# Systems Analysis and Optimization of Local Water Supplies in Los Angeles

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**Abstract:** Los Angeles, which relies on large infrastructure systems that import water over hundreds of miles, faces a future of reduced imports. Within Los Angeles and its hundreds of water agencies, the capacity to adapt to future changes is influenced by laws, institutions, and hydrogeology. This paper presents a systems analysis of urban water management in metropolitan Los Angeles County to assess opportunities for increasing local water reliance. A network flow model was developed to investigate management tradeoffs across engineered, social, and environmental systems. With an aggressive regional demand target, increased stormwater capture (300%), and prioritized water reuse from existing facilities, imported water supplies can be cut by 30% while maintaining landscapes, economic productivity, and groundwater resources. Further reducing imports (by 40–50%) is possible through actions to promote additional reuse, recharge, conservation, and groundwater access. Reducing imported water without significant conservation results in likely groundwater overdraft. Fragmented networks of agencies in Los Angeles create an uneven landscape of vulnerability to water shortages. The paper discusses model applications, research needs, and policy implications of results for dry-climate cities. **DOI:** 10.1061/(ASCE)WR.1943-5452.0000803. 

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## Introduction

For centuries, cities have faced water management challenges (Baker 1948; Blake 1956; Duffy 1990; Frontinus 1973; Hall 1998; Wilson 1998). Inadequate disposal of wastes, both organic and manufactured, affect the quality of local surface water and groundwater. Imperviousness increases runoff, pollutant loads, and flood risks (Brabec et al. 2002; Duncan 1995; Hollis 1975; Lee et al. 2002; McCuen 1979; Schueler 1994). Intensive water consumption and limited local surface water supplies, especially in arid regions, require cities to import water from remote sources or deep underground (Melosi 2000, 2011; Tarr 1984).

Systems analysis of urban water includes engineered infrastructure; local hydrology and hydrogeology; and social, institutional, and economic factors. Cities built complex infrastructure and governance systems to manage water resources. Supplies from groundwater, surface runoff, distant sources, and in some cases recycled water, are treated and distributed to end-users. Pipe networks, either combined or separate, then collect wastewater and stormwater runoff for treatment and discharge to local watersheds (Loucks et al. 2005). Local climate patterns, along with the legacies of existing systems, shape how cities meet evolving water supply challenges (Howe and Smith 1994; Melosi 2011; Tvedt and Oestigaard 2014). Increasingly, urban water planners look to hybrid models of infrastructure, designing systems that integrate centralized and distributed designs, while also linking water sources of varying quality with appropriate end-uses (Daigger 2007; Hering et al. 2013; Mitchell 2006; Novotny et al. 2010). New treatment and sensor technologies can support the safe operation of innovative designs (Asano 2006; Leverenz et al. 2011; Metcalf and Eddy 2007; NAS 2015). Simulation and optimization models assist in planning all aspects of these systems. Most urban water models simulate processes at hourly or daily intervals appropriate to water quality assessments, distribution systems' needs, and stormwater operations (Loucks et al. 2005).

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Yet, cities are only one type of user in much broader water distribution networks (Draper et al. 2003; Hale 2015). Cities rely on places beyond municipal boundaries for water. In arid and semiarid climates, urban water systems extend far upstream (Melosi 2011; Swyngedouw 1997; Tarr 2001). Many cities of western North America developed in areas of highly seasonal, limited precipitation. Federal and state governments supported large-scale water conveyance infrastructure through the 20th century to move snowmelt and runoff to areas of higher demand. Across California today, 10% of water is used by cities, while 50% is dedicated to environmental uses, and 40% is used by agriculture. Of the portion used by cities, approximately half goes to outdoor landscapes (Hanak et al. 2011; Hanak and Davis 2006).

Historic expectations of urban water consumption across western North America are increasingly strained by population growth, water scarcity, climate change, and environmental water needs (Gober 2010; Hanak and Lund 2012; Medellín-Azuara et al. 2008; Tanaka et al. 2006). Urban water agencies in California have responded to past intermittent water scarcity by incentivizing indoor conservation, mandating outdoor cutbacks, and building new storage. Some agencies implement advanced treatment to support nonpotable or indirect potable reuse (IPR). Others contract to acquire agricultural water, though such transfers can be controversial (Libecap 2005; Lund and Israel 1995). Aging infrastructure and water quality requirements are pressuring cities to reassess traditional centralized models of water management (Hering et al. 2013; Kiparsky et al. 2013; Porse 2013; Sedlak 2014). Yet, behavior is still important. Urban residents often overestimate the amount of water needed to maintain even existing landscapes (Mini et al. 2014a, b). Given the challenges, both supply-side (water reuse, stormwater capture, water and groundwater quality) and demand-side (indoor and outdoor water conservation), actions are necessary for future management.

Los Angeles County, part of a vast urbanized region of southern California, is an outsized case study in urban water planning. Across metropolitan Los Angeles County and its 88 distinct cities where 1 0 million people reside, more than 100 sizable agencies (agencies with over 200 connections) supply water, of which nearly 60% currently originates from imported sources (DeShazo and McCann 2015; Pincetl et al. 2016). Historically, imported water also critically supplied groundwater recharge in spreading basins, which have for decades infiltrated hundreds of thousands of acre-feet of stormwater, recycled water, and imported water each year into local aquifers (Blomquist 1992; LACDPW 2014; Porse et al. 2015). The Metropolitan Water District of Southern California (MWD), the large water importer that serves the entire southern California region, arose to fund and sell imported water, supporting Los Angeles' rapid growth.

Today, long-term supply and demand projections in Los Angeles are spurring some water agencies to reconsider heavy reliance on imported water, instead looking to maximize locally available supplies (LADWP 2015a). The City of Los Angeles, the largest and most populous municipality in Los Angeles County, has stated goals to reduce its reliance on purchased water by 50% by 2025 (Office of the Mayor, Eric Garcetti 2015). Expanding existing stormwater capture, water recycling, and conjunctive use of local surface and groundwater resources can all contribute to preserving local supplies (Mihelcic et al. 2003). Demand reductions through indoor and outdoor conservation help supplies go further (Cahill et al. 2013; DeOreo and Mayer 2012). Innovative policies and financing mechanisms can support such changes, especially given fiscal pressures facing water agencies. For instance, localities look to pay for stormwater infrastructure upgrades by monetizing benefits of enhanced recharge in water supply aquifers (Brandt 2015; Porse et al. 2015). These strategies all contribute to emerging water management practices in the region.

Several conceptual frameworks already exist that describe systematic approaches to urban water management strategies that Los Angeles is exploring (Daigger 2011; Novotny et al. 2010). For instance, *water sensitive cities* emphasize adaptive infrastructure that supports changes in behavior and operations (Brown et al. 2008). *Sustainable urban water management* meshes economic, physical, and institutional perspectives across sectors to incorporate broader resident participation. Technological innovation and institutional changes are key (Hering et al. 2013; Kiparsky et al. 2013), but without understanding historical lessons and social attitudes, technological fixes may be inadequate (Bulkeley and Betsill 2005) or yield unforeseen consequences (Tarr et al. 1984). Impediments to more sustainable urban water management are often institutional rather than technical (Brown and Farrelly 2009; Hale 2015; Marsalek et al. 2001). Urban water governance systems are fragmented, lack community-based input, and slow to change (Heaney and Sansalone 2009; Marsalek et al. 2001; Niemczynowicz 1999). Droughts, evolving social preferences, and other external factors can motivate new approaches (Saleth and Dinar 2005). Data at multiple temporal and spatial resolutions is necessary to evaluate progress (Cominola et al. 2015; Gleick 2003; Pincetl et al. 2016). Feedback loops reinforce behavior and environmental effects in coupled and complex systems (Gunderson and Holling 2002; Liu et al. 2007; Ostrom 2009; Pataki et al. 2011; Pincetl 2010).

## Purpose of Study

This study describes a systems analysis of urban water in metropolitan Los Angeles County to understand opportunities for transitioning the region to a supply regime dependent on local water sources. It simulates the current system and investigates key systematic uncertainties including: (1) the potential for local water reliance given current institutions, infrastructure, and scientific knowledge; (2) tradeoffs in supply, demand, and shortages with greater local water reliance; (3) system wide effects (if any) from increased conservation; and (4) baseline water demand to support efficient indoor and outdoor uses. The study presents a network-flow model, *Artes*, which uses optimization to assess how reduced imported water supplies and increased use of local water resources, including groundwater, stormwater capture, and recycled water, affect water scarcity within the current hierarchical network of agencies and allocations. The model is novel by incorporating both physical systems and institutional constraints such as established water allocations and pumping rights. The study shows how flexible and adaptable modeling tools can be highly useful in a landscape of evolving models and data. It concludes with policy implications and areas for future research.

