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ABSTRACT

Water reuse with Advanced Water Treatment (AWT) is increasingly appealing for urban areas seeking water supply reliability. In cities facing water scarcity, how can large-scale reuse support reliability and how do reuse operations affect water quality, energy use, and water conservation? This paper presents a systems analysis of metropolitan-scale water reuse and its effects on water supply and quality. For the case study of Los Angeles County, California, USA, hydroeconomic modeling is used to evaluate reuse as a contributor to water supply given urban water conservation, drought-induced water scarcity, and costs and benefits for supply and demand. Results indicate that AWT can be a viable source of supply especially when coupled with conservation. Across modeled scenarios, reuse provides as much as 30% of regional supplies. New water reuse with AWT becomes viable when imported water availability is 50% or less of historic values. Existing indirect potable reuse operations in the county remain important. Systemwide energy intensity of operations increases with greater reuse in the absence of water conservation. Modeled influent flow rates to wastewater treatment plants resemble historical values, but extreme flow events could pose risks. The paper offers a holistic framework to evaluate water reuse as a component of urban water management.

1. Introduction

Water reuse is a source of supply for urban, industrial, and agricultural needs throughout the globe. Alternatively described as water recycling or Advanced Water Treatment (AWT), water reuse involves treating sewage, discharge water, or runoff to high levels for safe use or disposal. Water reuse operations go beyond conventional facilities where wastewater is treated through primary, secondary, and tertiary processes such as sedimentation, filtration, coagulation, and nitrate removal (Asano 2006; Leverenz, Tchobanoglous, and Asano 2011; Linstedt 1982; Metcalf & Eddy 2003; NRC 2012).

Water reuse operations are typically categorized by level of treatment and end-use. Non-potable reuse (NPR) describes treated wastewater that is sent to end-uses with low

risk of direct human contact, such as outdoor irrigation or industrial use. Indirect potable reuse (IPR) describes operations where treated wastewater is sent to a potential water source, such as a groundwater basin or downstream city, via an environmental buffer. These can be groundwater basins, streams, or rivers. Direct potable reuse (DPR) is the process of introducing highly treated wastewater into a drinking water supply system for pre-treatment without an intermediary environmental buffer and long residence time (Leverenz, Tchobanoglous, and Asano 2011; Tchobanoglous et al. 2011). In practice, since public water and wastewater treatment works were developed in the late nineteenth and early twentieth centuries in modern industrial cities, vast populations of urban and rural dwellers have received water supplies through indirect potable reuse (Melosi 2001; Tarr 1984). Contemporary facilities in industrialized regions emphasize higher levels of treatment and monitoring to ensure safety. In the U.S., most wastewater treatment plants have moved to secondary and, to a lesser extent, tertiary levels of treatment (EPA 2016). Effluent can supply appropriate end-uses through 'fit-for-purpose' supply strategies, which match the level of treatment with required risk reduction to achieve public health and environmental quality standards (Sedlak 2014).

The prevalence of water reuse operations at any level varies. In some places, such as Israel or Windhoek, Namibia, reuse comprises a significant portion of total supply, while in other locations such as Spain and Singapore, reuse is an important source, but contributes less than 50% (Friedler 2001; Gerrity et al. 2013; Jiménez and Asano 2008; Lahnsteiner and Lempert 2007; Lefebvre 2018; Luthy and Sedlak 2015). For most places, water reuse is a small portion of municipal supplies.

In California, highly-treated wastewater effluent has supplied non-potable and indirect potable reuse operations for decades (Allen and Elser 1979; Mills 1998). In recent years, water reuse has provided approximately 863 million cubic meters (MCM) of annual supply (700,000 acre-feet, or ac-ft) for non-potable and IPR end-uses including irrigation, industrial operations, and groundwater recharge. To date, the state has no Direct Potable Reuse facilities, but since 2010 California has been developing frameworks for implementing DPR regulations and pilot projects are underway (SWRCB 2016; SWRCB 2018). Many agencies have undertaken independent feasibility studies, pilot projects, and sizeable field testing in anticipation of future rules allowing some level of direct potable reuse for municipal supplies (City of San Diego 2012; MWD 2016; WateReuse California 2019). The studies have been motivated by increasing concerns of future water scarcity as well as local agency interest in more reliable supplies.

Recycled water is an increasingly important for water supply resilience in California's Mediterranean climate. The state receives most annual precipitation in winter months, while demands peak in hotter summer months driven by irrigation for agriculture and urban landscapes. Climate variability and extremes are expected to increase with more extreme precipitation events of greater intensity affecting runoff, water supply availability, and drought risk (Dettinger et al. 2011; Swain et al. 2016; Diffenbaugh, Swain, and Touma 2015). The entire American Southwest is expected to see increased drought and reduced availability of future water for agriculture and growth (MacDonald 2010). Studies indicate that Eastern Sierra snowpack is expected to decrease, which would also decrease spring runoff volumes and, without additional surface storage or groundwater recharge, reduce availability of imported water during the late summer and early fall months (Costa-Cabral et al. 2013; Musselman et al. 2017). These factors combine to

challenge a system already seeking to increase capture and use of stormwater for recharging the regional groundwater basins that are critical for supply.

Increased reliance on water reuse operations in a metropolitan system introduces several types of uncertainty for water supply and wastewater operations. First, is water reuse cost-effective within a semi-arid metropolitan region that experiences periodic water scarcity, and how does it compare to other sources of supply? Second, how would other management goals, especially long-term efforts to reduce water demand through conservation, affect the potential for and value of new investments in water reuse? Increased conservation in buildings can reduce the volume or increase the concentration of effluent available for reuse (DeZellar and Maier 1980; Koyasako 1980; Maier, DeZellar, and Miller 1981; Tran, Jassby, and Schwabe 2017). Third, would changes in the quantity and quality of sewage produced in buildings affect existing treatment processes? Reuse facilities must meet standards of public safety given growing recognition of existing and emerging contaminants such as chemicals, residual pharmaceuticals, and plastics (Chaudhry et al. 2017; Mitch and Sedlak 2002; NRC 2012; Roccaro 2018; Snyder et al. 2003; Soller, Eftim, and Nappier 2018; Wilcox et al. 2016). Finally, what are the systemwide energy use implications of significantly expanding water reuse operations at the metropolitan scale? This paper presents a systems analysis of metropolitan-scale water reuse including effects on water supply reliability, energy intensity of operations, and effectiveness of existing treatment operations. Using an integrated hydroeconomic modeling framework for urban water management, the analysis evaluates the role of reuse as a source of supply across scenarios of supply and demand, including drought-induced water scarcity from reduced out-of-basin water imports. Model outputs are then compared with historical monitoring data for influent flow and contaminant concentrations to evaluate potential risk that altered rates of water use may have on existing wastewater treatment facilities. Finally, the systemwide implications for energy use of new AWT operations are evaluated. A case study of Los Angeles (LA) County, California, USA, is considered by incorporating a comprehensive set of regional factors into the hydroeconomic modeling, including costs of supply and demand, existing infrastructure capacity, detailed hydrologic modeling, groundwater management, and water access and rights for over 100 water supply agencies covering 10 million people. Results offer insights regarding the role of large-scale reuse operations within an existing system based on current economic and capacity constraints, and the analysis demonstrates an integrated approach relevant to urban water systems analysis in cities everywhere.

