the bottom of the input field section). Note how all the results have adapted to these new inputs, including all the bar charts, the energy intensity of the targeted water savings (red dots), the mean system energy intensity, and the map showing the selected pressure zones for program deployment.

Figure 7. Full Water Conservation Dashboard with Results from 20% Commercial and Residential Water Reduction Targeted at the Five Most Energy Intensive Pressure Zone
4 CONCLUSION

The WEMap tool advances a number of promising analytical functionalities for water utilities to optimize decisions at the complex water-energy interface. The core benefits of the tool include: integration of large, asset-specific water flow and energy consumption data sets of varying temporal resolution (hourly to daily to monthly); specification of EI by pressure zone by aligning water-energy data with the infrastructure network design; incorporation of water consumption data by customer type at the shared spatial resolution of the pressure zone; a suite of tools to estimate anticipated water, energy, and GHG savings from targeted water conservation programs; and, an easy-to-use web-based data application to explore the results generates from all of these analyses. The integrated, web-based data platform is immediately useful for conducting EI analyses and has great potential to improve information flows and advance decision-making capabilities more broadly at water utilities.

While the WEMap tool provides substantial value in its current version, there remains a huge opportunity in the expansion of the design and capabilities of the tool. In discussions with a wide range of water and energy utilities in the Western United States, we have identified a great number of ways to expand the utility of a broader cloud-based computational platform for utilities to optimize their operations by integrating from a range of internal and external sources. Moreover, leveraging the platform to connect an extended network of utilities opens up a wide range of opportunities to transfer analytical modules, benchmark utility performance metrics, and to share best practices between users, among many other potential benefits.

To enable these broader capabilities, CWEE intends to advance more secure data privacy and security protocols that will allow for the seamless incorporation of more sensitive data (e.g. critical infrastructure information and private customer data) into the cloud-based WEMap environment. This particular initiative represents a significant challenge in securing and integrating data through wide-ranging institutional partnerships, but it is also the most essential component to advancing more intelligent and connected water-energy information systems.

ACKNOWLEDGMENTS

The Authors would like to thank the Cynthia & George Mitchell Foundation for supporting this research. We would also like to thank the Austin Water utility for sharing data and providing essential insights to enhance the research results.

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Appendix A

Figure A-1. Graphical representation of average EI by individual asset and cumulative energy intensity by pressure zone. Water source (Lake Austin) is represented by light blue oval; pumping stations are dark blue ovals; water treatment plants are light green triangles; pressure zones are dark green rectangles; and the arrows depict both flow direction and relative volume of water flows (arrow thickness).
Figure A-2. Map of average EI by pressure zone for the Austin Water utility