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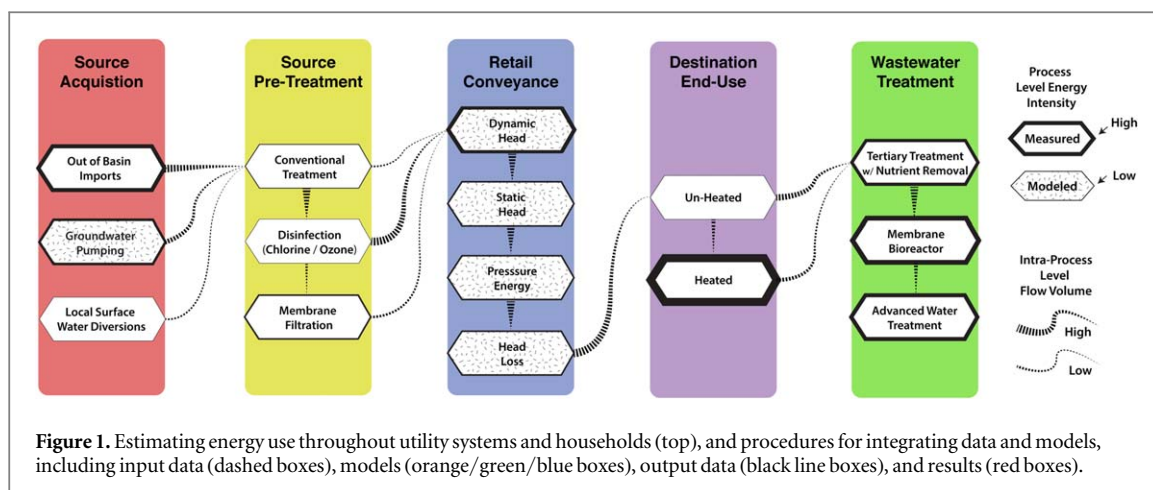
Supplementary material for this article is available [online](#)

Abstract

Reducing energy consumption for urban water management may yield economic and environmental benefits. Few studies provide comprehensive assessments of energy needs for urban water sectors that include both utility operations and household use. Here, we evaluate the energy needs for urban water management in metropolitan Los Angeles (LA) County. Using planning scenarios that include both water conservation and alternative supply options, we estimate energy requirements of water imports, groundwater pumping, distribution in pipes, water and wastewater treatment, and residential water heating across more than one hundred regional water agencies covering over 9 million people. Results show that combining water conservation with alternative local supplies such as stormwater capture and water reuse (nonpotable or indirect potable) can reduce the energy consumption and intensity of water management in LA. Further advanced water treatment for direct potable reuse could increase energy needs. In aggregate, water heating represents a major source of regional energy consumption. The heating factor associated with grid-supplied electricity drives the relative contribution of energy-for-water by utilities and households. For most scenarios of grid operations, energy for household water heating significantly outweighs utility energy consumption. The study demonstrates how publicly available and detailed data for energy and water use supports sustainability planning. The method is applicable to cities everywhere.

1. Introduction

Energy and water resources are highly connected in cities (Kenway *et al* 2011, 2015, Liu *et al* 2016, Lam *et al* 2017b). Urban water agencies use energy to acquire, extract, pump, treat, and discharge water supplies to end-users, while residents and businesses need energy to heat water in buildings (Escriva-Bou *et al* 2015, Kenway *et al* 2015, Spang and Loge 2015, Chini *et al* 2016, Wakeel and Chen 2016, Lam *et al* 2017a, 2017b, Yu *et al* 2018). Investigating relationships between energy and water consumption can reveal strategies to reduce operational costs and greenhouse gas (GHG) emissions associated with urban water sectors, both within cities and across



broader regions connected by common infrastructure systems. Actions that reduce these energy needs may yield social and economic benefits (Stokes and Horvath 2009, Rothausen and Conway 2011, Bartos and Chester 2014, Mo *et al* 2014, Malinowski *et al* 2015, Chini *et al* 2016).

Better quantifying energy use for urban water management by utilities and end-users can provide insights that inform targeted policy interventions (Mo *et al* 2010, Zhou *et al* 2013, Escriva-Bou *et al* 2018). In comparing the relative contribution of energy use for water management by utilities and end-users, planning models have shown that residential in-home water heating needs exceed utility operations in cities (Escriva-Bou *et al* 2015, 2018). Yet, few studies offer comprehensive empirical examples of the relative contribution of utility and household energy use in a metropolitan region. Multiple factors make detailed regional analyses a challenging task, including varied jurisdictional boundaries and sparse available data for infrastructure operations, energy supplies, and end-user consumption (Perrone *et al* 2011). Two questions are important. First, what is the energy intensity of existing and alternative urban water supply operations that characterize the multi-step procedures for acquiring, conveying, treating and distributing water and sewage throughout a system (Mo *et al* 2014, Porse *et al* 2018b)? Second, in case study cities, what are the relative contributions of utility and end-use energy consumption for water management in cities across diverse climate and geographic regions? Simultaneously evaluating these through a comparable quantitative framework can build on existing research and quantify the relative energy used for water management by utilities in buildings (Kenway *et al* 2015, Sanders and Webber 2015, Raghavan *et al* 2017, Kenway *et al* 2019).