2. Methods

The analysis for the case study of metropolitan Los Angeles included three components. First, hydroeconomic modeling is used to simulate and optimize regional water urban water supply and demand management decisions using linear programming and a link-node network representation of the regional urban water management system. Building on an existing model, *Artes* (Porse et al. 2017), data for newly proposed water reuse operations is incorporated into the hydroeconomic framework to evaluate the viability of expanded reuse operations. Second, results from the hydroeconomic modeling for wastewater production and influent flows in facilities are used to evaluate potential effects on existing wastewater treatment operations by comparing model results with

historical records of influent wastewater flow and constituent concentrations. Third, implications for water conservation and systemwide energy use are evaluated. The sections below describe: 1) case study background on Los Angeles water management, 2) model formulation and new reuse operations, 3) data sources, 4) model calibration, 5) procedures to incorporate energy intensity of new reuse operations, 6) modeled scenarios, and 7) procedures to assess design implications for operational efficiency of wastewater treatment facilities.

2.1. Case study: water management and wastewater treatment in Los Angeles

The Los Angeles metropolitan area is highly urbanized. Ecological and climate zones in LA are diverse, spanning estuaries, highland mountains, cool coastal areas, and hot-dry interior lands. Across the county, native landscapes mix with dense urbanization. Today, the region is home to over 10 million people. The region grew through strategic use of local water supplies coupled with acquisition of rights to distant water sources for imported supplies (Davis 1993; Erie and Brackman 2006; Pincetl, Porse, and Cheng 2016). In recent years, water agencies across LA County used approximately 1,800 million cubic meters (MCM) (1.5 million acre-feet) of water from groundwater, imported, recycled, and surface water sources (Federico et al. 2019). A large portion of demand is dedicated to outdoor irrigation driven by horticultural practices and landscape preferences of residents (Pataki et al. 2013; Pincetl et al. 2013; Avolio et al. 2015).

Of the 1.5 million acre-feet of typical annual demand, almost sixty percent has historically been supplied from out-of-basin imports through three major infrastructure systems: the Colorado River Aqueduct that draws from the Colorado River at the California-Arizona border, the California State Water Project (SWP) that diverts water from rivers in northern California through the Sacramento-San Joaquin Delta, and the Los Angeles Aqueduct that brings water from the Owens Valley in California's Sierra Nevada Mountains to the City of Los Angeles (Figure 1). These water conveyance systems were completed between 1914 and 1972. The primary water importing agency, the Metropolitan Water District of Southern California (MWD), was created through state legislation in 1927 and approved by local voters to import water to the region, first from the Colorado River and subsequently from California's SWP. MWD distributes imported water to over 100 different water delivery entities (Figure 2a) within a hierarchy of agencies across Southern California, including in LA County (Pincetl, Porse, and Cheng 2016).

In addition to imported supplies, local hydrology and water sources are also important. The urbanized parts of LA County include five large watersheds. Runoff collects from surrounding mountain ranges and drains through channelized rivers towards the Pacific Ocean (Figure 2b). The region experiences a Mediterranean climate, with warm-to-hot summers and precipitation occurring in late fall, winter, and early spring months (Kottek et al. 2006). Regional precipitation averages across parts of LA County range from 30 to 50 centimeters annually, with higher totals falling in surrounding mountains (LA County 2011; NOAA 2018). A network of interconnected groundwater basins (Figure 2c) contains, by rough estimate, over 50,000 MCM of total capacity. Annual allowable groundwater pumping allocations for regional agencies are approximately 780 MCM. Groundwater basins have been intensely managed for decades, typically providing thirty to forty percent of supplies. Stormwater is actively captured across

Figure 1 . Major sources of imported water supply to Los Angeles County.

over 20 capture basins (Figure 2d), combined with recycled water, and infiltrated through managed aquifer recharge, with an annual average of 246 MCM since 2007 (LACDPW 2014; USBR and LACDPW 2016). While inexpensive imported water provided a source for recharge in past decades, today, most recharge relies on stormwater capture and recycled water (ULARA Watermaster 2013; CB/WCB Amended Judgment 2013; LADWP 2015b).

An extensive and uniquely interconnected system of wastewater treatment plants, often referred to as water reclamation plants (WRPs), exists in Los Angeles (Figure 3). The facilities treat water to secondary and tertiary levels for discharge to local waterways, but over 222 MCM of influent is further treated to standards of reuse for non-potable uses such as irrigation and groundwater recharge (SWRCB 2016). Wastewater facilities are managed by several agencies, including the City of Los Angeles Bureau of Sanitation, the Los Angeles County Sanitation Districts (LACSD), and the Water Replenishment District of Southern California (WRD). Table 1 details operational parameters of existing facilities used in the model.