## Existing Water Management in Los Angeles

The institutional architecture of water supply and distribution in Los Angeles includes agencies that import water, wholesaler agencies that resell water, and retailer agencies that deliver water to end-users (Erie and Brackman 2006; Ostrom 1962; Pincetl et al. 2016). Two state water project contractors, the San Gabriel Valley Municipal Water District with four member agencies and the vast Metropolitan Water District of Southern California (MWD) with 17 Los Angeles County member agencies, import water from northern California through the Sacramento–San Joaquin Delta. MWD gets additional imported water through the Colorado River Aqueduct, while the Los Angeles Department of Water and Power (LADWP) imports water to City of Los Angeles residents from the Owens Valley and Mono Lake (as allowed by legal restrictions) through the Los Angeles Aqueduct. Nearly 100 sizable agencies are involved in selling water to end-users, including public water agencies, private



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investor-owned utilities, and nonprofit mutual water companies (DeShazo and McCann 2015; Pincetl et al. 2016). Some agencies such as the LADWP import as much as 90% of water annually (LADWP 2015b).

Additionally, hundreds of private and public entities have rights to pump groundwater from basins and subbasins that comprise seven adjudicated groundwater areas lying entirely within Los Angeles County. The groundwater management structure arose decades ago, supported by significant volumes of imported water, to preserve groundwater resources, establishing a system of codified groundwater rights that have grown more consolidated and publicly-controlled over time (Blomquist 1992; Langridge et al. 2015; Porse et al. 2015). Municipal stormwater agencies, the Los Angeles City Bureau of Sanitation, the Los Angeles County Sanitation Districts, and the Los Angeles County Department of Public Works (LACDPW) manage sewage, rainfall, and stormwater runoff across a region punctuated by a limited number of storms per year that can be extreme downpours. Regional water quality boards oversee state and local water regulations to control point and non-point sources of pollution. Finally, nonprofit organizations are involved in environmental planning, land use, conservation, equity, and many other issues (Hughes and Pincetl 2014).

Regional water resources in Los Angeles are highly modeled (Table S1). Agencies use hydrologic, hydrogeologic, and water supply models to manage groundwater, water supply, and flood control operations. But dispersed responsibilities across agencies have created a fragmented collection of modeling tools that function on different time steps, geographic scales, and sectors. Given the myriad models, along with the likelihood of future institutional changes and climate variability, new tools that are flexible, adaptable, and open-source can be most useful to evolve with new scientific information and tools.

## Methods

The presented model, *Artes*, is a network flow model that uses optimization to estimate the potential for maximizing water supplies from local sources given existing allocation agreements, hydrology, and infrastructure. It depicts the layers of interlinked systems involved in Los Angeles' urban water management, including water supply, wastewater, and stormwater systems, anthropogenic and ecologic drivers of water use, surface hydrology, and groundwater basins (Fig. 1). *Artes* is built using custom processing scripts developed in *Python* and an optimization engine (*Gurobi*) to maximize flows of local supplies in the Los Angeles water management network (JetBrains 2015). It provides a flexible structure to assess options and potential water

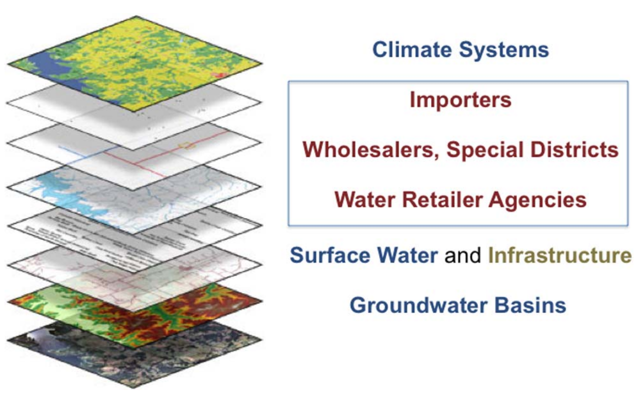


**Fig. 1.** Hierarchy of the urban water management system in Los Angeles (image courtesy of USGS)

shortages across scenarios of supply and demand. Like all models, interpreting its results requires a clear delineation of goals and inherent assumptions. To that end, the model was developed to:

- Determine the extent to which local water supplies, including groundwater, water reuse (nonpotable and IPR) and stormwater capture, could meet water demands across Los Angeles County, based on current infrastructure and knowledge of hydrology and hydrogeology;
- Assess tradeoffs in per capita water demand and available imported water supplies for water retailer agencies in Los Angeles Country;
- Investigate system wide effects (if any) from increased conservation;
- Estimate baseline urban water demands to support indoor and efficient outdoor water uses, including maintaining existing tree canopy cover, using experimental data;
- Minimize assumptions and extrapolations about future water demands; and
- Compare modeled and historic groundwater pumping and managed aquifer recharge to assess the potential for groundwater overdraft. The model purposefully does not report a calibrated value of groundwater recharge through natural infiltration or distributed stormwater recharge because of the uncertainty in current models.

*Artes* does not explicitly incorporate water quality requirements. Complementary studies address the role of water quality regulations in local water supply enhancement (Gold et al. 2015). Model formulation and analysis procedures are outlined subsequently and depicted in Fig. 2.

### Formulation

The model uses a general network flow optimization framework (Ahuja et al. 1993; Bazaraa and Jarvis 1977; Jensen and Barnes 1980), which has been applied to numerous water management problems (Draper et al. 2003; Harou et al. 2009), including southern California (Diba et al. 1995). The primary decision variable in *Artes* is flow ($Q_{ijk}$) between nodes $i$ and $j$ over link $k$ in the depicted network. The model maximizes flows (supplies) from local sources, including groundwater, spreading basins, and recycled water, to minimize shortages. Specifically, the model objective function [Eq. (1)] maximizes the sum ($Z$) of the difference between flows from local sources ($Q_a$) and shortages ($S$) across all retailers, such that

$$\text{Max} Z = Q_a - cS \tag{1}$$

where $c$ = arbitrary constant used to relate flow and shortages. Supplies from local sources are represented mathematically as flows where $i$ is in the set of local source nodes

$$Q_a = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} (Q_{ijk}) \quad \text{where } i \in \{\text{Local Sources}\} \tag{2}$$

Shortages are the difference between the demands for node $j$ ($D_j$) and the sum of supplies to node $j$, such that

$$S = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} (D_j - Q_{ijk}) \tag{3}$$

Model constraints [Eqs. (4)–(6)] preserve network flows ($Q$) and limit volumes based on storage and flow capacities of features. For a given node $j$, the sum of inflows must equal the sum of outflows and storage during time $t$

