nature sustainability

ARTICLES

https://doi.org/10.1038/s41893-018-0068-2

The economic value of local water supplies in Los Angeles

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Los Angeles imports water over long distances to supplement local supplies. Reduced reliability of the available imports is driving many local agencies to promote conservation and enhance local water sources. These include stormwater capture, water reuse and groundwater. But financial considerations are often a significant impediment to project development, especially when comparing new and existing sources. Here we demonstrate a comprehensive approach for evaluating the economic implications of shifting to local water reliance in Los Angeles County. We show that local water supplies are economically competitive. Results from integrated hydroeconomic modelling of urban water in Los Angeles identify cost-effective water supply portfolios and conservation targets. Considering costs across the 'full-cycles' of urban water supply that span agency boundaries yields better comparisons of planning alternatives. Throughout the region, many water retailers could successfully mitigate effects of imported water cuts while still supporting drought-tolerant landscapes, but some would suffer due to over-reliance on imports. Updating economic assessment methods would support needed innovations to achieve local reliance in Los Angeles, including infrastructure investments, institutional reforms, many more drought-tolerant landscapes and reallocated groundwater rights.

In western North America, massive infrastructure systems convey water over hundreds of miles to support cities, farms and economic growth. The systems were twentieth-century solutions to seasonal water scarcity, but today imported water supplies are strained. Cities are looking to water conservation and local sources of supply as future solutions. But integrated planning remains a challenge. Here, we assess economic implications of transitioning to local water supply reliance. We enhance an integrated model (Artes) of urban water management in Los Angeles County (LA County) with annualized costs for water supply sources (local and imported) and water conservation. We model cost-effective options for mitigating the effects of imported water cuts affecting nine million people within a hundred agencies, and denote associated policy options. The approach allows for a more holistic assessment that improves upon current studies, which typically compare nominal and annualized prices of different options. The concept of urban water supply trains, which include the multiple steps of acquiring, treating, distributing, and discharging or reusing water, is presented to understand emerging cycles of water supply. The analysis enhances current studies that often emphasize single agency perspectives, but also shows how existing assumptions and infrastructure shape what appear to be cost-effective options.

Systematic studies of urban water management necessarily include many aspects of operations[1–4]. Engineered pipe and channel networks move surface water and runoff. Water supply utilities build and maintain systems to keep taps running. Complex networks of agencies oversee the acquisition, distribution and use of urban water and wastewater[5,6]. Landscapes and outdoor water use are especially important drivers of water demand in California, as half of urban water use goes to irrigation and trees[7–10]. Economics and social attitudes shape the expectations of residents and utilities for water supply. In many cities across the globe, climate change and population growth will test operating assumptions in the current systems[11].

Los Angeles County is an immense laboratory for exploring the future of urban water in seasonally dry climates (Fig. 1). The county currently receives 55–60% of its annual water supplies from imported sources, which include northern California through the Sacramento–San Joaquin Delta, the Colorado River basin, and the higher-altitude Owens Valley. The remainder comes from local sources, including groundwater pumping, recycled water (non-potable or indirect recharge) and stormwater capture[5,12,13]. Of the water imported to southern California by the giant Metropolitan Water District of Southern California (MWD), Los Angeles County agencies receive approximately 40%. The City of Los Angeles receives additional imports from the Owens Valley. A shift to becoming primarily reliant on local sources is significant in a region famous for its efforts to import water[14–16].

Previously, to understand the feasibility for transitioning metropolitan Los Angeles to a water supply regime dominated by local sources, we assembled research spanning engineering, ecologic and sociologic aspects of urban water management[5,9,10,17–22]. Key aspects of the work were synthesized in an integrated urban water resources model, Artes, which simulates the agencies, landscapes, infrastructure and hydrology that make up Los Angeles's water systems with nearly 25% of California's population. Artes helps explore tradeoffs in conservation, imported water reductions and alternative supply sources, using optimization and a network structure of links and nodes to simulate flows across the vast metropolitan region[12,19].