In recent years, non-potable and indirect potable reuse have comprised 5–10% of annual regional supplies in LA (Gold, Federico, and Pincetl 2015; Porse et al. 2017). Facing future water scarcity from imported supplies, regional agencies have proposed new water reuse operations that would significantly expand existing capacity for Advanced Water Treatment (Table 2). The City of Los Angeles has stated goals to reuse all influent in coming decades and a joint initiative by the County of Los Angeles and the Metropolitan Water District of Southern California (MWD) is slated to build large-scale water reuse operations from LA County's primary wastewater facility (LACSD
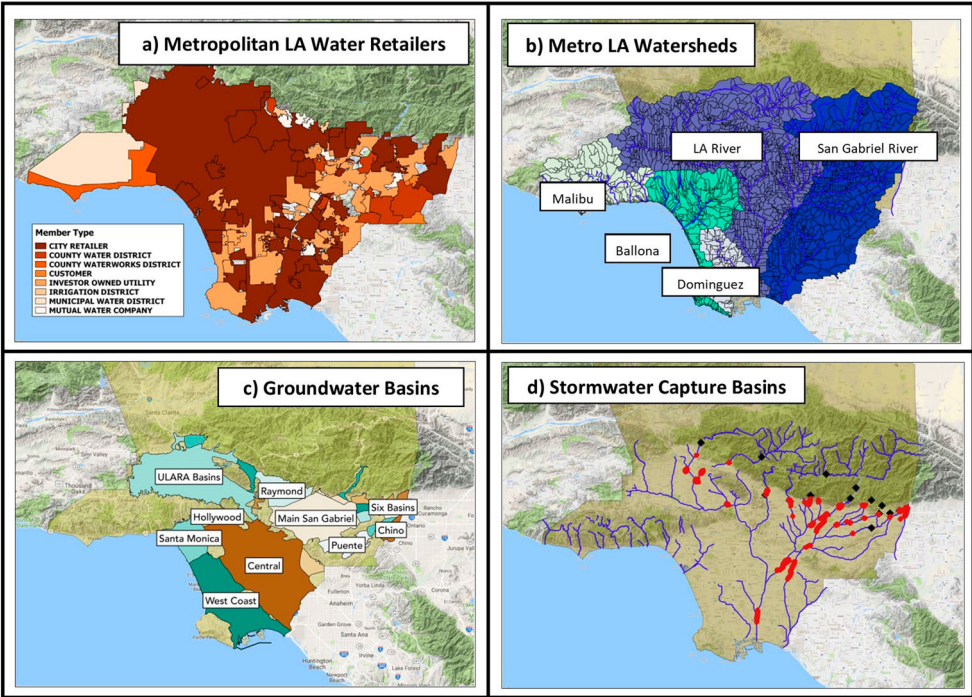
Figure 2 . Within Los Angeles, a complex system of water management includes (a) Water supply agencies, (b) Major watersheds associated with rivers, (c) Groundwater basin management areas, (d) Stormwater capture facilities.

Table 1 . Operational treatment capacity parameters for current wastewater treatment and water reuse facilities, based on data from available sources. The parameters were used as constraints in the modeling (WRP = water reclamation plant).

Name	Design Capacity (MCM/day)		Total Annual Capacity (ac–ft)	Existing Reuse Capacity (mgd)
	Dry Weather	Wet Weather		
Burbank WRP	0.04	0.04	17.02	0.03
LA-Glendale WRP	0.06	0.09	34.03	0.06
Hyperion WRP	1.35	2.55	885.48	0*
LA County Joint Pollution Control Plant (JWPCP)	1.2	1.2	544.91	0
La Canada WRP	0	0	0.27	0
Long Beach WRP	0.08	0.08	34.06	0.03
Los Coyotes WRP	0.11	0.13	55.51	0.03
Edward Little WRP (Total Reuse)	0.14	0.14	63.76	0.14
Edward Little WRP (Title 22)	0.19	0.19	84.87	0.11
Malibu Mesa WRP	0	0	0.27	0
Pomona WRP	0.05	0.05	20.43	0.04
San Jose Creek WRP	0.3	0.3	136.22	0.3
Santa Monica Urban Runoff Recycling Facility (SMURF)	0.002	0.002	0.68	0.3
Tapia WRP	0.05	0.05	22.47	0.05
Terminal Island WRP	0.09	0.09	40.87	0.02
Donald Tillman WRP	0.24	0.3	122.61	0.1
Whittier Narrows WRP	0.05	0.05	20.43	0.05

*Hyperion WRP sends effluent to the Donald Tillman WRP for advanced water treatment and may have new water reuse capacity in future years.
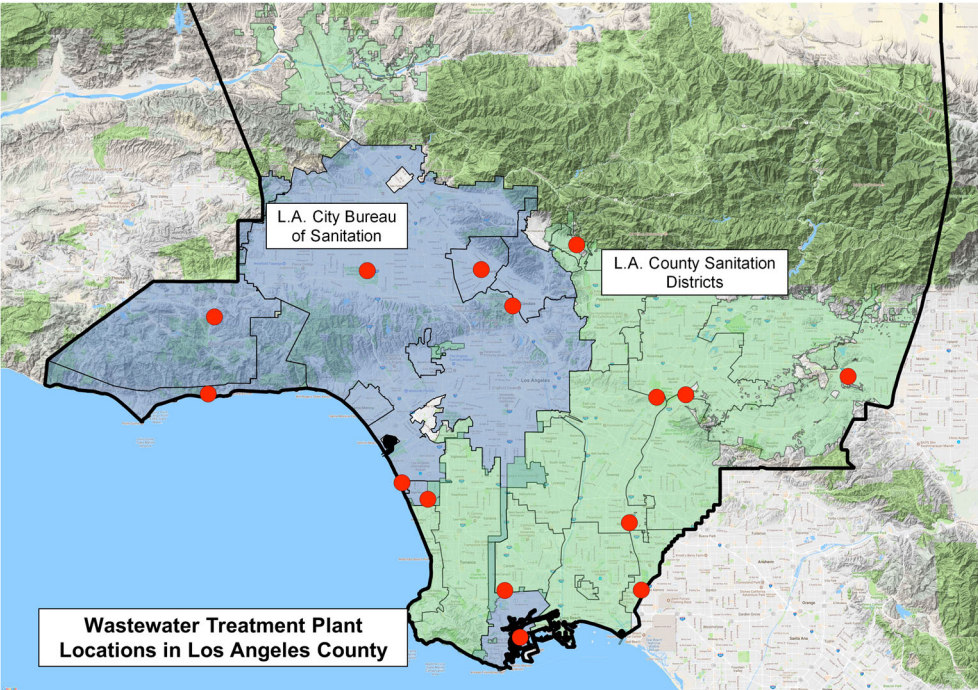
Figure 3 . Wastewater treatment facilities in metropolitan Los Angeles.

Table 2 . Proposed new water reuse operations and associated costs added to the model for this analysis. Many operations are being flexibly designed to provide either indirect or direct potable supplies as existing and emerging regulations allow (MCM/Day = millions of cubic meters per day).