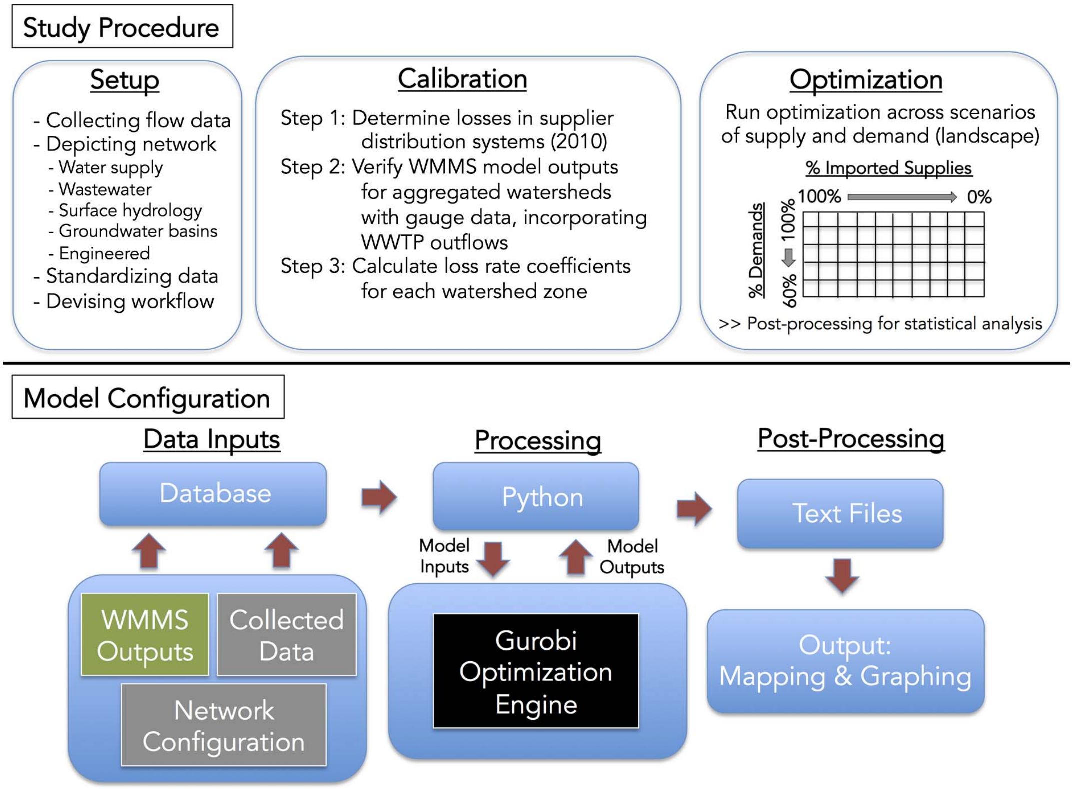


**Fig. 2.** Description of study procedures and configuration of the *Artes* model

$$\sum_{i=1}^{I}\sum_{k=1}^{K} Q_{ijkt} + I_{jt} = \sum_{i=1}^{I}\sum_{k=1}^{K} Q_{jikt} + R_{jt} + L_{jt} \qquad (4)$$

Some nodes, including watersheds and conveyance infrastructure, have $I_{jt}$ external inflows, 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 step, the flows across link $k$ cannot exceed the capacity $C_{ijk}$ [Eq. (5)]:

$$Q_{ijkt} \leq C_{ijk} \qquad (5)$$

Finally, flows are nonnegative [Eq. (6)]:

$$Q_{ijkt} \geq 0 \qquad (6)$$

Table S9 in the Supplemental Data details model variables.

## Model Development

The *Artes* database used here includes 332 nodes and 682 links across subsystems. Modeled features all received distinct nodes in the network. These included watershed areas (47), water retailers (103), water wholesalers and importers (18), groundwater basins (13), regional dams and conveyance infrastructure (26), spreading basins (26), and wastewater treatment and reclamation plants (17). Fig. 3 displays maps for 4 layers of LA water systems, including groundwater basins, watershed areas, water retailers agencies, and municipal water district wholesalers. Each node has associated attributes for demand, supply, and capacity, but attributes are zero when appropriate. For instance, demand nodes have monthly demands and inflow/outflow capacities, but only reservoirs and spreading basins have specified storage capacities. Network links were delineated by specifying the beginning and ending nodes, with associated flow capacities. Some nodes such as treatment plants have specified intake rates for wet (October–March) and dry (April–September) months derived from operating discharge permits associated with flow capacities, extrapolated to monthly volumes. *Gurobi* uses a database and associated attributes to build the network flow model and associated constraints.

Surface hydrology, in particular, was incorporated in *Artes* based on the Water Management Modeling System (WMMS) developed by LACDPW (LACDPW and Tetra Tech 2009). The Water Management Modeling System is a continuous model of hydrology and hydraulics in Los Angeles County, including major flood control infrastructure, but not wastewater sewers. It uses a 25-year time frame (1986–2010) and its outputs are calibrated to observed flows and water quality measurements (gauge data) at the hourly level across 2,600 subwatersheds. Of these 2,600 subwatersheds, approximately 2,200 in metropolitan Los Angeles were aggregated into 47 watershed zones to include in *Artes*. The watershed zones subdivide the major river watersheds of the county and correspond with upstream runoff zones for key system features such as spreading basins and surface water junctions. Hydrologic parameters for each watershed zone, including precipitation and losses to evaporation and groundwater infiltration, were derived from WMMS. Aggregated values for modeled precipitation, watershed inflows and outflows, and evaporation losses in each zone for the unaltered system are used to constrain optimized routing within *Artes*. The WMMS software system incorporates the loading simulation program in C++ (LSPC) for routing. Precipitation, evaporation, groundwater infiltration, and total runoff from upstream watersheds were calculated for each of the 47 watershed zones by processing output data from WMMS.

## Data

Data was compiled from existing models, documents, reports, and agency databases. The data is historic (up to 2010), corresponding



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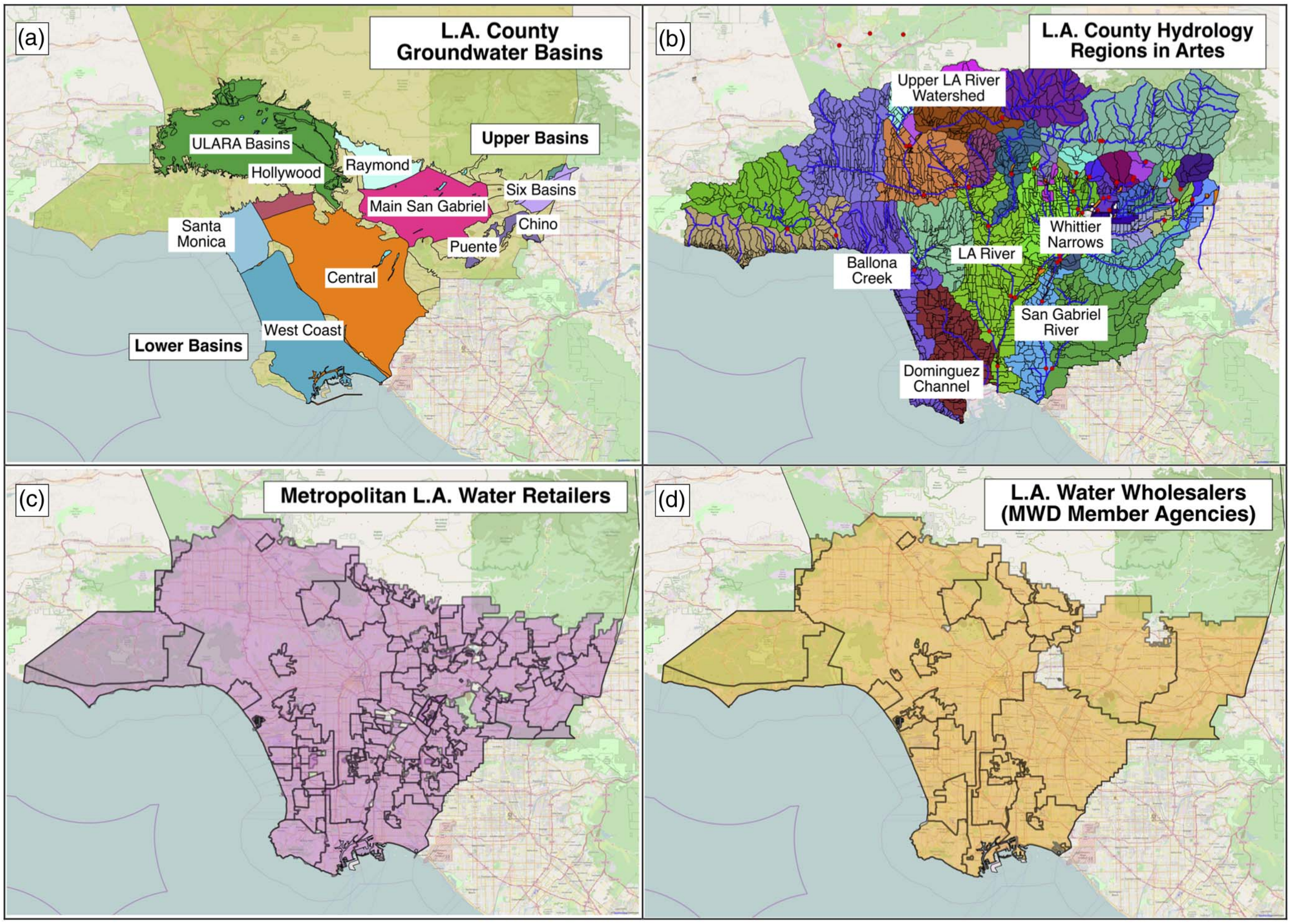


**Fig. 3.** Layers of urban water management in Los Angeles in *Artes*, including (a) groundwater basins; (b) hydrologic regions aggregated from WMMS to correspond with surface and infrastructure features; (c) water retailers; (d) municipal water district wholesalers

with available data at the time of development. It captures past droughts but does not reflect the most recent drought (2011–2016). The quickly evolving landscape of water data availability in California provides an opportunity to update the analysis with new data, emphasizing the need for flexible approaches.