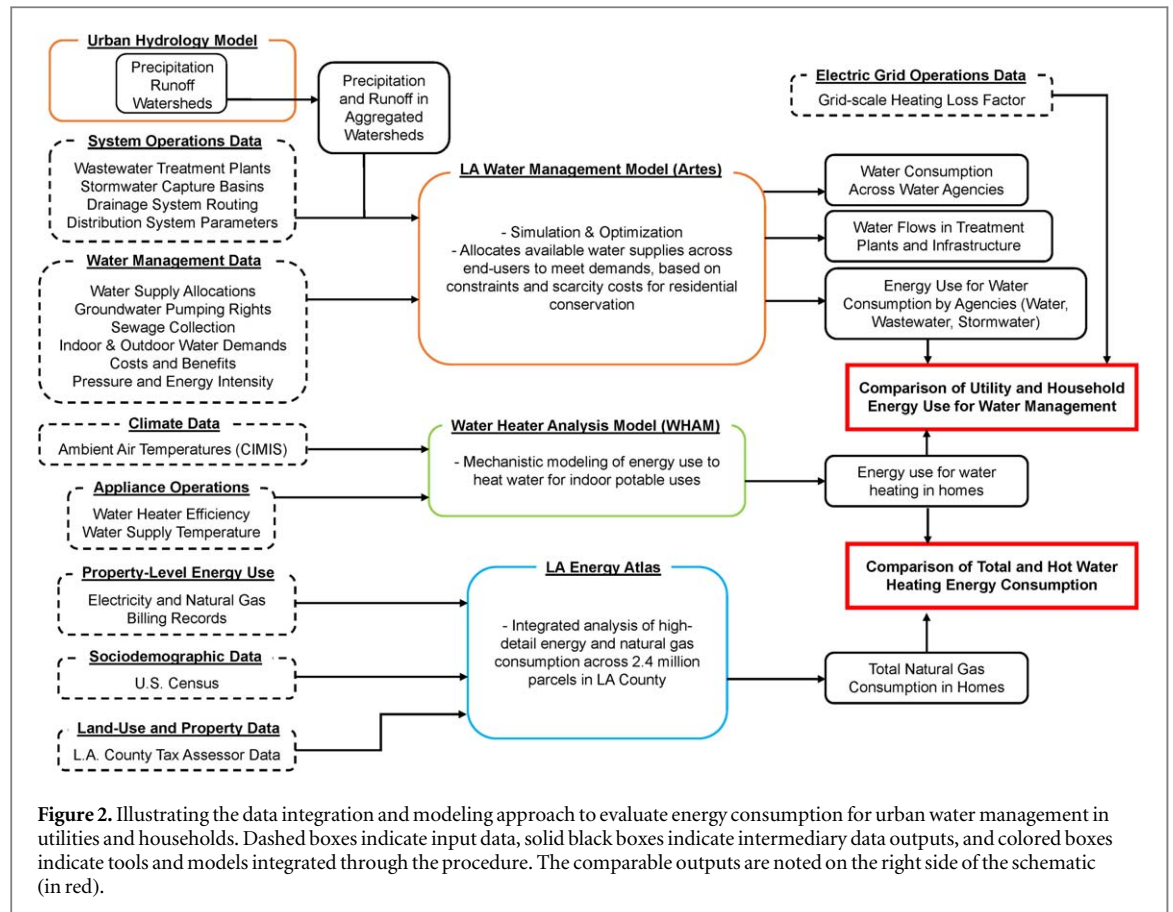
In this paper, we present an analysis to quantify the energy needed for urban water management in metropolitan Los Angeles (LA). We develop novel modeling methods and combine multiple unique and large-scale data sets to evaluate energy needs for urban water use across various stages of utility management (acquisition, pumping, water and sewage treatment, distribution, and disposal) as well as in homes. In addition, we evaluate opportunities to reduce system-wide energy use for water management through better use of alternative supply sources such as stormwater capture and water reuse. We quantify the electricity intensity (EI) of various urban water ‘supply trains’ (Porse *et al* 2018b), including a novel approach for estimating distribution energy within a local urban water supply pipe network. The methods and results are widely relevant for regional and national policies focused on the important task of reducing energy use and associated greenhouse gas emissions of urban water systems.

2. Methods

To consider energy use for water management in LA County, the study combined several large models and data sets, including: (1) a model of water resources management simulating demand and supply scenarios for over one hundred cities and water agencies, (2) property-level energy use billing records; and (3) and modeling of energy for in-home residential hot water heating (4) electric grid operations data (figure 1).

The approach summed the estimated total for utility water management and residential use across each step of the urban water cycle, based on integrating available data inputs, models, and actions to compare outputs (figure 1). Data inputs and outputs for the modeling were integrated through a spatially-explicit, bottom-up procedure that normalized geographic and temporal differences in data availability to the greatest extent possible (figure 2).

The supplemental information section for this article extensively describes the methods, contributing models, formulation for the simulation and optimization procedures, data sets (including spatial and temporal resolution), and data integration methods.



2.1. Study region

The study evaluated energy use for water management for nearly 10 million people in metropolitan LA County. A diverse and fragmented network of water agencies is responsible for providing and disposing of water supply (figure S1 in supporting information is available online at stacks.iop.org/ERC/2/015003/mmedia) (Ostrom 1962, DeShazo and McCann 2015, Pincetl *et al* 2016). The majority of residents and businesses are served by a hundred sizeable water supply agencies (>3000 connections) that report water supply and demand, while additional agencies provide wastewater, flood control, and stormwater management services (Porse *et al* 2017).

The current system relies on imported water for a majority of supply from three main sources: the Colorado River Aqueduct (CRA), the California Aqueduct through the State Water Project (SWP), and the Los Angeles Aqueduct to the Owens Valley. While all the sources convey water over significant distances, two of them (CRA and SWP) require significant energy to get water over high elevations into the LA Basin, causing the electricity intensity to exceed that of many other urban areas (Garrison *et al* 2009, Sanders 2016, Sokolow *et al* 2016, Sowby and Burian 2017, Stokes-Draut *et al* 2017, Mika *et al* 2018) (see *Supporting Information*).

In 2017, LA County used approximately 1,840 million cubic meters (1.5 million acre-feet) of water from groundwater, imported, recycled, and surface water sources. Nearly 59% of countywide water demands were met by imported water, with local groundwater and recycled water supplies providing 41%. The LA region is a Mediterranean climate with warm-to-hot summers (Kottek *et al* 2006). Regional precipitation averages across parts of LA County range from 12–20 inches annually in winter months, with higher totals falling in surrounding mountains (LA County 2011, NOAA 2018). Municipalities use this precipitation to recharge groundwater basins as a source of supply. Groundwater recharge operations largely rely on stormwater capture and recycled water (CB/WCB Amended Judgment 2013, ULARA Watermaster 2012, LADWP 2015).