Reported findings demonstrated that a water supply regime in Los Angeles highly dependent on local sources could still support urban life, existing trees and landscapes with native and drought-tolerant vegetation[9,10,12,19,21]. Understanding the real-world

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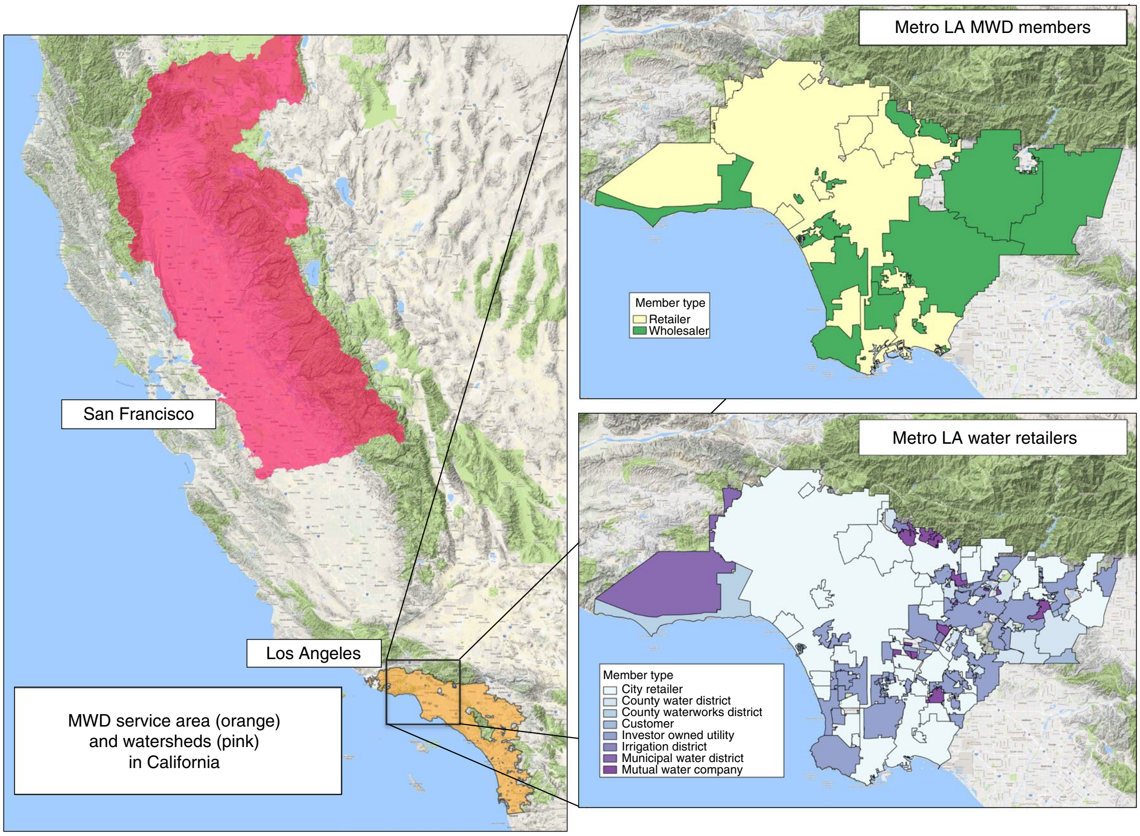

Fig. 1 | Hierarchy of water systems and supplies in Los Angeles. Sources: ref. [65] and California Center for Sustainable Communities at UCLA. Map data: ©2018 Google.

implications of this shift to local supplies required quantifying the effects of conservation and imported water reductions on residents, businesses and landscapes. For instance, the Artes model includes agency-specific water allocations (budgets) based on empirical assessments of outdoor residential water use linked to actual water needs of the Los Angeles tree canopy, along with commercial, industrial and indoor residential use. For the City of Los Angeles too, the largest jurisdiction and water user in Los Angeles County, conservation and modest infrastructure investments can go far in meeting stated local supply goals[21]. The model code and data are openly available[12].