Relevant data included groundwater pumping and recharge values, 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 time period of 1986 to 2010, with wastewater influent and effluent available for 1996 to 2010. Detailed descriptions of the data sources are provided in the Supplemental Data.

### Network Model Calibration

Calibration involved a multistep process. First, water distribution system losses, which included irrigation (evaporation, evapotranspiration, and groundwater recharge) and leakage, were calibrated for 2010, the only year with reasonable estimates of annual water supply and demand values across all retailers. 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 the sewer network pipe service areas (Fig. S1). For 2010 estimated monthly demands, the percentage of losses was determined as the difference between the total inflows and total outflows in a service region. Based on the treatment flow networks, Los Angeles County was aggregated into two regions: (1) the Los Angeles County joint service area comprised of eight treatment and recycling plants, and (2) the City of Los Angeles area comprised of four plants, the Edward C. Little recycling facility that accepts inflows from several sources, the Tapia treatment facility in the Las Virgenes Municipal Water District, the Santa Monica recycling plant, and the Burbank reclamation plant. This resulted in aggregating retailers into two main groups feeding each system. Delineating losses with higher spatial resolution was not possible because of routing within the interlinked sanitary sewer systems and limited data. Analysis determined that in the Los Angeles County collection network, urban system losses ranged from 33 to 55%, with higher values in summer months. In the City of Los Angeles collection system including Los Angeles, Burbank, Glendale, and others, losses ranged from 1 to 34%. As comparison, a limited survey of Los Angeles County water retailers reported up to 4% losses from leaks alone, though this is likely a low estimate (Naik and Glickfeld 2015).

Next, simulated runoff, evapotranspiration, and infiltration data obtained from outputs of a WMMS model run was compared to actual stream flow records for the downstream gauges in regional watersheds: Malibu Creek, Ballona Creek, Los Angeles River, and San Gabriel River. The WMMS model includes surface hydrology features, spreading basins, and flood control dams. Calibration results verified the accuracy of the underlying hydrologic model for the Los Angeles River and San Gabriel River watersheds without wastewater treatment plant (WWTP) outflows, with Nash-Sutcliffe



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**Table 1.** Statistics for Comparing Modeled and Measured Flows in San Gabriel and Los Angeles River Watersheds to Demonstrate Accuracy of WMMS Hydrologic Model

| Watershed | Mean | Standard deviation | Nash-Sutcliffe (all months) | Nash-Sutcliffe (summer) |
|---|---|---|---|---|
| | | San Gabriel River Watershed | | |
| % Diff: Gauge versus Model | −54% | +/− 51% | 0.604 | −0.341 |
| % Diff: Gauge versus (Model + WWTP outflows) | 12% | +/− 31% | 0.794 | 0.50 |
| | | Los Angeles River Watershed | | |
| % Diff: Gauge versus Model | −72% | +/− 41% | 0.790 | 0.736 |
| % Diff: Gauge versus (Model + WWTP outflows) | 25% | +/− 52% | 0.767 | 0.788 |



efficiency (NSE) of 0.790 and 0.604, as shown in Table 1. But WMMS does not include outflows from wastewater treatment and water reclamation plants (WRPs), which spill treated wastewater outflows into the surface water network. Adding WRP outflows to the WMMS watershed flows according to the drainage network (Fig. S3) increased the accuracy of WMMS for the San Gabriel River compared to gauge data (NSE = 0.794), but slightly decreased it in the Los Angeles River (NSE = 0.767). However, seasonal effects are important. When just considering summer months, adding WRP effluent flows increased accuracy for both watersheds (Table 1). For the Ballona Creek watershed, which has no WRP outflows upstream of its gauge, the NSE of modeled flows in all months was 0.163 but increased to 0.402 for just summer months. As shown in Fig. 4 and Fig. S4, WMMS results overestimated peak runoff volumes, likely related to calibration procedures. Additional details are provided in the Supplemental Data.

Third, after verifying the WMMS hydrologic model for use in the altered system with WRP outflows, WMMS monthly results for precipitation and total outflow were imported into the *Artes* database. 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.

This multistep approach, which was necessary because of the lack of more specific data on losses, has two limitations. First, calibrating loss rates using 2010 data could underestimate reuse in scenarios with reduced demands. Presumably, lower demands result from conserving outdoor water that contributes to loss rates. A city with less outdoor irrigation may also have lower loss rates than historic values. Second, the optimization does not include a full hydrologic model balance because accurate estimates of evapotranspiration and groundwater recharge are not yet incorporated into a calibrated model for Los Angeles County. For the period of 1996 to 2010, system losses were calibrated by constraining outflows within a range of tolerance [75–125%, see Eq. (11) in Supplemental Data] to actual outflows.

### *Analysis Procedures*

The network model was run over multiple iterations with varying levels of water demands and imported water supplies, creating a matrix of outcomes for quantifying shortages, groundwater pumping, stormwater recharge, and imported water flows. Scenarios of demand and imported supply were chosen to create a grid of equal intervals. Model runs varied imported supplies (0–100% of historic) and demands (60–100% of 2010 reported values) to develop a landscape (Fig. 2) of scenarios that address the dynamic nature of the local supply question.

Scenarios were defined by manually altering input data or *Python* source code. In total, 55 model iterations were run to create the landscape of outcomes. The objective function multiplication factor ($c$) relating local supply flows and shortages was set at 100

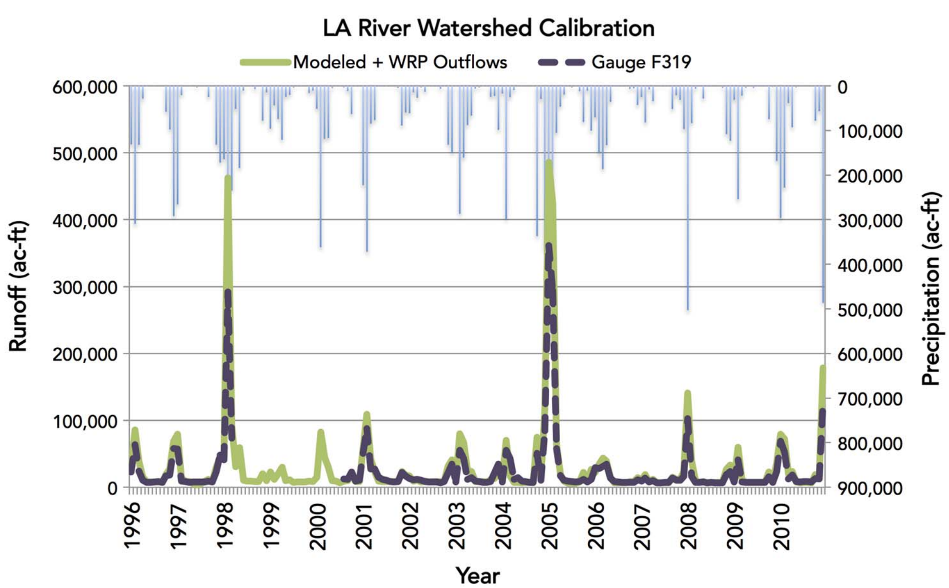


**Fig. 4.** Comparing modeled and actual stream flow values for the Los Angeles River; dashed lines represent actual stream gauge data, while solid lines represent modeled data that combine runoff and treatment plant outflows; precipitation is seasonal, as shown by bars

to minimize shortages in the baseline case (100% demands and imported supplies) and kept constant through runs.

An additional model run scenario was developed to test a water budget approach to urban water planning. The authors call this the sustainability planning (SP) scenario. For each retailer, reported populations (2010, corresponding with water demands) were used to determine the total water demand of a retailer based on (1) minimum supplies for health, safety, and indoor uses set at 50 gallons per capita per day; (2) commercial and industrial (CII) demands based on 2010 data; (3) existing urban tree canopy needs, based on experimental data for the City of Los Angeles and extrapolated to Los Angeles County, and calculated as a per capita monthly value; and (4) efficient ground cover landscapes. The SP demands were then analyzed across several scenarios of imported water. Specific methods to calculate this scenario are provided in the Supplemental Data.