2.2. Water management modeling

A network flow model with simulation and optimization was used to evaluate effects of regional water management decisions on energy use, both system wide and for individual water agencies (Porse *et al* 2017). The model incorporates sociologic, environmental, hydrologic, and economic parameters to evaluate the benefits and drawbacks of management options. The network model includes over 100 management agencies, groundwater basins and sub-basins, river and stream segments, hydrologic zones (47) corresponding to key environmental and infrastructure components that were aggregated from over 2,000 sub-watersheds in an

underlying urban hydrology model (LACDPW 2013), wastewater treatment plants, stormwater capture basins, and regional dams and reservoirs that are part of water supply infrastructure. It simulates and optimizes water management decisions at a monthly time step across 15–25 years of operation. It includes 25 years of calibrated monthly rainfall and runoff estimates. The model has previously been used to assess multiple aspects of water supply and demand management in the region (Porse *et al* 2018a, 2018b, Pincetl *et al* 2019). A full description of the formulation, data, and assumptions used in developing the model are available in previous studies and the *Supporting Information* for this article.

We used a hydroeconomic modeling framework that minimizes system wide costs to meet demands with available supplies. Flow decisions within the optimization are routed based on least cost allocations to meet demands given available supplies, allocation agreements, groundwater pumping rights, and flow capacities:

$$\text{Min } Z = (C + L) - B \quad (1)$$

In the equation above, Z is the difference between the sum of costs and benefits to move flows across the entire system. Unit costs for moving a volume of water are based on annualizing retail costs of water management from reported sources that include capital and operational costs, or where necessary, unit costs derived from physical modeling. The total costs include costs of water supply (C) and the sum of estimated economic losses from reduced demands (L) that are associated with reductions in outdoor water use. The dollar value is equal to the weighted sum of flows, based on the flow volume between two points in the network and the specified unit cost.

The economic value of losses associated with each water supplier is assessed using a demand function procedure with estimated water prices and elasticities of demand derived from existing sources (Jenkins *et al* 2003, Buck *et al* 2016, Porse *et al* 2018b). The model formulation includes constraints that emphasize minimum deliveries of water to districts for health and safety (in-home residential) and commercial and industrial needs. Outdoor water use is targeted for cost-effective conservation. Benefits (B) are limited to benefits published in previous work associated with large-scale stormwater capture, which monetize the recreational values of new stormwater capture facilities.

We ran the model with successive scenarios of available imported water supply to evaluate the energy use and electricity intensity effects of reducing imports. Model runs varied the amount of available imported water supply from 0% to 100% of historic deliveries (1986–2010). The range of available imported water does not represent the range of likely outcomes, but rather a full scope of potential outcomes. Variation in model outputs for electricity intensity, resultant per capita use, and water utility supply portfolios between scenarios result from the flow allocation procedure associated in the low-cost formulation.

2.3. Electricity intensity data

Each link within the network flow model received a value of electricity intensity, which is electricity use divided by the unit volume of water (kilowatt-hours per acre-foot or kilowatt-hours per kiloliters, kWh/AF or kWh/m³, respectively). We assigned electricity intensities to links based on the characteristics of flow and technology (table 1). For instance, for a link between a groundwater basin and a water supply agency that simulates groundwater pumping allocations, the EI was based on the electricity needed to pump and treat groundwater from a given well and then convey it to a central point in the retailer's system. For a link between a water supply agency node and wastewater treatment (reclamation) plant that receives sewage, the EI represents consumption from conveying water to the plant and then treating it according to the treatment train associated with that plant. Reported data from utilities, physical modeling, and existing peer-reviewed published data were all applied to the links. The supporting information has a full description of data sources and modeling methods used to identify EI values.

2.4. Electricity intensity for urban water 'supply trains'

Another approach to examining electricity intensity of water management calculates EI across 'supply trains' that comprise the multiple steps of water provision from source to disposal. This includes importing, pumping, treating, conveying, and distributing water to end-users, then collecting and treating sewage. Traditionally, supply chains were linear, moving from the source (a local stream, a distant watershed, or a local groundwater basin) to end users through pipes, and finally to sewage treatment plants and disposal. Emerging supply trains are more circular, with some percentage of treated wastewater being reused through advanced treatment processes for non-potable reuse, indirect potable reuse (IPR), or even direct potable reuse (DPR). DPR is not currently available for public water supply agencies in California, but will likely be part of future water portfolios pending ongoing regulatory decisions.

To estimate electricity intensity across these full cycles of urban water management, we first evaluated ranges of potential electricity intensity for each of eight processes: imported water for potable supply, imported water for groundwater recharge, groundwater pumping, existing centralized stormwater capture, IPR, non-potable reuse, and DPR. The approach summed estimated values from table 1 together associated with a supply train.

Table 1. Electricity intensity of water supply and treatment, by source and technology, in units of kWh m^{-3} . The electricity intensity of State Water Project imports includes values with and without system hydropower generation. An equivalent table with values reported in units of kWh/AF is provided in the *supporting information* (Sources: Compiled from Mika et al (2018), WaterReuse Foundation 2015, and correspondence with the California Department of Water Resources).

Technology/Water Source	Electricity intensity (kWh m^{-3})	
	Low	High
Groundwater Pumping ^a	0.21	0.50
Water and wastewater treatment processes		
Conventional water treatment	0.08	0.11
Disinfection (chlorine or ozone)	0.02	0.04
Membrane-based water treatment	0.26	0.40
Secondary treatment without nutrient removal	0.28	0.36
Tertiary treatment (nutrient removal and filtration)	0.42	0.51
Membrane bioreactor (MBR)	0.60	2.29
Brackish water desalination	0.81	1.64
Advanced water treatment ^b	0.86	1.05 ^c
Imported Water		
Colorado river aqueduct imported water	1.62	1.94
State water project imported water	2.09 (2.52) ^c	2.62 (3.66) ^c
Los angeles aqueduct imported water	-1.82 ^d	-1.82 ^d
Distribution (within a retailer system)	Ranges from 0–1.13	
Ocean desalination	2.51	3.89

^a Derived from local studies from cities in Los Angeles County and agricultural pumping well values reported through the California Agricultural Water Electrical Requirements.