Here, we analyse economic implications of transitioning to local water supply sources. Many of the barriers, economic or others, to local supply reliance and new infrastructure in Los Angeles County are actually institutional, related to current agency structures that segment urban water flows and funding. Notably, nearby regions of southern California offer similar lessons and progress, having promoted water reuse and stormwater capture at the watershed scale to an equal or greater extent[23,24]. The challenge for metropolitan Los Angeles is not water scarcity, but water allocations and accounting procedures across an enormous number of agencies. To finance new urban water systems, local agencies must reconfigure procedures and reorganize[25]. Such challenges, however, are not new. The need to improve planning in fragmented metropolitan and resource governance systems is recognized[4,26–28]. Los Angeles is a well-studied example in this regard. Starting in the 1930s, agencies organized to pay for imported water and improve groundwater management[29,30]. Rethinking once again current operating assumptions is a critical area for innovation[31]. Accounting procedures and associated institutional innovations that influence the financial viability of various options are an important component.

Economic advantages of local water supplies

To investigate the economic implications of shifting to local water supplies in Los Angeles County, we expanded Artes to include (1) a hydroeconomic framework with costs (prices), benefits, and estimated monetary losses from residential water conservation, and (2) new upgrades to managed aquifer recharge and water reuse infrastructure as identified in regional planning documents[32–34]. Such data are found across many sources (Table 1) and are typically not compiled and reported together with sufficient detail across geographic scales in Los Angeles.

Both the accounting procedures and the time frames used in economic assessments make a significant difference in projecting cost-effective options. Comparing annualized estimates of supply costs by source, based on historic inflation (2%) and rate increases (3–7%), local sources appear cost-competitive and the reported unit costs quoted in public discussions, which often mix current and long-term annualized costs for various supply sources, do not provide good comparisons. Current prices for treated imported water through MWD appear cost-effective, but when costs are annualized (considered over a longer time period of 20 years that includes future rate estimates based on historic increases) greater cost parity emerges across sources. Using annualized numbers, many existing local sources, including managed aquifer recharge through stormwater capture and non-potable recycled water, are already cheaper. In addition, the cost of MWD imported water through the currently debated large-scale project to reconfigure conveyance within the Sacramento–San Joaquin Delta, California WaterFix, is likely to further increase the unit costs of imported water, with estimates varying from \$0.12 to \$0.32 per m^3 (\$150–400 per acre-foot, or ac-ft)[35,36]. Table 2 reports ranges for unit costs associated with supply sources and conveyance in Los Angeles County from the collected sources.

Table 1 | Data sources for costs and benefits of each stage in water supply

Cost of supply/shortage source	Data sources
MWD imported water (tier 1 treated)	Ref. [56]
MWD imported water following 'Delta Tunnel' upgrades (estimated for tier 1 treated)	Ref. [56]
Groundwater pumping	Refs [21,57]
Existing large stormwater capture	Ref. [59] and L. Alexanderson, Los Angeles County Department of Public Works, personal communication)
Proposed large stormwater capture upgrades	Ref. [59]
Existing recycled water	Refs [57,58]
Proposed recycled water upgrades	Refs [21,52,57]
Conveyance and water transfers	Ref. [52]
Cost of residential water shortages	Refs [37–39,64]

The estimates are based on reported prices, not summed costs for production, operations, and maintenance.

We also estimated economic effects of residential water shortages using a linear demand function method with retailer-specific domestic water rates. This yields an estimate of the perceived monetary loss to residents from reduced residential deliveries that specifically supply outdoor irrigation[37,38]. The unit value of economic losses varied by retailer, with estimates ranging from $0.41 to $3.46 per m^3 ($500−4,270 per ac-ft) based on standard methods using available data for median incomes, utility water rates, and published estimates of demand elasticity[38,39]. These were also annualized for a 20 year period based on assumed price increases.