Postprocessing software calculated statistics of flows for annual groundwater pumping, stormwater capture, recycled water, imported water use, and other flows, which were compared to historic annual and, when available, monthly values. Maps were generated to identify likely shortages faced by retailers across scenarios of historic supply and demand (including reductions of years that were already drought years with low imports) given current infrastructure, institutional arrangements, and laws.

As noted, while the model does include the potential routing of water to vadose zone nodes for groundwater infiltration, *Artes* is not intended to reliably estimate or report total groundwater storage. While many of the Los Angeles County groundwater basins have existing models and monitoring wells that groundwater masters use to regulate pumping, safe yield estimates are decades old and many basins are currently drawn down, raising questions about the future viability of current operating assumptions. In particular, previous estimates of natural recharge included less imperviousness from urbanization. Moreover, WMMS and other existing regional models all simplify surface-to-groundwater infiltration and subsurface flows. Thus, instead of reporting a maximum potential value of groundwater infiltration like other models, which could perpetuate high expectations of water use, this analysis compares results to past pumping and recharge, which gives an indication of the likelihood of overdraft. Results best represent a target for required known recharge via stormwater capture and recycled water infrastructure.

Notably, *Artes* does not report optimal solutions. The formulation and constraints typically result in a primal infeasible solution, i.e., no solution exists that satisfies all of the requirements. Constraints for observed flows in subwatersheds and demands for some smaller retailers such as mutual water companies and selected municipal utilities cannot be met through the model configuration based on available data. *Gurobi* uses the Simplex method to solve linear programming problems. Upon determining infeasibility for the current basis, *Gurobi* iterates through pivots until identifying a feasible solution for the dual or primal problems. For this analysis, *Gurobi* consistently identified a feasible solution to the dual problem while the primal problem remained infeasible and thus not optimal because noted constraints are not met. Presented results are feasible dual problem solutions that, despite nonoptimality, yield insights for urban water management. Relaxing key constraints could improve performance.

## Results

For each model run scenario, key metrics of annual averages are calculated and then compared across scenarios (Table 2), including relative percentage of supplies from each source (imported water, groundwater, recycled water), the percent of annual water demands covered by managed aquifer recharge, the percent of shortages in relation to demands, and per capita consumption. Results are best

**Table 2.** Summary of Average Annual Results from Optimized *Artes* Model Scenarios with Varied Percentages of Total Demands and Historic Imported Water Supplies

| Field | Scenario A | Scenario B | Scenario C | Scenario D | Scenario E | Scenario F | Scenario G |
|---|---|---|---|---|---|---|---|
| Demand (%) | 100 | 100 | 100 | 80 | 80 | 60 | SP |
| Imported water supply (%) | 100 | 50 | 0 | 50 | 20 | 40 | 70 |
| Average annual volumes (acre-ft) | | | | | | | |
| Groundwater pumping | 659,332 | 668,692 | 668,692 | 665,226 | 664,432 | 660,340 | 518,484 |
| Managed aquifer recharge | 533,690 | 447,413 | 446,619 | 493,158 | 457,142 | 568,479 | 521,712 |
| Imported water for recharge | 14,743 | 0 | 0 | 570 | 51 | 2,580 | 13,753 |
| Spreading grounds intake | 889,166 | 798,222 | 805,205 | 828,033 | 807,886 | 844,076 | 896,811 |
| Net groundwater extractions | 125,642 | 221,279 | 222,073 | 172,068 | 207,290 | 91,861 | −3,228 |
| Imported water use | 1,138,102 | 572,788 | 0 | 570,468 | 228,611 | 455,324 | 797,345 |
| Reuse (nonpotable or IPR) | 141,526 | 163,923 | 119,183 | 153,986 | 147,227 | 109,919 | 64,457 |
| Surface supplies | 15,119 | 15,585 | 15,585 | 12,538 | 11,983 | 8,636 | 7,811 |
| Total demand | 1,693,834 | 1,693,834 | 1,693,834 | 1,335,067 | 1,335,067 | 1,016,300 | 1,181,460 |
| % Supply source of total annual supply | | | | | | | |
| % Supply as imported (%) | 58 | 40 | 0 | 40 | 22 | 37 | 57 |
| % Supply as groundwater (%) | 34 | 47 | 83 | 48 | 63 | 54 | 37 |
| % Supply as reuse (%) | 7 | 12 | 15 | 11 | 14 | 9 | 5 |
| % Supply as surface water (%) | 1 | 1 | 2 | 1 | 1 | 1 | 1 |
| SW capture as % of supply (%) | 44 | 43 | 44 | 52 | 54 | 68 | 62 |
| % Shortages (%) | 5 | 25 | 58 | 12 | 32 | 3 | 10 |
| Per capita use, GDP, based on total demands (total deliveries) | 151 (172) | 151 (125) | 151 (70) | 121 (123) | 121 (92) | 90 (109) | 105 (122) |

Note: Baseline scenario has 100% of demands and imported water supplies. Scenarios with 80% (of 2010) demands are close to actual 2015 drought reductions. The sustainability planning (SP) scenario uses 30% less imported water than the baseline.



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interpreted in relation to the optimized baseline scenario (100% of 2010 demands and 100% of historic imported water supplies).

### *Baseline Scenario: Demands and Supplies*

In the optimized baseline scenario shown in Column A of Table 2 (100% of 2010 demands and 100% of historic imported water supplies), total reported annual demands across Los Angeles County are 2,085 mcm (million cubic meters) [1.69 million ac-ft (acre-feet)], which equates to an average of 151 gallons/person/day (gpd). These demands are consistently met, with an average annual shortage of 5% [at least 81.4 mcm (66,000 ac-ft)] resulting from discrepancies between demand and known supplies in the current system. No data exists for supply sources of very small retailers, while a few retailers in the county use more water than they are guaranteed access to purchase.

Imported water is the largest percentage of average annual supplies (58%), followed by groundwater (34%) and reuse that includes nonpotable and IPR (7%). These numbers are close to historic 2010 values, indicating how current infrastructure, institutional arrangements, and water demand expectations constrain local water supply goals (Pincetl et al. 2016). Average annual groundwater pumping [813 mcm (659,332 ac-ft)], which is maximized as a local source, is close to the total assessed operating safe yield of the adjudicated basins [795 mcm (644,655 ac-ft) annually]. Yet, average annual net groundwater extractions, which are the difference between pumping and managed recharge, are 154 mcm (125,642 ac-ft), indicating potential long-term overdraft. Imported water traditionally supported operating yields higher than the assessed native safe yield [514 mcm (410,000 ac-ft) annually]. Notably, several groundwater basins in Los Angeles are currently drawn down (WRD 2015).

Influent flows to water recycling plants averaged 125% of historic values [504 mcm (409,000 ac-ft)]. Actual water reuse (nonpotable and IPR) in model results averaged 173 mcm (141,000 ac-ft) and comprised 7% of total demands, with the difference revealing constraints in distributing recycled water. This does not include several projects currently underway to increase local reuse. Modeled flows to water reuse plants are higher than historic values, while the larger downstream Hyperion wastewater treatment plant sees reduced flows (Fig. S5). The desire to capture more water upstream for reuse and recharge drives this trend, which could ultimately increase treatment costs, make more concentrated effluent downstream, or yield stranded assets.

### *Baseline Scenario: Managed Aquifer Recharge and Ocean Outflows*

Total annual managed aquifer recharge in the optimized baseline scenario, which includes both captured stormwater and diverted recycled water, averaged 44% of total demands [931 mcm (755,000 ac-ft)]. This volume exceeds the historic annual average of 247 mcm (200,000 ac-ft) and represents an annual increase of 200% or more across years. The annual value is higher than historic, but not unreasonable. The largest recorded annual capture volume was 810 mcm (657,000 ac-ft) (2004–2005) and analysis indicates the total volume of potential stormwater capture from current infrastructure in the Los Angeles River and San Gabriel River watersheds (based on seven months) is over 814 mcm (660,000 ac-ft) (USBR 2014). In model results from the baseline scenario, the average annual capturable runoff, calculated by summing both recharge and overflow discharges from spreading grounds, was much larger [1,097 mcm (889,000 ac-ft)], revealing infiltration capacity constraints. Imported water contributed more to recharge in wetter years. The results can usefully be interpreted as the necessary volume of managed recharge, through either centralized or distributed facilities, which is known to reach drinking water aquifers. Finally, annual outflows to the Pacific Ocean through river mouths were 863 mcm (700,000 ac-ft).