Facility	Proposed Design Capacity (MCM/ Day)	Destination	Source
Hyperion Wastewater Treatment Plant: New Reuse	0.51	Edward C. Little Reclamation Plant Central/West Coast Basin Groundwater Replenishment (modeled as recharge through Rio Hondo Spreading Grounds)	Los Angeles Department of Water and Power (2019)
Los Coyotes WRP: newly included connections	0.03	Montebello Mutual Water Company Golden State Water City of Lynwood City of South Gate City of Pico Rivera City of Monterey Park	LA County Department of Sanitation (2015)
Whittier Narrows WRP: Newly included connections	0.05	City of Arcadia City of El Monte	LA County Department of Sanitation (2015)
Joint Water Pollution Control Plant: New Reuse Capacity (LA County and MWD)	0.45	Whittier Narrows Dam (Rio Hondo) for groundwater replenishment Long Beach Coastal Injection Wells (proposed) Santa Fe Spreading Grounds Eaton Wash Spreading Grounds Garvey Reservoir (MWD) Injection into MWD's water treatment plant for distribution	MWD (2016)

2015; LADWP 2015a; MWD 2016). These facilities could support future operations with Direct Potable Reuse.

2.2. Formulation

The hydroeconomic model, *Artes*, was developed to understand the potential to maximize local water supplies in LA County and has been used to evaluate many aspects of future urban water management (Porse et al. 2017). *Artes* incorporates data from hundreds of sources on water utility operations, surface hydrology, climate, hydrogeology, wastewater operations, and stormwater infrastructure. It includes a central database and open-source software that supports analysis at multiple geographic and temporal scales in LA. Model outputs quantify agency-specific and regional totals for water flows, potential shortages that are calculated as the difference between expected demands and available supplies, and annual use of water sources to understand regional water supply portfolios given assumptions of conservation and imported water availability.

The objective function (Equation 1) uses a least-cost formulation, calculated as the difference between total costs and assessed benefits. Total costs (C) include supply and distribution costs and assessed economic damages (D) associated with residential outdoor water conservation, while benefits (B) are limited to recreational benefits associated with large stormwater capture basins (Porse et al. 2018):

$$Min \; Z = (C + D) - B \tag{1}$$

Total costs and economic damages from reduced deliveries depend on the flows of water across links in the system, each of which have associated cost coefficients. During a time step t, supply costs (Equation 2) are equal to the product of the volume of flow from node i to node j across link k (Q_{ijk}) and the specified unit cost of flows across link k (c_{ijk}):

$$C = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} c_{ijk} Q_{ijk} \tag{2}$$

Economic damages (Equation 3) for residential water conservation during a time step are similarly calculated by summing the product of volumetric shortages from reduced deliveries (S_{ijk}) from node i to node j over link k, and the unit cost associated with assessed economic damages for node j (d_j):

$$D = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} d_j S_{ijk} \tag{3}$$

Unit costs for damages were estimated as agency-specific welfare losses and based on a linear demand function procedure with estimated elasticities of demand and water prices derived from existing sources and existing work in California (Porse et al. 2018; Buck et al. 2016; Jenkins and Lund 2000). Economic losses capture costs of water use reductions, especially outdoor water use reductions achieved by changing irrigation habits and replacing lawns. Some costs are not considered, such as potential revenue losses for utilities or additional costs to mitigate effects of water conservation actions on utility operations. Further details are included in the *Supplemental Data* section.

Volumetric shortages (S) for a demand node j during a time step are the difference between the demands for node j (M_j) and the sum of flows (supplies) to node j (Equation 4).

Minimum demands include health, safety, and industrial demands (H_j) associated with indoor residential populations that use 189 liters per capita per day (50 gallons per person per day), which is based on current indoor consumption and policy targets in California, as well as reported commercial and industrial uses (Equation 5):

$$S_{ijk} = (M_j - Q_{ijk}) \tag{4}$$

$$Q_{ijk} \geq H_j \tag{5}$$

Economic benefits B (Equation 6) during time t associated with certain stormwater capture uses are calculated across all nodes as the product of the flows and the unit value of benefits for that node (b_j):

$$B = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} b_j Q_{ijk} \tag{6}$$

A continuity equation preserves flows into and out of each node during time t (Equation 7):

$$\sum_{i=1}^{I} \sum_{k=1}^{K} Q_{ijkt} + I_{jt} = \sum_{i=1}^{I} \sum_{k=1}^{K} Q_{jikt} + R_{jt} + L_{jt} \tag{7}$$

Some nodes, including watersheds and conveyance infrastructure, have I_{jt} inflows from external sources, while all nodes have R_{jt} storage capacity and L_{jt} losses during a given time step based on loss rates included in the water balance. For a given time, the flows across link k cannot exceed the capacity C_{ijk} (Equation 8):

$$Q_{ijkt} \leq C_{ijk} \tag{8}$$

Finally, Eq. 9 represents a lower bound so flows across links cannot be negative:

$$Q_{ijkt} \geq 0 \tag{9}$$

The processes for validating and calibrating the hydrologic and economic formulations within the *Artes* model are extensively documented in multiple peer-reviewed sources (Porse et al. 2017; Porse et al. 2018). Additional peer-reviewed studies have used *Artes* to evaluate implications of local water reliance on supply reliability, stormwater capture impacts on streamflow, groundwater management, energy use, and key themes for future water sustainability (Pincetl et al. 2019; Porse et al. 2015; Porse and Pincetl 2018; Porse et al. 2018).

2.3. Data sources

Data were compiled from existing models, documents, reports, and agency databases. The data are historic (up to 2010), corresponding with available data at the time of development. It captures past droughts but does not reflect the most recent droughts (2011–2016, 2020–2022).

Relevant data included groundwater pumping and recharge, water demands, institutional water transfer agreements, assessed tree canopy water needs, historic

wastewater and water reuse flows, historic imported water supplies, and precipitation and evaporation. Data covered the period of 1986–2010, with wastewater influent and effluent available for 1996–2010. Detailed descriptions of the data sources are provided in the *Supplemental Data* section.