Using these estimates of unit values for water supply costs and residential water conservation, optimization in Artes identified low-cost water supply portfolios given a proscribed cutback in imported water of 50% (see Methods and Supplementary Information for details). In other words, in the model scenario reported here, imported water was a limited resource. The result (based on summing costs, benefits and losses) was a supply regime that, on average, uses imported water for 37% of total supplies (Fig. 2a). To achieve this goal, regional stormwater capture, infiltrated into Los Angeles's sizeable groundwater basins using existing spreading grounds represented in the model, constituted more than 40% of annual demand, with 561 million cubic metres (mcm, or 455,000 ac-ft). This volume of infiltration is already achieved in some wet years across Los Angeles County with existing infrastructure. Further, water reuse is shown to comprise 16% of supplies and is primarily constrained by existing infrastructure. More details are provided in the Supplementary Information.

From the model results, the countywide use per person was 340 litres per capita per day (lpd, or 90 gallons per capita per day, gpd), which is close to our previous estimates based on a bottom-up methodology for quantifying water demands across sectors and species-specific outdoor water needs (Fig. 2b)[19,40]. Median per capita use across agencies was lower (287 lpd, or 76 gpd) because of variations in use throughout the county (Fig. 2). These variations result from two factors. First, the optimization procedure preferentially routes water through retailers with cheaper recycled water capacity to support recharge and non-potable uses. Several retailers involved in water recycling have per capita use higher than mean values. Second, some retailers (12% of those with reportable results in Artes) have unrealistically low resulting values of per capita deliveries that do not meet health and safety minimums. This occurs because these water providers are highly reliant on imported water and cannot get access to enough water given the modelled allocation limits based on actual interagency water distribution agreements. Such retailers will face significant shortages from imported water cutbacks without systematic planning, source diversification, and new groundwater pumping rights that would require reallocating regional agreements. These are all likely to increase the cost of water supply.

The analysis demonstrated several key points. First, residential outdoor water use conservation is highly effective for managing long-term reductions in imported water use. The resulting cost-effective estimate of per capita water use (340 lpd, 90 gpd) is close to values from our prior work, which determined that a regional water use target of approximately 378 lpd (100 gpd) could support existing trees and low-water landscapes, businesses and industries, and indoor use (Supplementary Information)[9,12,41]. Importantly, economic losses for residential outdoor water use cutbacks are included based on water prices, but replacing thirsty turf with drought-tolerant landscapes offers the opportunity to mitigate some or all of these monetized losses. The linear loss estimation method may underestimate losses from significant cutbacks, but changing expectations about the need for lawns, epitomized by significant demand for lawn replacement incentives during the drought, calls into question if any economic losses would actually accrue from new, well-planned landscapes.

Second, small changes in benefits applied to centralized stormwater capture activities affect long-term groundwater sustainability. In particular, slightly increasing the monetized benefits associated with stormwater capture in the model inputs makes a significant difference in long-term groundwater overdraft[16,21]. A 10% increase (as a percentage of unit cost) in monetized unit benefits attributed to centralized stormwater capture yields an additional 61 mcm (50,000 ac-ft) of infiltration. But the value of such benefits is not currently standardized across water utilities and groundwater basins, each of which has separate governance structures that include supervisory boards and groundwater masters in charge of overseeing pumping and recharge operations that allocate yields to pumpers based on codified allocations. Updating accounting procedures to include benefits of alternative sources would help promote innovations in regional management.

Accounting for full cycles of water supply in Los Angeles

Planning documents typically report the costs of various supplies, imported water, surface water, groundwater, and others, as single values. Imported water has a set price from the MWD, for instance. But in reality, water in cities flows through cycles. From this perspective, assessments should describe costs across the many steps involved in supply, treatment, conveyance, use and discharge or reuse. Including these many steps in analysis and reporting would more holistically assess the full cycles of water supplies.

Using this full-cycle perspective, multiple configurations of flows for urban water supply emerge, each with unique costs and stages (Table 3). We call these supply trains, a term that is analogous to the multistep processes (treatment trains) used to treat wastewater. For instance, a traditional supply train for imported water in Los Angeles includes input flows through aqueducts and surface reservoirs, purification in local treatment plants, storage, distribution to buildings, sewage collection and treatment, and discharge. A stormwater capture supply train for centralized groundwater recharge includes runoff capture and diversion to infiltration basins, groundwater recharge, groundwater pumping and water treatment, all with associated costs and time requirements. Current cost assessments of supply options, however, often focus on just one part of a supply train, such as conveyance and infiltration of stormwater runoff.