### *Comparing Scenarios*

Comparing results from 55 model runs across scenarios of demand and imported supplies shows how shortages and the relative percentage of local supply sources vary (Fig. 5). Cutting imports by 50% or more without significant conservation (>20%) yields both shortages and groundwater overdraft, as shown in Columns B, C, D, and E of Table 2. Groundwater pumping and managed recharge are consistent across scenarios as optimized local supply sources. Cutting imports by 50% or more also eliminates available imported water for spreading grounds, which resembles current conditions in

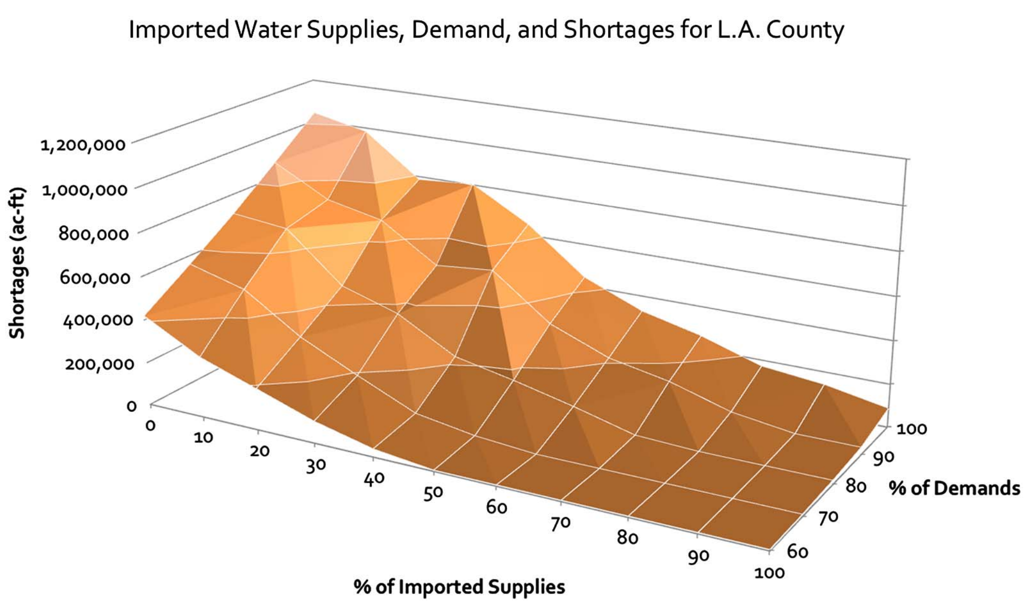


**Fig. 5.** Results from 55 model iterations showing relationships between imported water availability, demand reductions, and shortages for all retailers across Los Angeles County



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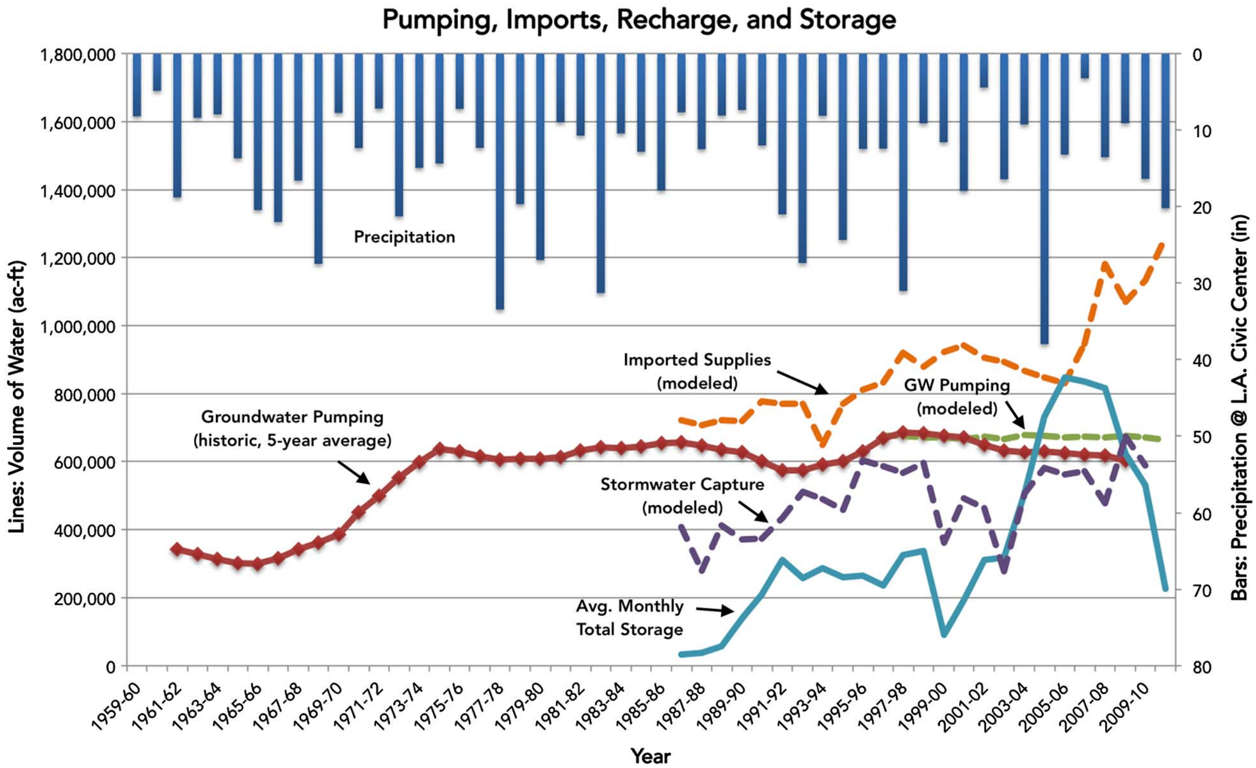


**Fig. 6.** Comparing modeled and historic sources of water supply in Los Angeles County for a scenario of reduced imported water availability (80% of historic) and full demands (based on 2010)

most years. Even cutting imported water by only 20% without conservation increases average annual shortages by 5%, ranging from 83 to 392 mcm (68,000 to 318,000 ac-ft) annually (4–18%) and concentrated in dry years (Figs. 5 and 6). Stated differently, cutting imported water by 20% exacerbates shortages during dry years or when supplies are diverted to reservoir storage. Without 30% conservation, groundwater overdraft likely ensues in the current system. Despite more recharge, in most scenarios of reduced water imports, conservation under 20% of the baseline yields long-term groundwater overdraft, as shown in Fig. 7 and Table 2. Total demand in the 80% demand scenarios is close to the 2015 conservation numbers in Los Angeles County that resulted from contingency plans during an historic drought. Scenarios where imported supplies exceed demands cause discontinuities in the results, as shown in Fig. 7.

Shortages vary by geography and are related to the supply sources of various agencies. For instance, in a scenario with 80% of 2010 demands but only 20% of available imported water supplies, areas of the coastal plain experience the greatest average annual shortages by volume, with LADWP showing the highest shortages [Fig. 8(a)]. However, when considered as a percent of total demands smaller agencies, including mutual water companies and county water districts, also rank high. This demonstrates the vulnerability of smaller agencies that rely on a limited number of supply sources [Fig. 8(b)].