^b Not used in this study, but provided for reference. Values basin on the Advanced Water Treatment system from the Orange County Water District beyond secondary treatment, including treatment technology includes filter screens, membrane filtration, cartridge filtration, reverse osmosis, advanced oxidation, decarbonation, and lime stabilization (WaterReuse Foundation 2015, p 11).

^c Net and gross electricity intensity values (gross EI in parenthesis). Net electricity intensity values include electricity produced within the system from hydropower, while gross electricity does not include these offsets to consumed electricity.

^d While the Los Angeles Aqueduct produces energy through hydropower, it is sold to the electric grid outside of the LA Basin. Thus, we considered its energy intensity to be 0 kWh m^{-3} in evaluating energy-for-water of Los Angeles.

^e The City of Santa Monica operates a facility that treats urban runoff through advanced treatment with microfiltration and UV disinfection for irrigation and non-potable use. The reported EI of the facility is 4.26 kWh m^{-3} , which is a high outlier and only applied in the modeling for that specific link.

The electricity intensity of a supply train is unique to a given retailer and its supply sources. We then calculated the total energy intensity along paths within the network using a matrix approach with network analysis metrics. The total EI was estimated by applying a weighting factor to a link equal to the link's EI and summing values throughout the network by calculating *path distances*, which are the number of links (steps) between any two nodes in a network topology. The EI-weighted path distance was estimated for identified supply trains using network analysis software.

2.5. Energy use for residential hot water heating

In California, nearly 60% of water used for indoor residential needs is heated (DeOreo *et al* 2011). This water heating comprises 20%–25% of residential energy use and nearly 90% of water heaters are run by natural gas and propane (US EIA 2009, DeOreo *et al* 2011). Previous research outlined a method for estimating energy use from in-home water heating based on an existing approach, the Water Heater Analysis Model (WHAM) (Lutz *et al* 1998), which was adopted for systems modeling (Escriva-Bou *et al* 2015). We applied the WHAM method here to estimate energy to heat water for indoor potable uses. We collected data for residential water use and appliances, retailer-specific demands, daily temperatures (2018), electric grid operations, and assumptions for appliance operation and penetration of natural gas water heaters. LA County has distinct climate regions, with cooler regions along the coast and hotter inland regions. Average daily temperature data was collected using data from the California Irrigation Management System (CIMIS). Across California, approximately 90% of residential water heaters are fueled by natural gas, with remaining water heaters fueled by electricity or propane (US EIA 2009). We similarly assumed that in LA County, 89% of water heaters were driven by natural gas (recovery efficiency = 0.76) and the remaining 11% were fueled by electricity (recovery efficiency = 0.55 assuming older units), where recovery efficiency is the percentage of heat produced by the energy source that goes towards heating water.

Natural gas is a primary fuel source, while grid-supplied electricity is a secondary energy source. To compare energy for water heating and grid-supplied electricity used by utilities, we converted the estimated amount of electricity needed by water utilities to an equivalent amount of energy using a heating loss factor (in BTUs/kWh). The heating loss factor rate estimates the efficiency of electricity production associated with power plants on the grid. Heating loss factors for grid-supplied electricity are a complex metric to calculate (Marnay *et al* 2002, Weber *et al* 2010). We estimated comparable electricity use (in kWh-thermal equivalent) from utility operations and in-home water heating based on a range of heating loss factors from 3,000–12,000 BTUs/kWh. The upper end of this range represents heating losses in scenarios for grid-supplied electricity with a high percentage of thermal plants, while the lower end represents scenarios of an electric grid primarily fueled by renewable sources such as solar, wind, and hydroelectric generation. A full description and data sources are available in the *Supporting Information*.

2.6. Sensitivity analysis

For estimated outputs that relied on assumed parameter values rather than reported data, we performed an analysis to characterize the effects of uncertain input parameters using Monte Carlo Analysis or single-factor analysis. This applied to estimates of energy use for residential water heating through the WHAM approach, along with estimates of energy for pumping in distribution systems. For each calculation, contributing parameters were varied by specified percentages from the assumed values to assess the resultant effects. In estimating residential water heating, the single factor method was used to evaluate a range of outputs associated with varying each of four parameters by up to 10%. In evaluating energy in distribution systems, a Monte Carlo approach estimated how retailer-specific energy intensity for pumping varied between assumed and randomized parameter inputs. Combinations of input factors were randomly selected based on a range of $\pm 50\%$ from the assumed value, and statistics for resultant energy intensity values were used to quantify the resultant change in EI for distribution and pumping.

3. Results

Results indicate that promoting water conservation and reducing imported water supplies reduces energy use across the water management system, but households use more water-related energy than utilities. Results are presented below by topic.

3.1. Energy use by water utilities

We estimated electricity use for water operations as both gross and net consumption, which can have implications for the overall emissions associated with water management (table 2). Gross electricity use is the total amount consumed at any point within the system, while net electricity use considers electricity produced within the system as part of its operations (*see Supplemental Information*). Reducing imported water, which is typically the most energy-intensive source of LA County's current water supply, also reduces the energy needed for managing the region's urban water. Modeling results show that when imported water supply availability is equal to 100% of historic allocations, the average annual total gross electricity use across water utility operations is equal to 4,100 Gigawatt Hours (GWh). Net energy use, which accounts for upstream electricity production from hydropower in the imported water systems, is 3,200 GWh.

Table 2. Energy use for modeled operations across LA water agencies by scenarios of imported water availability. An equivalent table in standard units is presented in the *Supporting Information* section (GWh = gigawatt hours, lpd = liters per person per day, MCM = Million Cubic Meters).

Scenario: Imported Water Availability	Modeled % from Supply Sources ^b			Avg. total water supply (MCM)	Annual gross electricity use (GWh)	Annual net electricity use (GWh)	Per capita water use (lpd)
	% Imported	% Groundwater	% Recycled Water				
				100%	61%	30%	8%
70%	45%	44%	10%	1,294	3,230	2,600	370
50%	38%	49%	12%	1,193	2,600	2,150	344
30%	26%	59%	14%	1,076	1,930	1,690	310
0% ^a	5%	76%	17%	892	1,030	970	257

^a % imported water used in this scenario is from initial available storage.