Table 2 | Current and annualized unit costs of water supply sources in Los Angeles County

Cost of supply/shortage source	Annual cost increase rate	Cost per m^3 (per ac-ft)		Benefits per m^3 (per ac-ft)[b]
		Current	Annualized[a]	
MWD imported water (tier 1 treated)	0.06	\$0.76 (\$942)	\$1.20 (\$1,476)	NA
MWD imported water following 'delta tunnel' upgrades (estimated for tier 1 treated)	0.06	\$0.93 (\$1,142)	\$1.45 (\$1,790)	NA
Groundwater pumping	0.07	\$0.28 (\$340)	\$0.47 (\$582)	NA
Existing large stormwater capture	0.04	\$0.16 (\$200)	\$0.21 (\$256)	\$0.03 (\$40)
Proposed large stormwater capture upgrades	NA	NA	\$0.30–1.61 (\$371–1,988)	\$0.03 (\$40)
Existing recycled water	0.06	\$0.29–\$0.85 (\$355–\$1,050)	\$0.45–1.33 (\$556–1,646)	NA
Proposed recycled water upgrades	NA	NA	\$0.83–1.65 (\$1,023–2,043)	NA
Conveyance and transfers	0.06	\$0.08 (\$100)	\$0.13 (\$157)	NA
Cost of residential water shortages	NA[c]	\$0.41–\$3.46 (\$500–\$4,270)	\$1.05–7.64 (\$1,300–9,437)	NA

Detailed sources are provided in the Methods and Supplementary Data.[a]Annualized costs were calculated over a 20-year period, except for unit costs extracted from the Los Angeles Basin Study for stormwater capture, which calculated unit costs based on a projected 50 year lifetime. [b]Benefits values based on existing large stormwater capture basins. [c]Rate of increase in shortage estimate related to assumptions of water rate increases.

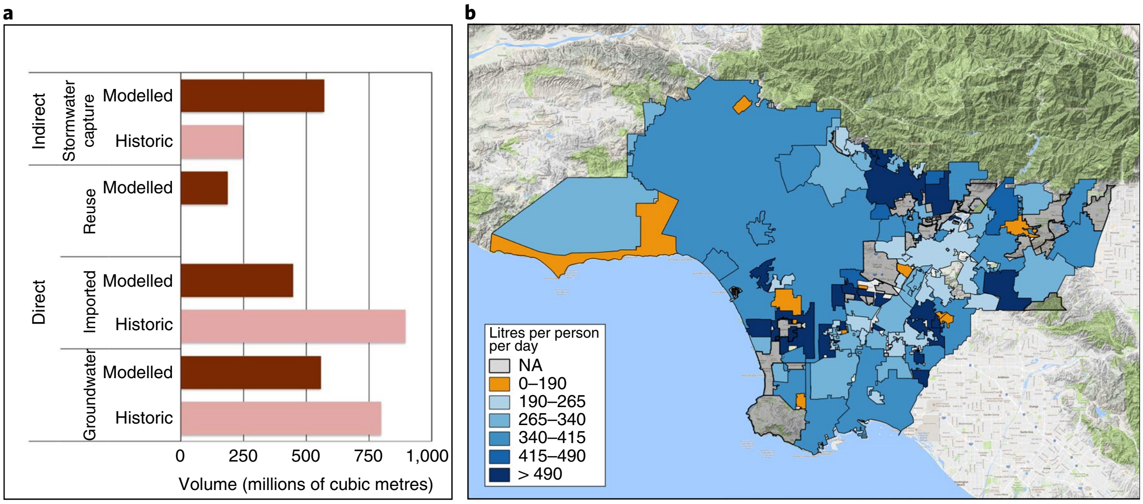

Fig. 2 | Model results. **a**, Average annual volume of water supply from each available source based on a 50% cut in historic imported water. **b**, The resulting modelled per capita use across Los Angeles water retailers, with vulnerable retailers in orange.