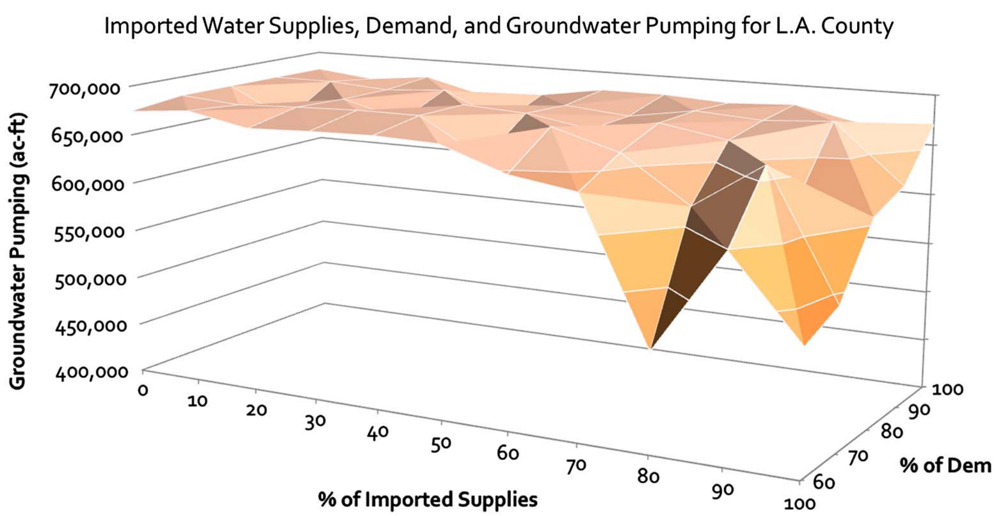


**Fig. 7.** Relationships between imported water supplies, demand reductions, and groundwater pumping across model scenarios; dashed lines show operational and native safe yield for pumping from adjudicated groundwater basins in Los Angeles County



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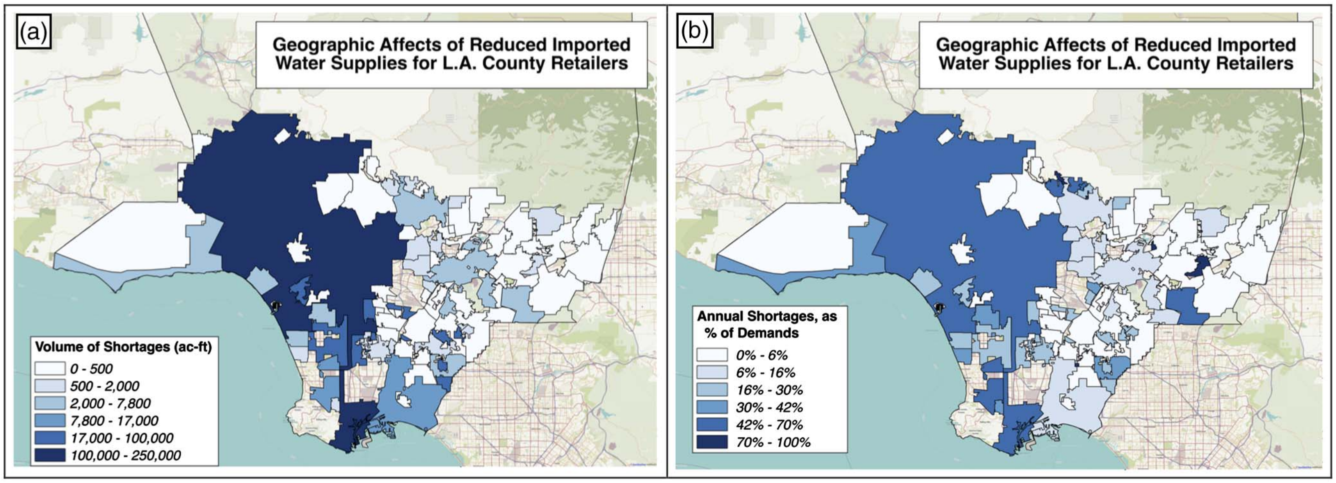


**Fig. 8.** Geographic distribution of shortages among Los Angeles County retailers for a model scenario of 80% of demands and 20% of imported water supplies (Table 2), shown as (a) volume of shortages (ac-ft); (b) shortages as % of annual demands

### *Sustainability Planning Scenario*

For the sustainability planning scenario, where demands include efficiency improvements for indoor uses and outdoor irrigation that supports existing trees and low-water landscapes, total demands are estimated to be approximately 71% of 2010 numbers, which equates to 105 gpd. Using those demands in *Artes,* results show that in the current system of water transfers and infrastructure, imported water supplies could be cut by 30% with low risk of long-term groundwater overdraft and relatively small shortages [148 mcm (120,000 ac-ft)] primarily caused by mismatches in allocations (Column G in Table 2). Managed aquifer recharge again significantly exceeds historic values (Fig. 9). Reuse is lower than other scenarios, while shortages increase by a modest 5% over the baseline (Table 2). Additional model runs indicate that imported water reductions of 40 to 50% for SP demands are within reach. Changing institutional arrangements (water transfers and groundwater rights), or increasing supplies from wastewater reuse or stormwater capture by 247 mcm (200,000 ac-ft) annually could meet demands with a low-risk of groundwater overdraft, even with 50% reduction of historic imports.

## Discussion

Model results yield synthetic insights that demonstrate tradeoffs and address important policy implications, as described in Table 3.

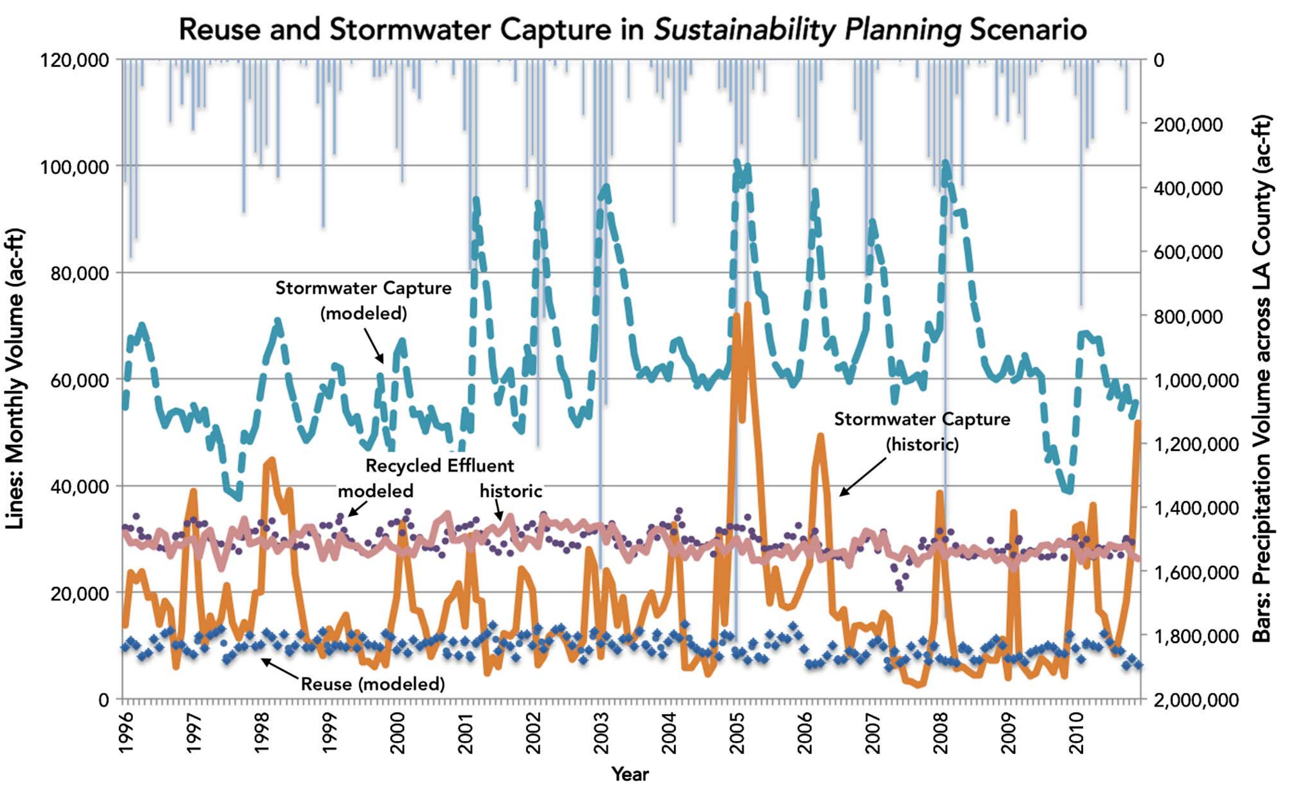


**Fig. 9.** Alternative water supply sources for Los Angeles County in the sustainability planning scenario



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**Table 3.** Summary of Key Insights and Policy Implications from *Artes* Results