^b Does not report surface water use, which is approximately 1%.

In contrast, in a scenario without available imported water that induces water use reductions from present (2018–19) values across many retailers, the average annual total gross electricity use drops to 1,000 GWh. This value assumes that local agencies take no action to boost in-basin water supplies such as recycled water, but instead rely on conservation alone through existing mechanisms such as pricing, water efficiency rebates for turf and appliance replacement, and municipal irrigation cutbacks. This is not a likely scenario, but the range of values offer a lower and upper boundary on system wide electricity use. More likely, agencies would seek alternative sources such as reuse to replace imported water, which could be equally energy intensive. Detailed modeling of this source substitution was outside the scope of this study, but tradeoffs are discussed further in the *Discussion* section.

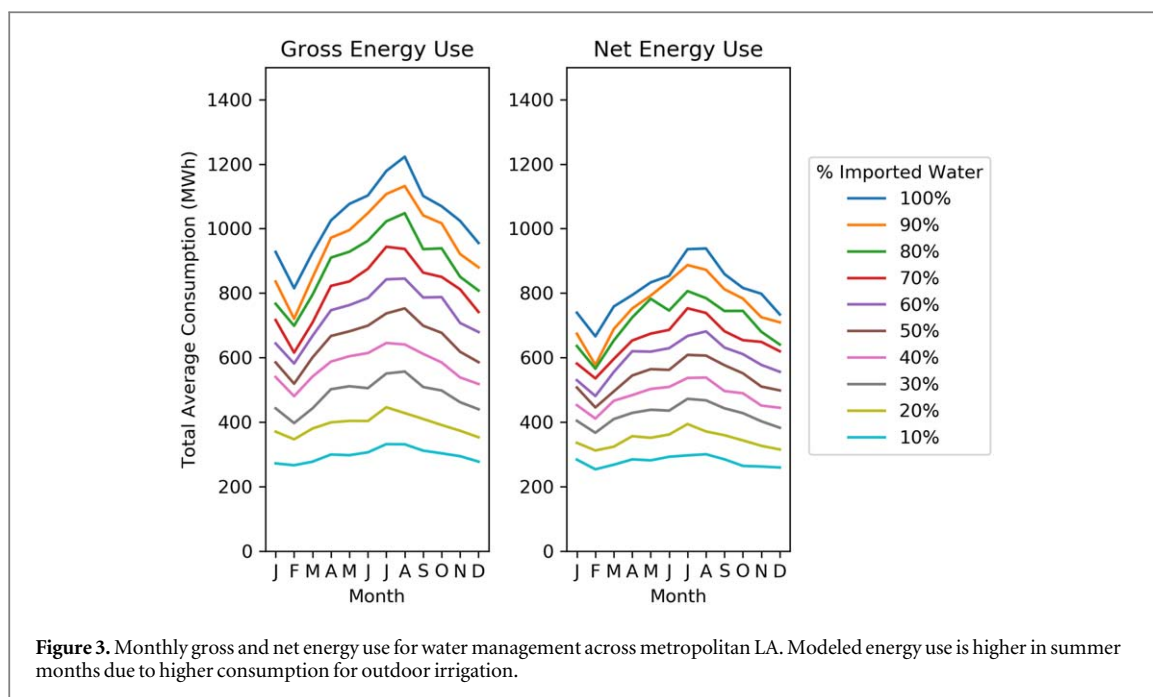
For the scenario with 100% available imported water supply, per capita use is approximately 390 liters per person per day (lpd, or 103 gallons per person per day, gpd). This per capita value is near consumption values in some of the region's cities following the severe 2011–16 California drought. It represents 'cost-effective' per capita water use when using the cost-minimizing formulation with retail prices as a marker of the economic value of conservation for outdoor water use. For the lower boundary, without any available imported water supplies and no supply replacement, total per capita use is limited to 257 lpd (68 gpd), which is only representative of current values in few coastal LA communities. For most of the county, this value is a highly aggressive target based on current land use patterns and landscape conversion efforts, likely only achievable in cooler communities with limited tourism and industrial uses.

The results illustrate a close relationship between water conservation and energy use reductions, which also holds true in comparing net energy use across scenarios. In the scenario with 100% imported water, average annual water supply from all sources is 1.1 million AF with an average annual net energy use of 3,230 GWh. In the scenario with no available imported water, average annual consumption is 888 MCM (720,000 AF), while average annual net electricity intensity is 970 GWh. Thus, a 35% reduction in water consumption yields a 75% reduction in energy consumption for water management.

Seasonal differences in energy consumption for water by utilities are also apparent, primarily due to changes in water supply (figure 3). Net energy use is higher in summer months, owing to increased volume of deliveries for outdoor irrigation. For the scenario with fully available imported water supplies, average monthly electricity consumption ranges from 700 MWh in February to 950 MWh in July and August. Promoting outdoor water conservation - a continued target for future policies - would reduce the energy use most in warmer summer months. In California's Mediterranean climate with little summer and fall precipitation, irrigation is used prominently to maintain lawns, shrubs, and trees.

Model results allow for estimating energy by both geographic region and process, including imports, groundwater pumping, treatment, distribution and collection, and sewage treatment, in each scenario of imported water availability. Importing water accounts for the largest amount of energy across all regions (table 3). Differences in jurisdictional boundaries across water supply, wastewater, and stormwater agencies in Los Angeles, however, makes it difficult to fully compare energy use by sector across geographic regions at the sub-county level.

Across modeled scenarios of imported water availability, while total energy use decreases significantly with reductions in imported water, imports are still the largest contributor to system wide energy use until only 10% of historic levels are available (figure 4). The total electricity intensity of the system also decreases with reduced imports and water demand. As noted, these model results include indirect and non-potable reuse from existing



and modest new capacity that comprises no more than 20% of total supplies in any scenario (see *Supplemental Information*).