The network-wide optimization procedure in Artes takes into account the costs across cycles, and reveals the importance of equitably comparing traditional and emerging options[42]. Unlike typical practices that segment costs among agencies, costs are assessed from source to sink of flows, regardless of agency boundaries. In past eras, sinks were typically downstream watersheds or the ocean. Today, sinks may be upstream groundwater recharge basins, irrigated parks or even buildings. A locally reliant water supply regime would more closely resemble a closed-loop system, whereby a greater percentage of water is retained and recirculated in a basin rather than discharged to the ocean[43]. To function, access to local water storage capacity, namely groundwater basins in Los Angeles, becomes even more critical. Reducing wastewater and stormwater outflows reduces the need for upstream imports, provided that water can be moved quickly enough through successive stages of treatment, distribution, use, collection and treatment, and storage.

The implications of full-cycle accounting for water utilities are significant. For instance, groundwater pumping is one potential source of water and agencies plan for the associated direct costs of energy and conveyance for this supply source. But the full-cycle cost of groundwater supply also includes recharge, treatment, pumping and conveyance. Such duties are typically spread across agencies in Los Angeles, including stormwater agencies and mission-driven special water districts. The cost of groundwater for a water supply utility may include only pumping and conveyance, but comparing the costs of groundwater to imported water deliveries from the full-cycle perspective then incorporates the multiple steps of the supply chain to more realistically show the costs and benefits for the whole system.

Institutional fragmentation is a root driver of shortcomings in accounting for full-cycle costs. Fragmentation shapes how urban regions manage and pay for water services[6,27]. Benefit–cost analysis is essential for public decision-making, but more holistic accounting frameworks are needed for Los Angeles and similar regions to equitably deal with scarcity and better utilize local sources. Additionally, accounting procedures used to assess benefits and

Table 3 | Urban water supply trains for delivering water in Los Angeles from various sources

Supply train	Stages to end-use	Estimated total cost $ per m^3 ($ per ac-ft)	Notes
Imported water for supply	Capture and storage >> conveyance >> local storage >> treatment >> delivery	$1.20–1.45 ($1476–1,790)	Traditional water supply train based on modernist infrastructure model. Comprises ~60% of Los Angeles supplies today. Cost estimates are for delivery of treated water with and without SWP upgrades
Imported water for recharge	Capture and storage >> conveyance >> local storage >> conveyance >> infiltration	$1.08–1.33 ($1,325–1,639)	Traditional supply train to augment groundwater supplies. MWD discontinued a cheaper recharge rate, but can use untreated
Groundwater pumping	Pumping >> treatment >> conveyance >> delivery	$0.59 ($739)	Cost-effective and available supply source. Pumping rights were allocated decades ago to prevent overdraft. Recharge is the primary concern. Current basins have available storage capacity in Los Angeles
Existing large stormwater capture	Capture >> filtering and sedimentation >> spreading and infiltration >> pumping >> treatment >> delivery	$0.81 ($995)	Centralized capture and recharge practised and monetized for decades in Los Angeles. Values based on current Los Angeles County operations
Proposed new large stormwater capture	Capture >> filtering and sedimentation >> spreading and infiltration >> pumping >> treatment >> delivery	$0.90–2.21 ($1,110–2,727)	Los Angeles area agencies have assessed new large stormwater capture basins, including converting flood control infrastructure for multipurpose use. Urbanization limits land for new large basins
Indirect potable reuse	Sewage collection and treatment (tertiary and disinfection) >> conveyance >> spreading and infiltration >> pumping >> treatment >> delivery	$1.25–$2.14 ($1,551–2,641)	Conveyance in purple pipes to 'environmental buffers', or recharge basins, for infiltration and later pumping
Non-potable reuse	Sewage collection and treatment (tertiary and disinfection) >> conveyance >> delivery (irrigation, CII)	$0.45–1.33 ($556–1,646)	Conveyance in purple pipes. Total costs estimated based on current unit delivery prices. More direct than IPR
Direct potable reuse	Sewage collection and treatment >> conveyance >> delivery (all potential end-uses)	NA	Costs net yet well characterized. Not currently legal in California