| Insight | Description | Policy implications |
|---|---|---|
| Institutions and path dependence | Maximizing local supplies in the current management system resulted in a supply portfolio closely resembling 2010, illustrating expectations of demand, institutionalized water transfers, and groundwater rights inhibit greater use of local water in the current system. | Building new infrastructure without addressing institutional arrangements would likely result in vulnerability for some retailers and residents. Updating groundwater rights and transfer agreements alone could decrease shortages in a future of reduced imported water availability. |
| Preventing groundwater overdraft | Business as usual in the current system yields likely groundwater overdraft. Reducing demands by more than 20% and boosting stormwater capture by 300% can inhibit this risk. | Better scientific information and modeling tools, namely models of distributed recharge and regional coupled surface-to-groundwater flows, are necessary to manage aquifers. |
| Replacing imported water | Reducing water imports increases the percentage of supply from groundwater and other sources. With no imports, groundwater makes up nearly 80% of total supplies and reuse comprises 22%, but chronic shortages arise (45%). | Alternative supply sources are finite. Reducing imported water results in a system with new timing and flows of water. Using local sources multiple times in a year becomes necessary. Reducing imports, though, would benefit aquatic ecosystems and hinterland areas where dry-climate cities get water. |
| Short-term versus long-term conservation | Conservation frees up available imported water to be recharged and stored in reservoirs and groundwater basins. Possible limits of conservation (urban water demand hardening) have not been reached in Los Angeles. | Conservation as a way of life is necessary, but many current retailers rely on drought shortage contingency plans for authority to take conservation measures.When imported water is available in years with rainfall, it can be stored in reservoirs and groundwater basins. |
| Changing effluent flows | Promoting stormwater capture, conservation, and water reuse reduces flows to larger downstream wastewater treatment plants and increases flows to smaller, upstream plants. | Less water in the system from reduced imports results in fundamental changes to the timing and location of flows, even possibly sunk investments. |
| Stormwater as indirect source | As demands lower, the role of stormwater increases. But stormwater is primarily an indirect source used to recharge groundwater, not part of a direct supply portfolio, in current schemes. | The timing of infiltration and pumping determines how much and often stormwater can be used as a supply. Better data and models can reduce uncertainties around the volume of recharge that reaches drinking water aquifers. |
| Urban ecology | Understanding ecology in urban landscapes, namely water use needs for native and imported plant and tree species, can help in devising better targets for outdoor urban demand. | Outdoor water use accounts for 50% of urban demands in California. Urban water utilities must gain more ecological expertise to devise effective water budgeting approaches. |
| Systems analysis | As clean available water supply is a necessary resource for cities, urban water systems analysis must incorporate institutional and social considerations. | In future arid climate cities, urban water managers have the task of simultaneously understanding technologies, people, plants, and plants as part of an integrated systems view. |

The results are also subject to a number of limitations. First, modeled processes are not all fully coupled. Feedback is limited to continuity equation calculations within and between time steps that maintain the volume of water and does not link demand reductions to changes in evapotranspiration. Second, the current model does not incorporate economics or explicit water quality requirements, which drives many decisions regarding public spending for urban water systems. Third, as noted previously, *Artes* does not include a linked representation of surface and groundwater flows, so reasonable estimates of recharge that reach drinking water aquifers are limited to spreading basins. Countywide estimates of incidental recharge, termed *native safe yield* in groundwater adjudications, total 514 mcm (417,000 ac-ft) annually, though the decade-old estimates are uncertain due to changing land uses and irrigation practices. Fourth, model results may overestimate stormwater capture because as a monthly model, there is not sufficient temporal resolution for extreme hydrologic events. Modeled recharge volumes in *Artes* are better interpreted as a regional goal for the quantity of water known to reach drinking water aquifers through both centralized and distributed means. Fifth, data limitations include monthly demand estimates for retailers, population estimates, per capita calculations, and system losses (infiltration, evaporation, and leakage). System losses do not include losses in wastewater treatment plants, while recently improved data collection procedures for California water agencies offer better estimates of per capita consumption. Sixth, *Artes* is not currently a forecasting model and does not include future population growth. The relationship between population and water use in Los Angeles may change with many factors, including densification. To minimize assumptions, a stated goal, the analysis uses recent demands and population estimates. Finally, model results may underestimate potential reuse in scenarios with lower demands, as distribution system loss rates are calibrated based on current demands with higher outdoor uses, but scenarios with lower demands presumably include outdoor water use conservation and lower loss rates.

Results highlight the need for better data and scientific information in key areas of urban water management. For instance, groundwater recharge (from natural and irrigated infiltration), which in turn affects quantifications of stormwater capture and infiltration, is a significant uncertainty. Better knowledge of urban hydrogeology, and its relationship to urban form, is required to protect and enhance watersheds and drinking water aquifers in urban areas (Fink 2011). Calculating accurate urban water balances, given uncertainties in surface-to-groundwater recharge, is challenging. Even as cities look to use landscapes and distributed stormwater infrastructure, underlying knowledge of surface-to-groundwater infiltration inhibits the ability of agencies to fund such programs across agency siloes. Beyond urban hydrogeology, too, data shortfalls abound. Account-level usage, indoor versus outdoor consumption, and flows in water supply and wastewater pipe networks are all critical pieces to integrated systems analysis, but fragmented data sets across public utilities and private companies makes integrated urban water management challenging. Not only siloed expertise, but also siloed data, is a challenge for future operations.

The SP scenario demonstrates the possibility of institutionalizing water conservation while still protecting economic security, urban amenities, and groundwater basins. It also shows that there is no free water. In the current system, demand reductions lead to a nearly 1:1 possible reduction in imported supplies. This occurs in the context of a system built on imported water, where some retailers would disproportionately experience shortages without access to groundwater or recycled sources. Either institutional or infrastructure solutions are necessary to meet more extensive local water supply goals.

Urban water demand hardening describes a phenomenon where successful past conservation measures make future savings more difficult to achieve. Over time, a lower floor of water use is achieved across urban water users. While such a floor associated with an industrialized dry-climate city does exist, Los Angeles County has not reached it. Demands in the base case scenario with imported water (2010) were 150 gpd, while consumption in the SP framework averaged 105 gpd across the county. By comparison, cities in Australia achieved total per capita urban water consumption levels of 63–106 gpd in recent droughts (Cahill and Lund 2013). Any lower limit is likely to change over time. Water use habits of urban residents are shaped not only by water prices and lot sizes, but also by changing social norms and regulations. Public sentiment can and does change. For these reasons and more, urban water managers must collaborate more with ecologists and planners to understand coupled linkages inherent in sustainable water planning if dry-climate cities are to exceed expectations of urban water conservation.

## Conclusions

Expectations of water supply and use in Los Angeles are changing. Spurred by financial pressures and growing water scarcity, some agencies are now planning for a future of reduced water imports. This study presented a model using optimization to assess the degree to which metropolitan Los Angeles can reduce its reliance on imported water. Using a network flow model, results illustrated key relationships, tradeoffs, and systematic insights for urban water management across the hundreds of water agencies in Los Angeles County.

The combination of increasing annual stormwater capture by an average of 300%, increasing current reuse, and reducing demands to 105 gpd allows for a 30% reduction of imported water that protects economic security, urban landscapes, and groundwater resources. Additional cuts to imported water are possible with more conservation, investments in reuse and aquifer recharge, and reallocation of groundwater rights. Achieving more than 50% reduction requires significant new reuse and stormwater capture (distributed and/or centralized) infrastructure. Reducing water imports without conservation increases groundwater reliance and increases risk of overdraft.

The analysis demonstrates the usefulness of *flexible* and *adaptive* modeling approaches that can change over time with new models, data, and scientific information. Future research should continue to characterize key system uncertainties, including losses to leaks, evaporation, evapotranspiration, and groundwater recharge, along with better representation of coupled surface-to-groundwater flows. Studies could incorporate forecasting scenarios to consider future population and water use trends. They could also assess costs and benefits of scenarios, both economic such as fee-for-cost and environmental including monetized benefits or assessments of greenhouse gas emissions. Finally, future studies can examine important regional questions, such as the potential for planned water recycling projects, groundwater storage pools, or new institutional arrangements to alleviate scarcity.

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## Supplemental Data

Figs. S1–S6 and Tables S1–S9, and other material are available online in the ASCE Library (www.ascelibrary.org).

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