Precipitation, runoff, and recharge were incorporated into the analysis using an existing hydrologic model for LA County, the Watershed Management Modeling System (WMMS), and integrated into *Artes* (LACDPW 2013; Porse et al. 2017). WMMS includes 25 years of daily climate variables for over 2,000 small watersheds. These were aggregated into 47 watershed zones within *Artes* that correspond to key catchments for managed streams or infrastructure operations. Aggregated values of precipitation, watershed inflows and outflows, and evaporation losses in each watershed zone in *Artes* for the unaltered system serve as flow constraints within the optimization. Past work showed that incorporating wastewater system effluent discharges to simulate altered hydrologic flows improved the agreement of modeled stream flows with historic gauge data in several watersheds (Porse et al. 2017). Model calibration procedures are extensively documented (Porse et al. 2017; Porse et al. 2018; Porse and Pincetl 2018). The input data sets, software integration, and outputs are shown in Figure 4.

For wastewater treatment, past studies included current wastewater treatment and reuse operations, as well as some proposed small operations (Porse et al. 2017; Porse et al. 2018; Porse et al. 2018). Table S2 in the *Supplemental Data* section provides a detailed description of the previously modeled operations. For this study, new nodes and links were incorporated into the network model to represent network connectivity and flow for the proposed large-scale water reuse operations detailed in Table 2.

2.4. Calibration

Model calibration involved a multi-step process (Porse et al. 2017). First, water distribution system losses (evaporation, evapotranspiration, groundwater recharge, and
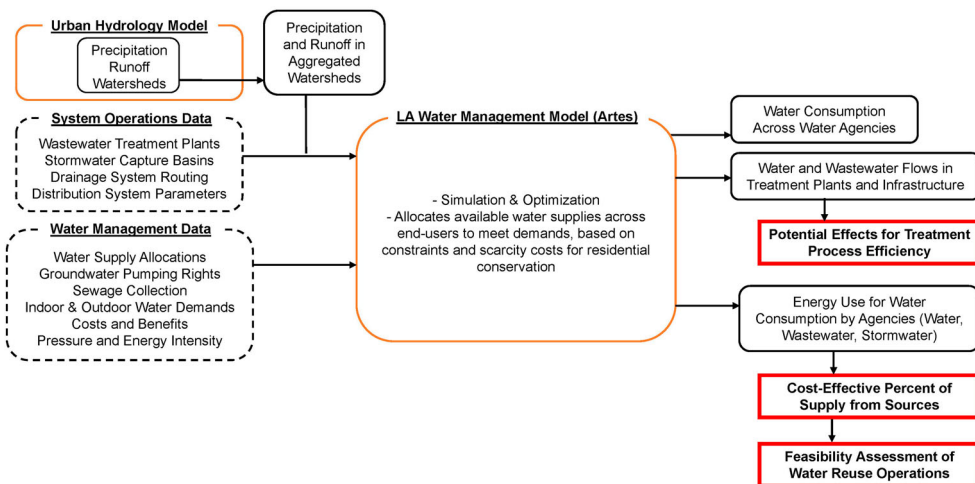

Figure 4 . Schematic depicting architecture and data flows of the *Artes* model

leakage), were calibrated for 2010, the only year with reasonable estimates of annual water supply and demand values across all retailers based on data available at the point of the model's development. Losses in urban water distribution networks were determined by summing all reported demands from retailers flowing to each of the wastewater treatment plants, based on sewer network pipe service areas. The percent of losses was determined as the difference between the total inflows and total outflows in a service region. Based on the collection system networks, LA County was aggregated into two regions: 1) the LA County joint service area comprised of 8 treatment and recycling plants, and 2) the LA City area comprised of 4 plants. This resulted in aggregating the retailers into two main groups feeding each system. Urban system losses for water supply distribution, household uses, and wastewater collection in the L.A. County network ranged from 33 to 55%, with higher values in summer months. In L.A. City including the cities of Los Angeles, Burbank, Glendale, and others, losses ranged from 1 to 34% (Porse et al. 2017). For comparison, a limited survey of L.A. County water retailers reported up to 4% losses from leaks within distribution systems alone, while statewide reporting indicated leak losses in distribution systems of over 7% (Naik and Glickfeld 2015; Rupiper et al. 2021).

Second, simulated runoff, evapotranspiration, and infiltration data obtained from outputs to the regional hydrologic model (WMMS) were compared to actual stream flow records for the downstream gauges in regional watersheds. Calibration results verified the accuracy of the underlying hydrologic model for the LA River and San Gabriel River watersheds without WRP outflows based on Nash-Sutcliffe efficiency (NSE) values of 0.790 and 0.604. Adding WRP outflows to the surface flows based on the drainage network increased the accuracy of calibration during summer months. Further details were previously reported (Porse et al. 2017).

Third, after calibrating the hydrologic model with WRP outflows, monthly results for precipitation and total outflow were imported into the *Artes* database. The monthly precipitation and upstream surface flows were added to watersheds as inflows. Losses to evaporation and groundwater infiltration were calculated for each watershed zone based on constraining the optimization to match outflows from watersheds to the WMMS values for each month.

2.5. Modeled scenarios

To evaluate the economic feasibility of water reuse operations over a variety of operational scenarios, water scarcity was imposed in the form of cutbacks in available imported water. Ten scenarios were modeled, with available imported water included as a percentage of the historic annual amount from each of the three primary imported water sources: Owens Valley, the Colorado River, and Northern California through the Sacramento-San Joaquin Delta. The modeled percentages ranged from 0 to 100%. For each scenario of available imported water, the formulation allocated water flows to agencies throughout the network based on least-cost options to deal with imposed water scarcity given existing institutional and legal constraints that govern access to water supply and rights. In scenarios with very low imported water availability from all imported water sources, this would instigate significant water conservation in most areas.

2.6. Effects of flow changes on wastewater treatment operations

Many wastewater treatment facilities and collection systems in California are aging and have not undergone comprehensive upgrades. Older treatment facilities were designed to specifications of influent flow and constituent concentrations in past decades. In recent surveys, a significant percentage of wastewater treatment managers have reported that changes to influent flow and quality during recent drought affected existing wastewater treatment and reuse facilities (Porse et al. 2023; Chappelle et al. 2019). Without upgrades and improvements, wastewater facilities can face challenges in maintaining process efficiency (percent of contaminants removed) and meeting permitted discharge limits of contaminants (Tran, Jassby, and Schwabe 2017; Schwabe et al. 2020; OWP at Sacramento State 2022).