Major stages include storage in reservoirs and groundwater basins, conveyance in aqueducts, surface canals, or pipes, *treatment* for water supply or wastewater, delivery through distribution pipes, and infiltration in landscapes or in large spreading basins. These general configurations could be sub-divided or combined. SWP, California State Water Project; CII, Commercial, Industrial and Institutional).

costs are not standardized across the region[15,16,21]. Thus agency fragmentation impedes holistic accounting of not only water supplies, but also of benefits and costs, which only reflects a specific water domain and associated legal and institutional constraints. As an example, many stormwater agencies cannot readily include avoided costs of purchasing imported water in assessing long-term finances of new stormwater projects that enhance groundwater recharge, as water supply duties are outside of their missions[16]. Doing so requires interjurisdictional or multijurisdictional (multilateral) arrangements. Previous studies have notably lacked an integrated analysis with a tool such as Artes capable of consistent and commensurable analytics across systems, a reflection of past water management strategies and assumptions that also influence what become economic externalities.

Los Angeles can capitalize on the demonstrated benefits of local water supply and conservation[20,21]. Intermediary agencies such as regional municipal water districts or the Water Replenishment District of Southern California, located within the hierarchy of agencies, are potential leaders in assembling projects. But current projects are often planned bilaterally, with agencies shopping and negotiating projects on a one-to-one basis. Moving towards forums and pooled funding structures that emphasize multilateral projects would reduce overall transaction costs in planning projects leading to regional water self-reliance.

This more cyclical and integrated model of water supply especially requires changing current practices and use of local groundwater storage capacity. The county is endowed with significant regional adjudicated groundwater basins, which annually supply as much as 616 mcm (500,000 ac-ft) and have additional space for storing infiltrated water. But many water supply agencies have no designated rights in these basins, which reduces motivation for infiltration and indirect potable reuse. Reforming groundwater rights to provide more agencies with storage capacity can increase incentives for collaborative project planning that improves water supply reliability.

Conclusions

Will Los Angeles continue its path towards increased use of local water sources? We show that achieving a local water supply regime in Los Angeles primarily dependent on local sources is possible and that embracing local water resources is a strategy that makes sense. Importantly, results indicate that local water supplies in Los Angeles are economically competitive and outdoor water use conservation remains cost-effective. Updated governance structures and financial practices are critical, but underemphasized, pieces to meeting regional goals. In particular, modelling simulated regionalized project planning with benefit–cost assessments spanning agency boundaries.

Although feasible, local water supply goals face challenges. Some of these are technical, such as operating current infrastructure with new norms. As an example, water treatment and reuse plants are currently designing retrofits to treat more concentrated sewage that results from urban water conservation. Additionally, better models of surface water and groundwater interactions are important for water supply agencies to fund distributed stormwater capture and infiltration[19]. But these challenges seem manageable in historical context. At the turn of the twentieth century, Los Angeles City built the longest aqueduct in the world up to that time, crossing harsh desert terrain to bring water from Owens Valley. It was a massive technological achievement. Technical solutions from earlier eras often become contemporary management problems[44].

But institutional challenges identified through the economic analysis are more engrained. In Los Angeles's fragmented institutional architecture, projects are usually internal to one agency or bilateral among two agencies. Multilateral planning processes and funding structures must emerge within Los Angeles County, such as pooled funds to support large regional projects that may not necessarily benefit all agencies immediately. Political realities also play a significant role. For instance, the 1996 ballot Proposition 218 in California was recently applied to water utilities, requiring suppliers to align the charge for services (water rates) with the actual cost of acquiring the water. This has complicated the process of instituting tiered rates to promote conservation that could help offset revenue losses from reduced water sales[25].