3.2. Energy use trends across water agencies

The energy needed to supply, treat, and dispose water varies across agencies in LA County. Depending on the sources of supply, differences in elevation across distribution networks, and wastewater treatment operations, system wide electricity intensity for a given utility ranges from nearly 0 kWh m^{-3} up to 4.13 kWh m^{-3} ($0\text{--}5,100 \text{ kWh A}^{-1}\text{F}^{-1}$) across retailers. The average value is 1.30 kWh m^{-3} (st. dev. = 0.96 kWh m^{-3}) and the median value is 0.93 kWh m^{-3} ($1,150 \text{ kWh A}^{-1}\text{F}^{-1}$).

The estimates of distribution energy for pumping water within an agency's water supply pipe system yielded significant geographic differences in EI. For most agencies, electricity intensity for local distribution ranged from 0 kWh m^{-3} up to 0.97 kWh m^{-3} ($0\text{--}1,200 \text{ kWh A}^{-1}\text{F}^{-1}$). The distribution is positively skewed, with 72% of systems having electricity intensity of less than 0.34 kWh m^{-3} ($420 \text{ kWh A}^{-1}\text{F}^{-1}$). The average EI for distribution system conveyance was 0.18 kWh m^{-3} ($225 \text{ kWh A}^{-1}\text{F}^{-1}$, standard deviation of $278 \text{ kWh A}^{-1}\text{F}^{-1}$). Mapping the data showed that systems with high EI were predominantly located at the northern and eastern periphery of the county, where elevation changes are greater (figures 5(a), S2 in *Supporting Information*). Sensitivity analysis based on randomized selection of inputs from the parameter range yielded an average increase of 25% to a retailer's energy intensity for pumping. Thus, with parameter uncertainty, the estimates of energy for distribution could be modestly larger.

Considering the hierarchical network of water governance in LA is also important when calculating electricity intensity. When all electricity use for water supply provision is attributed to local retailers, the EI for each retailer area increases (figures 5(b), S3 in supporting information). Doing so allows for comparing results here with other studies. For instance, in the City of LA, modeled values from this analysis ($1.44\text{--}1.51 \text{ kWh m}^{-3}$ or $1,785\text{--}1,860 \text{ kWh A}^{-1}\text{F}^{-1}$) are comparable to a previously reported assessment using a different approach (1.67 kWh m^{-3} or $2,071 \text{ kWh A}^{-1}\text{F}^{-1}$) with slightly higher water use (Lam et al 2017b).

Yet, organizational hierarchy is still important. Water retailer agencies in the region predominantly use energy to distribute, and in some cases treat, water within their systems. For most retailers that rely on imported water, the majority of energy use is incurred by the regional water importer agency, the Metropolitan Water District of Southern California (MWD). Water retailers are directly responsible for energy use to distribute and collect water in their systems, along with any local water treatment plants. Sanitation districts incur expenses associated with wastewater treatment. Within a fragmented water governance system such as Los Angeles, evaluating opportunities to reduce the electricity intensity of water supply and treatment requires recognizing the source-to-use pathways and their attendant energy inputs across agencies.

Table 3. Energy use for utility water management by regions and urban water sectors (GWh = Gigawatt-hours). Figure S2 in the *Supplemental Information* section illustrates boundaries for water supply and sanitation agencies.

Sector	Region	Average Annual Electricity Use (GWh)				Sum
		Imported	Groundwater Pumping	Water Treatment & Reuse	Distribution	
Supply, Acquisition, & Treatment	San Gabriel Valley	226	55	7	94	382
	Central/West Coast Basins	0	55	39	149	243
	Malibu/Las Virgenes	0	0	0	1	1
	Los Angeles City	102	37	25	185	348
	San Fernando Valley	0	5	3	30	38
	Santa Monica Basin	0	2	2	4	8
	Regional Supply Agencies	1,807	0	0	116	1,924
Wastewater Treatment & Reuse	LA City Wastewater Treatment & Reuse	0	0	128	31	32
	LA County Wastewater Treatment & Reuse	0	0	98	4	13
	Central/West Coast Basin Water Reuse	0	0	12	5	17
Recharge Operations		0	0	0	0	0
Not Assigned*		0	4	0	0	220
Totals		2,135	157	314	619	3,225

*Not Assigned consists of energy associated with pumping or discharging to drainage in local streams and the channelized stream network for the scenario with 100% available imported water supply.