The effects of modeled scenarios on treatment process efficiency were evaluated through two procedures. First, modeled influent flow rates were compared to historical influent flow rates during the period with available data (1996–2010). Second, the relationship between flow rate, contaminant concentrations, and treatment effectiveness was compared using historical operational data, with the intent of evaluating how lower influent flow rates from water conservation may affect influent constituent concentrations. For one facility with available data (Hyperion WRP), daily monitoring records of influent and effluent flow, Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS) from 2011 to 2019 were used to examine relationships. The treatment effectiveness was calculated for each day as the percent removal of BOD and TSS. Multiple regression with a semi-log model was used to evaluate relationships of influent flow and concentration as explanatory variables for percent removal. Two separate models were developed for BOD and TSS, with percent removal of a contaminant as a response variable and log-transformed values of influent flow and concentration of the contaminant as explanatory variables. The models were implemented in R Studio using the *lm* package.

2.7. Energy intensity of water reuse

Integrating potential reuse operations into the hydroeconomic framework required a newly developed representation of energy use intensity to simulate conveying and pumping water throughout the metropolitan region (Porse et al. 2020). Numerous studies have evaluated the energy implications of water management strategies in Los Angeles (Porse et al. 2020; Sanders 2016; Sokolow, Godwin, and Cole 2016; Stokes-Draut et al. 2017; Wilkinson, Wolff, and Shwom 2006). Replacing imported water sources with supplies from local reuse offers an opportunity to achieve net reductions in electricity consumption and associated costs, but additional pumping and treatment needs offset energy savings (Escriva-Bou, Lund, and Pulido-Velazquez 2015; Spang, Holguin, and Loge 2018; Stokes-Draut et al. 2017; Wilkinson, Wolff, and Shwom 2006). Greater use of in-basin sources with more moderate energy intensity could reduce systemwide energy intensity, but conveying water throughout a city such as Los Angeles also uses significant energy (Kenway et al. 2015; LADWP 2015a; Lam, Kenway, and Lant 2017; Sokolow, Godwin, and Cole 2016).

For this analysis, pumping energy needs and costs associated with new centralized water reuse were incorporated into the model using commercial electricity supply rates

that utilities pay to local investor-owned utilities (estimated as USD $0.10 per kilowatt-hour). Details on the methods and data are included in the *Supplemental Data*.

3. Results

3.1. Water reuse and regional water supplies

Model results indicate that new water reuse operations with AWT become economically viable when imported water availability is 50% or less of historic values. Across scenarios, existing and less expensive indirect potable reuse facilities in the county consistently make up 7–12% of supplies, regardless of imported water availability. For instance, in a scenario with 50% annual availability of imported supplies, indirect and non-potable reuse comprises 10%, while new reuse with AWT is only 1% (Figure 5). New and more expensive AWT facilities become more viable in scenarios when 50% or less of imported water is available, and AWT becomes especially viable as imported water availability falls to 30% of historic inflows. In these scenarios, existing IPR and proposed AWT provide 20% −30% of total regional supplies across the county. The increase occurs for two reasons. First, some recycled water that would be used for indirect potable reuse through groundwater recharge is instead diverted to AWT. Second, some agencies turn to more expensive AWT sources to meet demands and alleviate economic losses associated with shortages. Thus, significant disruptions in existing supply are needed to instigate adoption of AWT operations.

Examining localized results reveals how particular agencies may capitalize on cost-effective strategies for reuse. Water retailer agencies with access to a nearby reuse facility were more likely to receive a significant portion of supplies from reuse through the least-
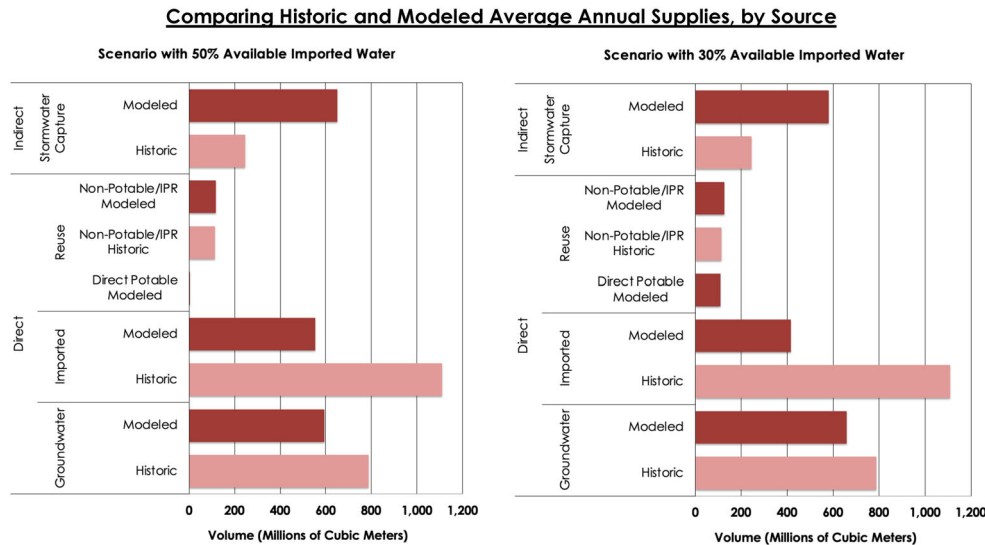

Figure 5 . Supply portfolios from the hydroeconomic modeling framework. The two scenarios modeled responses to an imposed reduction of 50% of historic imported water supplies with and without new large-scale reuse project capacity (MCM = Millions of Cubic Meters). The percentages represent the percent of total supply in the scenario from a source.

cost decision-making approach (Figure 6). Reducing pumping requirements to move water in the basin can significantly increase the cost-effectiveness of water reuse as a supply source.

3.2. Wastewater flows and treatment process efficiency

Promoting greater use of local water sources could affect wastewater treatment operations, with effects varying based on geographic location in the LA Basin (Porse et al. 2017; Porse et al. 2018). Comparing model results with historic data for the two largest facilities indicates that without AWT, modeled influent flow rates are less than historical values and design flows. However, once AWT becomes economically viable due to imported water scarcity, flow rates are boosted to maximize production (Figure 7). For instance, in the scenario with 30% imported water availability, influent flows to LA City's Hyperion Treatment Plant are less than the original design capacity of 450 million gallons per day (MGD, which is equivalent to 1.7 Million Cubic Meters, or MCM) for many years as reservoir storage is drawn down, but in later years that maximize AWT, influent flow rates are equal to or greater than recent historical levels. Similar trends occur in Joint Water Pollution Control Plant (Carson, or JWPCP) that is operated by the Los Angeles County Sanitation Districts (LACSD) and serves many of the cities and unincorporated areas in LA County outside the jurisdiction of the City of Los Angeles. This indicates that future urban water management options must balance opportunities for reuse with the cost-effectiveness of conservation as a demand management option.

Implications for these influent flow rates based on basic statistical analysis of monitoring data are inconclusive. Data for influent flow and constituent concentrations (BOD, TSS)

% of Supply from Reuse
- 0%
- 0 - 20%
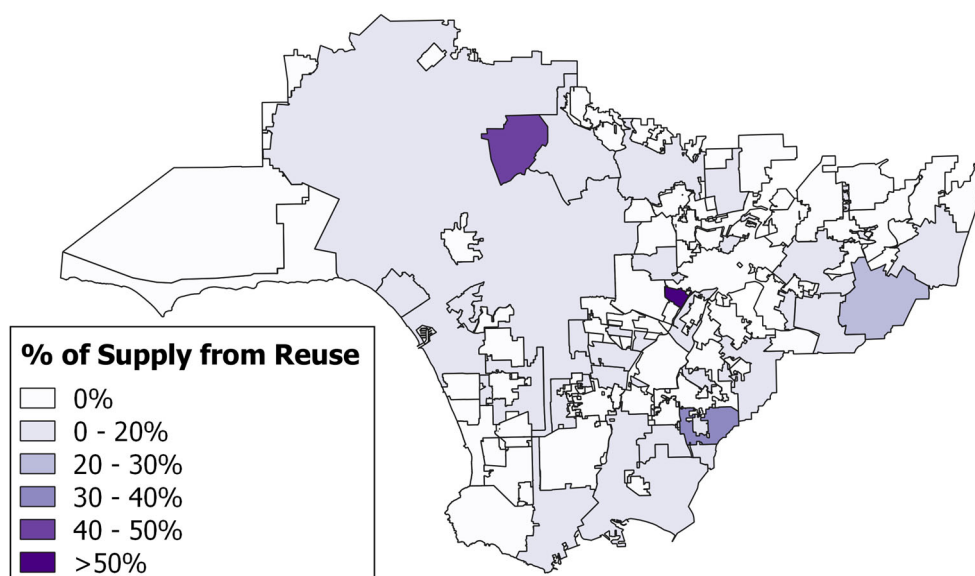- 20 - 30%
- 30 - 40%
- 40 - 50%
- >50%

Figure 6 . Water reuse as a percentage of supply for water retailers throughout LA County in the modeled scenario with an imposed 50% reduction in available imported water.
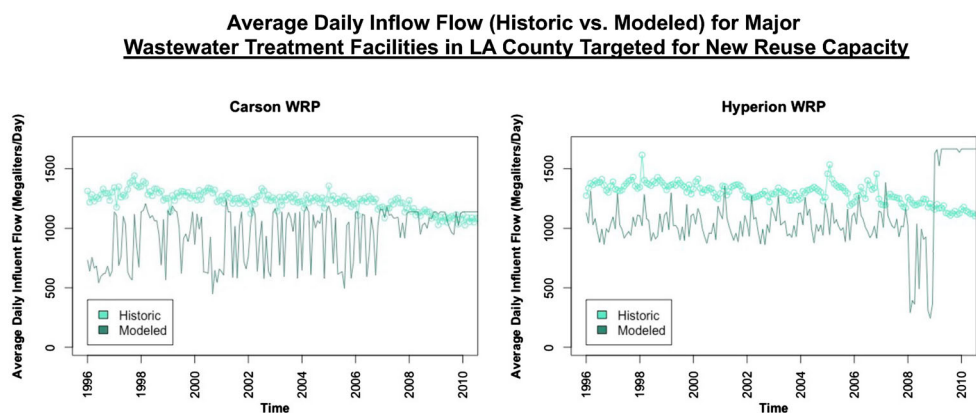
Average Daily Inflow Flow (Historic vs. Modeled) for Major
Wastewater Treatment Facilities in LA County Targeted for New Reuse Capacity

Figure 7 . Historic and modeled influent flows to the two largest wastewater treatment facilities in LA. The modeled flows are from a scenario with 30% available imported water, which represents extended water scarcity from drought.

for one of the two largest regional wastewater treatment facilities (Hyperion WRP) does not provide clear indications that future operations and treatment effectiveness would be significantly affected from future modeled flows. From 2011 to 2019, average influent flow was 326 MGD and average annual influent concentration of TSS and BOD was 399 and 313 mg/L per day. Average percent removal from influent to effluent was consistently 94–95%.

Multiple regression modeling indicated that flow was inversely correlated with percent removal of both TSS and BOD, while influent concentrations were positively correlated. For each 1% decrease in flow, percent removal of TSS increases by 0.027, which given that the response variable unit is percent, is equivalent to a 2.7% increase ($R^2 = 0.45$). Similarly for BOD, a 1% decrease in flow yields a change in percent removal of 0.026 ($R^2 = 0.29$). Both explanatory variables are statistically significant. Table 3 shows results. However, the low values for the coefficient of variation indicate that, in the modeled facility, other factors not captured in the model likely affect treatment process efficiency. Visualizing the percent removal of TSS and BOD as a function of influent concentration and flow rate reveals a weak positive correlation for both, whereby increased concentration corresponds with an increased percent removal (Figure 8). It is likely that additional operational and environmental control variables would be necessary to identify clear trends between influent flow and treatment process efficiency, but data was not available for this study. This would be an area for additional future investigation.

Table 3 . Results from multiple regression modeling with a semi-log formulation.

Explanatory Variables	Coefficient	Standard Error	t-value
Response Variable: Percent Removal of TSS ($R^2 = 0.44$)			
Intercept*	0.77	0.03	37.7
log(Influent Flow)*	0.027	0.004	−8.3
log(Influent TSS Concentration)*	0.56	0.002	33.8
Response Variable: Percent Removal of BOD ($R^2 = 0.29$)			
Intercept*	0.80	0.02	28.0
log(Influent Flow)*	−0.027	0.003	−7.2
log(Influent BOD Concentration)*	0.51	0.001	22.4

*Indicates statistically significant variables with $p < 0.001$

3.3. Energy use

Increased reliance on AWT would replace current imported water supplies to the region from the Sacramento-San Joaquin Delta and the Colorado River, which both require significant amounts of energy. Water conservation is a key driver of energy use reductions for water supply operations within the basin. In modeled scenarios, as imported water grows scarcer and demand reduces, the electricity intensity of the water supply system decreases until the threshold of 50% imported water availability (Table 4). Below 50% of imported water supply, systemwide electricity intensity increases again (Table 4). Drought years, which are identified as years with less than the 50th percentile of annual precipitation in the region during the modeled period, had higher average electricity intensity driven by greater reliance on AWT (Table 5).