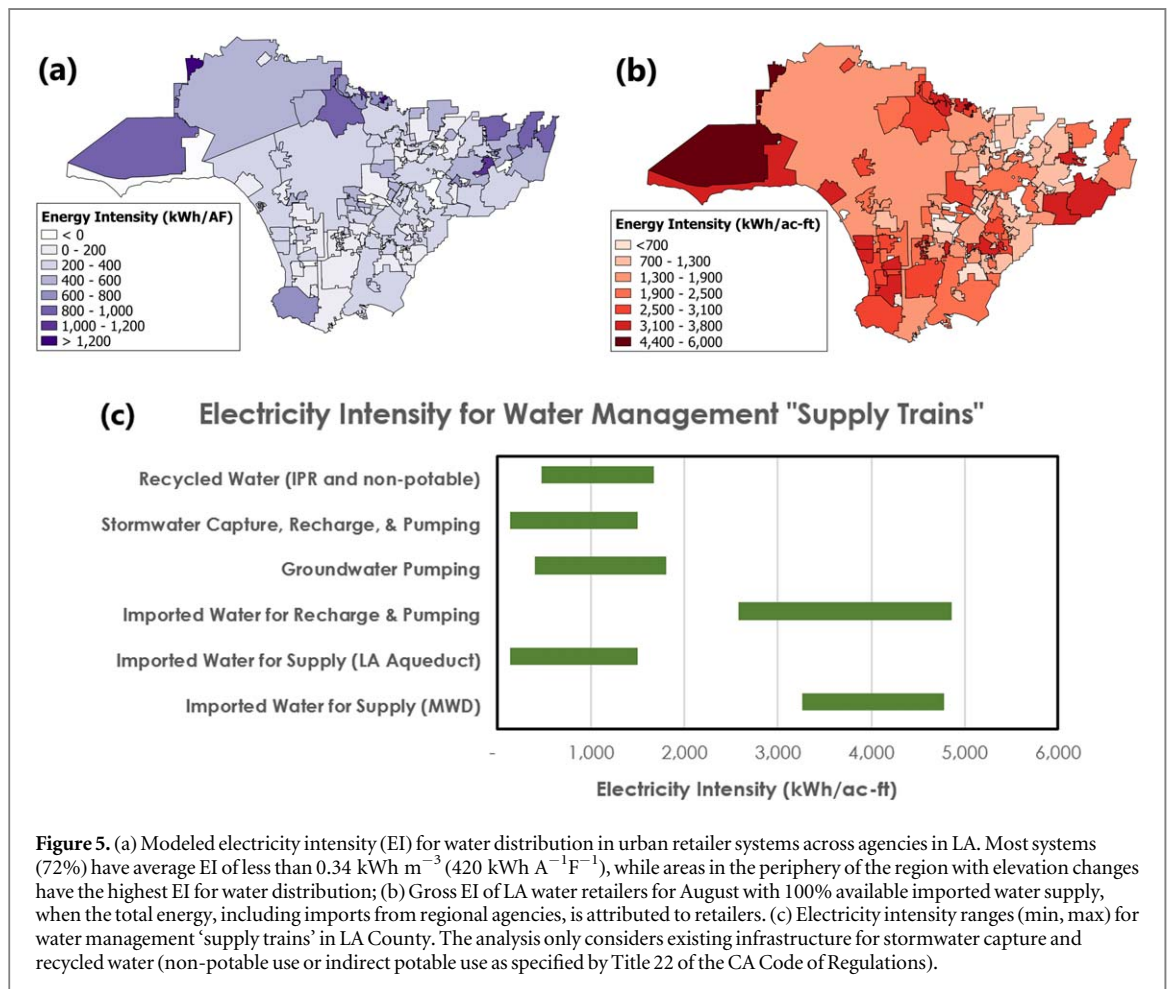
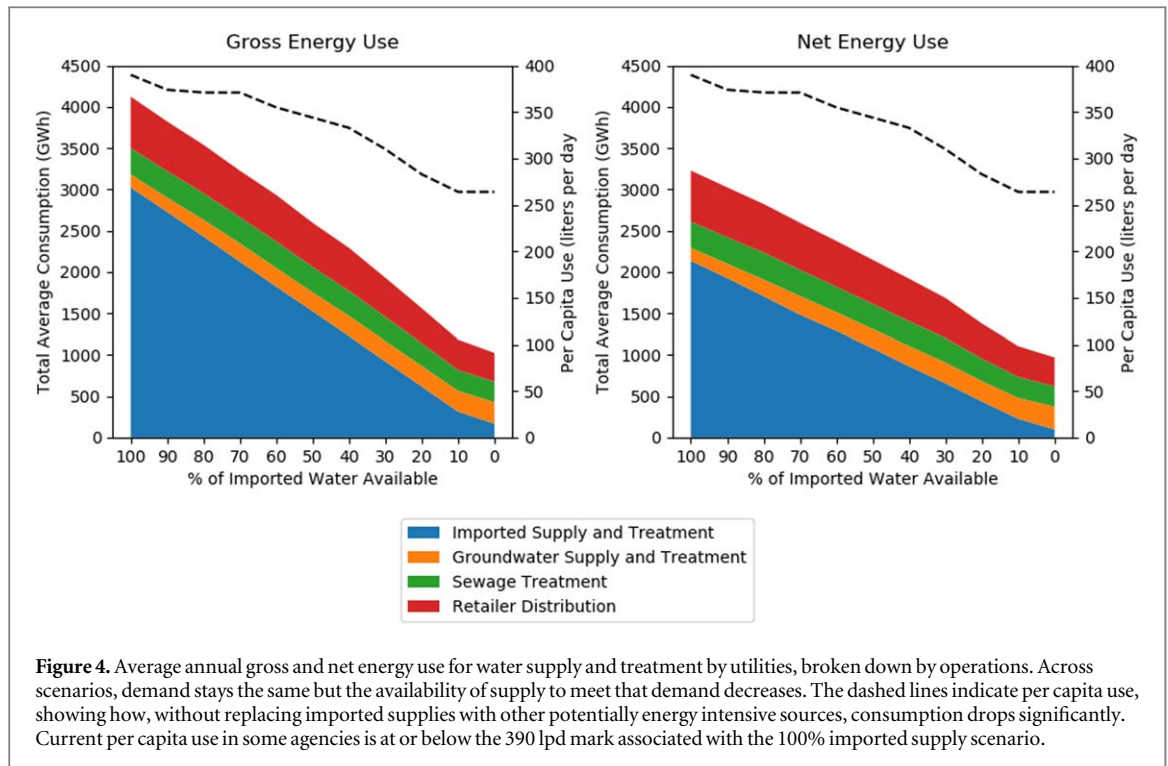


Table 4. Comparing estimated annual energy consumption for residential water heating and utility water management across scenarios of heating loss rates associated with the electric grid. (GWh = gigawatt hours, TrBTU = Trillions of British Thermal Units).

Heating Loss Rate (BTU/kWh)	Energy for Residential Water Heating (TrBTU)	Energy for Utility Water Management	
		Secondary Gross Electricity Use (GWh)	Primary Energy Use Equivalent based on Heating Loss Rate (TrBTU)
3,500			14
6,000	43	4,100	25
8,500			35
10,000			41

3.3. Energy use across water management ‘supply trains’

Summing electricity intensities across processes for water and wastewater management in the supply chain yields ranges of electricity intensities (figure 5(c)). Supply trains with existing stormwater capture that include eventual pumping and treatment as groundwater tend to have the lowest electricity intensity. The highest peak values are associated with supply trains for imported water, including both direct use and water imports that supply groundwater recharge operations. This is primarily due to the electricity intensity of the two largest supply sources for MWD (Colorado River Aqueduct and State Water Project). While pumping and treating groundwater alone typically lowers electricity intensity for a supply source, the range of electricity intensities across groundwater pumping supply trains is closer to indirect and non-potable reuse supply. The additional steps to pump groundwater and convey it to the treatment plant are equivalent to the energy needed for some portion of the treatment processes within reuse supply chains. Table S4 in the Supplemental Data lists the potential ranges of EI values for supply trains in LA County.