4. Discussion

Model results indicate that the feasibility of AWT as a source of supply is linked to scarcity of existing imported water supplies. New reuse operations become cost-effective after extended periods of limited imported water availability. Coupled with demand reductions via conservation and continued use of stormwater capture and water storage, water reuse from existing and proposed sources is estimated to comprise up to 30% of regional supplies, but only in scenarios of significant imported water scarcity. However, this modeled economic viability of new AWT operations is rooted in existing financial and economic practices. Imported water sources were built over a century ago. Retail unit costs for agencies to purchase annual imported water allocations from MWD have increased over time to cover costs for energy, maintenance, and infrastructure upgrades. Costs for new reuse infrastructure (or other supply options) typically incorporate both construction and long-term operational costs, which are also annualized over a future long period. While regional planning studies evaluate the future annualized costs of new sources such as reuse or stormwater capture, there is currently no consistency in
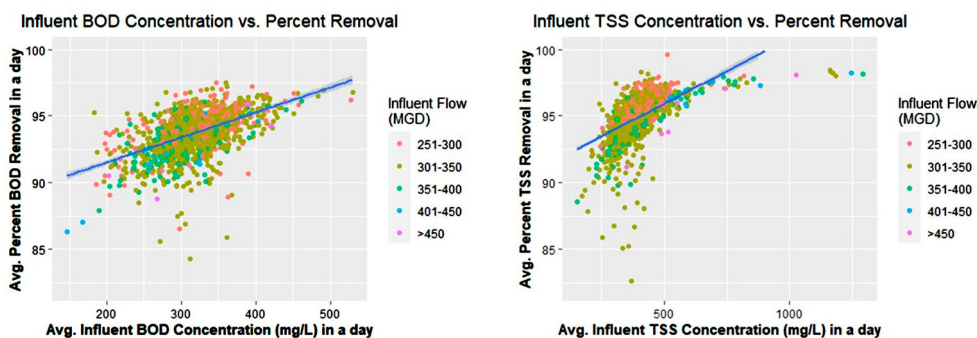

Figure 8 . Daily influent monitoring data for contaminant concentration and percent removal of Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS) for Hyperion WRP (2011–2019). Source: Based on data from the California Integrated Water Quality System and published by Keene, Babchanik, and Porse (2022).

Table 4 . Modeled scenarios of imported water availability with available reuse capacity, including both existing indirect potable reuse and newly proposed advanced water treatment.

Scenario: Imported Water Available	Modeled % from Supply Sources[b]			Average total water supply from all sources (MCM)	Average annual net electricity use (GWh/MCM)	Per capita water use (lpd[c])
	% Imported	% Groundwater	% Recycled Water			
100%	65%	27%	7%	1,530	2.6	438
70%	50%	42%	8%	1,431	2.1	408
50%	43%	46%	9%	1,351	1.6	386
30%	31%	51%	18%	1,332	1.8	382
0%[a]	17%	56%	27%	1,252	1.8	359

[a]% imported water used in this scenario is from initial available storage.
[b]Does not report surface water use, which is approximately 1%.
[c]lpd = liters per capita per day.

Table 5 . Average value of electricity intensity during drought, non-drought, and all years for the modeled scenario of 50% of historic imported water availability (kWh = Kilowatt-Hours). Drought and non-drought years are identified as years with greater or less than the 50th percentile of annual precipitation during the time period from 1986 to 2010.

Model Result Parameter	Non-Drought ($n = 8$)	Drought ($n = 7$)	All Years
Average % Supply from Groundwater	43%	45%	45%
Average % Supply from Imported Water	50%	41%	44%
Average % Supply from Non-Potable/Indirect Reuse	7%	12%	9%
Average % Supply from Direct Potable Reuse	0%	1%	0%
System-wide Electricity Intensity (kWh per MCM)	1.5	1.5	1.5

whether regional planning documents incorporate long-term escalation in annualized unit costs for existing annual water purchases. Thus, the existing imported water purchases can seem mistakenly cheaper. In a system with path dependence (Liebowitz and Margolis 1995), the financial viability of a new source such as reuse is subject to the implications of past decisions as well as circumstances of future ones.

The analysis is subject to limitations. First, the analysis at the monthly time step may fail to capture important dynamics that affect water and wastewater system operations, such as extreme daily peak flows and concentrations. Second, model results may overestimate stormwater capture as a contribution to water supply because the model does not have sufficient temporal resolution to represent extreme hydrologic events. This means that reuse could be underrepresented as a source of supply if stormwater capture and recharge are too optimistic. Third, the modeling does not incorporate water quality considerations. Emerging contaminants may push more communities to invest in Advanced Water Treatment. Finally, system losses from all sources including wastewater systems were estimated and may not reflect losses that occur in new AWT operations.

5. Conclusions

AWT operations were incorporated into an integrated urban water resources model, *Artes*, for metropolitan Los Angeles. The model was run across scenarios of decreased imported water availability, which is a main supply source for many agencies but faces future scarcity. Cost and energy requirements for advanced water treatment operations were drivers of the feasibility of the new AWT sources.

Results indicate that, without significant water supply scarcity in the form of available imports, new reuse operations would not be highly utilized based on the primary driver of cost-effectiveness. Across modeled scenarios that each span multiple years, reuse emerges as a significant source of supply only in scenarios with 50% or less imported water. During such times, modeled reuse supplies up to 30% of regional demands. Pumping costs to move treated water uphill in the basin are a significant limit on cost-effectiveness of water reuse due to the locations of current large wastewater treatment facilities. More localized water reuse operations, which were not explicitly included in the modeling, offer opportunities to reduce energy and pumping costs and increase economic viability of operations. Analysis of monitoring data indicates limited to modest risk to existing treatment operations from future influent flow rates and likely associated constituent concentrations. In summary, the modeling framework and results offer a template for integrating water reuse operations into integrated models of urban water planning.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability

Model documentation, data, and software are openly available (Porse 2022). Supporting data for the analysis is available as a supplementary file. Wastewater treatment facility data used to evaluate potential water quality and treatment effects is available through a Hydroshare repository (Keene, Babchanik, and Porse 2022).

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