3.4. Energy use for water in households

The minimum volume of residential water demands in the modeled scenarios, evaluated as the volume of water needed to supply health needs for in-home indoor uses, was estimated to be 1,014 million liters per day (268 million gallons per day) based on a 189 lpd (50 gpd) standard. The method for calculating this amount is described in previous research (Porse *et al* 2018b).

Using the WHAM approach for in-home water heating, the total primary energy use for indoor hot water is nearly 44 trillion British Thermal Units (TrBTUs) per year. This value assumed that for the 90% of water heaters fueled by natural gas and propane, indoor water use was 189 lpd based on regulatory limits, and approximately 60% of the total volume of indoor water use goes to end-uses that require heating (US EIA 2009, DeOreo *et al* 2011, Porse *et al* 2018b). This energy consumption estimate is specific to indoor water use, which is held constant in the water management modeling. Varying input parameters by $\pm 10\%$ through a sensitivity analysis resulted in a range of values from 39.6–48.8 TrBTU.

To put this value of energy consumption for in-home hot water heating in context, utility billing records from the database of 9.8 million residents in LA County report that in 2016, annual average natural gas deliveries to residential properties were 105 TrBTUs. This includes both primary energy from natural gas and secondary energy from delivered electricity consumed in homes. Thus, when compared to utility billing records, energy for heating water in homes comprised over 40% of total natural gas used in homes.

Compared to utilities, the energy-for-water use in homes (44 TrBTU) is nearly 2.5 times the modeled gross electricity used across all urban water management operations (imports, pumping, distribution, and treatment) by utilities for LA County (4,100 GWh) in the scenario of 100% available imported water that most closely resembles current operations. This ratio assumes upstream generation efficiency using eGRID values (4,400 BTU/kWh). If the electric grid draws on more thermal generation sources, the ratio decreases, while as the percentage of renewable generation increases, the ratio increases (table 4).

4. Discussion

Evaluating energy use by a large metropolitan water management system with varied agency jurisdictions requires setting boundary conditions. Another way to categorize energy use would be in-basin and out-of-basin uses. In-basin energy use for water refers to energy used by water utilities and consumption in buildings. Out-of-basin energy use is energy expended by water utilities outside of the metropolitan area to manage, treat, or import water for the city. Translating results to this categorization scheme, in-basin household use significantly more energy to heat water than the combination of in-basin and out-of-basin consumption for utility water management. Boundary conditions raise important questions about tradeoffs. If agencies in LA significantly

reduce imported water and replace it through a mix of local sources and conservation that lowers the overall electricity intensity of the metropolitan water system, it may not reduce overall energy use across the state. For example, if the imported water from the SWP or Colorado River typically sent to LA is instead diverted to other communities in Southern California, then energy use could remain steady or increase.

Alternative supplies that replace imported water and support more consumption have different constraints and energy use consequences. Replacing imported water through groundwater recharge with stormwater capture has low energy intensity, but is limited by precipitation and infiltration capacity. For recycled water, in Southern California's coastal cities, the EI of current water imports means that replacing such sources with indirect potable and nonpotable reuse would be at least energy-neutral or result in energy savings. IPR and nonpotable supplies consumed or recharged near the production source would have the best opportunity to augment supplies and retain energy savings. The geographic distribution of energy consumption, however, would change significantly. More electricity would be consumed within the LA metropolitan area, which could have implications for electricity management and grid operations. If LA water agencies increase investments in local sources such as recycled water, while overall energy may decrease, in-basin energy consumption would likely increase. This could affect local transmission and distribution grid circuits, which will be increasingly strained during future extreme heat days due to current capacity of electric grid circuits (Burillo *et al* 2018). Additionally, new reuse capacity with advanced water treatment could equal or exceed the EI of current imported sources, especially if pumped over long distances.

The results have policy implications for the water and energy sectors. Reducing energy use for water management and supply in cities requires policies that target both utilities and homes. In August 2019, the California Public Utilities Commission (CPUC) eased restrictions on electrification of natural gas appliances, which some see as a critical step in reducing carbon emissions (CPUC 2019). In developing policies to support energy use reductions by water utilities, California regulators must recognize that curbing energy use and greenhouse gas emissions are not primary missions for water utilities. Research must identify mechanisms to incentivize water and energy conservation across both utilities and end-users.

The analysis is subject to limitations. The geographic and spatial resolution of the modeling associated with available data is coarse. The analysis accounts for seasonal changes in water and energy use, but it does not incorporate how the underlying electricity intensity of operations, such as static versus variable speed pumps, influences system wide electricity intensity over time. The lack of detailed distribution pipe data led to the analysis approach based on pumping energy using Bernoulli's equation, elevation changes, and assumed system operations. Future work could further validate and refine the approach by comparing to real-world water network operations. Finally, the underlying water resource model using simulation and optimization is subject to limitations that have been outlined previously (Porse *et al* 2017, 2018b).

5. Conclusions

In this paper, we analyzed energy use for water management across the Los Angeles metropolitan region of 10 million people to understand the relative contributions of energy for water management operations and residential use. Using a model of over one hundred water management agencies in LA that simulates infrastructure operations, hydrology, and water demands, results indicated that reducing imported water use - a stated goal of several agencies in the region - would likely reduce the overall energy use and intensity of water management operations. Even using a mix of both water conservation to reduce demand and enhanced supplies through new water indirect and nonpotable reuse facilities, reducing water imports from Northern California and the Colorado River would have an overall effect of reducing energy use. Water conservation and stormwater capture are effective strategies for reducing energy use for water. The energy saved by replacing imported water with reuse depends on the treatment train of the new recycled water.

Yet, energy consumed by water utilities is significantly smaller than the energy consumed through natural gas water heaters in residences. Thus, to target energy use reductions for urban water management, policy strategies must think systematically to ensure that targeted actions in one or more sectors actually conserve energy overall, and that all possible actions are being taken concurrently. The analysis provides one of the largest and most comprehensive case studies of energy-for-water in a large metropolitan area available and offers a template with new modeling approaches and data that other cities can replicate and adapt.

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