Future management innovations are necessary to address these engrained challenges. Innovative funding mechanisms, new technologies, and internal institutional reforms that promote learning have all been identified as important reforms[25,31,45,46]. The results from this study reveal additional governance innovations that would promote longer-term, more holistic planning (Table 4), including revamping turf replacement incentive programmes for conservation, reforming existing groundwater rights, requiring reporting with nominal and annualized costs and promoting regional forums to facilitate full-cycle water supply planning. Coupling integrated hydro-economic modelling of water system operations across agencies can help assess real-world effects on businesses, homes, trees and landscapes in a holistic way to benchmark water demands. Yet, complex networks of agencies, which all have institutional practices that perpetuate the status quo, drive how economic analyses are constructed. Benefit–cost assessments focusing on just a few agencies and over limited time periods fall short as a decision metric.

Los Angeles is a city eager to reinvent itself. Thriving from creativity, change and growth, it is one of America's prolific urban laboratories. In the past, historic perceptions of water demand and imported water availability led to the development of a regional hierarchy of water agencies that funded huge water projects for imports. Today's changing perceptions are driving agencies to reconfigure operations and financing en route to new investments. The transition is realigning traditional politics and spurring agency innovations. The rate at which the transition occurs remains to be seen.

Table 4 | Examples of governance and policy innovations for enhancing local water reliance in Los Angeles related to economic aspects of regional governance

Policy innovation	Description
Create consistent enhanced funding streams for turf replacement programmes	Residential urban water conservation is relatively cheap, and replacing outdoor lawns using best available scientific information is a prime way to achieve conservation goals that also provide environmental benefits if using native plants. But boosting turf replacement during drought is sub-optimal. Replacing lawns during periods without rain reduces water savings, as plants need time and water to establish drought tolerance
Solidify water rights for stormwater capture	Stormwater agencies often cannot monetarily benefit from building infrastructure to capture and infiltrate runoff. In Los Angeles, groundwater adjudications and regional reports must clarify if stormwater is newly produced and thus deserving of credit for supply augmentation. This would incentivize more recharge, especially in cities without pumping rights
Require cost reporting with nominal and annualized costs	Planning documents such as urban water management plans should require agencies to report both nominal and annualized costs for all supply sources, using standardized and well-documented assumptions. This would help equate costs across established and emerging supply sources
Promote regional working groups for assembling full-cycle projects	Regional groups should promote more multilateral planning and information sharing forums to reduce the transactions costs of assembling projects within the complex network of agencies in Los Angeles. A regional working group could also take the lead in assembling studies that combine conservation and supply enhancement
Funding sources should require full-cycle cost assessments	Given the taxing restrictions for local governments in California, many stormwater and water reuse projects are funded through bond measures. Such sources should require unit cost reporting in both traditional and full-cycle methods

Methods

The Artes model of water resources in Los Angeles quantifies water supply portfolios and conservation in Los Angeles County based on varying scenarios of water demands, existing and new reuse and stormwater capture facilities, groundwater management and conservation[12,19]. Artes uses linear programming to perform network flow optimization, which has been used in many applications in infrastructure and water resources planning, to identify supply and demand options for enhancing local water supplies in metropolitan Los Angeles based on meeting stated objectives and constraints[34,47–50]. It incorporates regional water supply agencies, infrastructure, and surface hydrology to route flows within infrastructure and the surface water river systems based on the objective functions and constraints. It represents the watershed hydrology of Los Angeles County and, through a link-node network structure, additionally incorporates how agencies manage water in the region by including restrictions on flows to agencies (constraints) based on available supplies, demands, allocation agreements, groundwater pumping rights and flow capacities.

The model includes actual historic flows for imported water, collected from area agencies, along with historic wastewater outflow values to calibrate model performance. Hydrologic processes, including surface water flows and losses (evaporation, evapotranspiration and infiltration) are based on a hydrology model developed by the Los Angeles County Department of Public Works (The Watershed Management Modeling System, or *WMMS*)[51]. Artes incorporates data from hundreds of sources and performs flow calculations at a monthly time step across a period of up to 25 years using historical data. Model calibration procedures were previously described in detail[19].

In developing Artes, we collected and calculated key data, such as water needs of urban trees and landscapes based on in situ experiments, existing water allocations and groundwater pumping rights, seasonal water demands and potential stormwater capture capacity (Supplementary Information)[9,10,18,21]. The data and software are openly available, providing a comprehensive set of water data and analytical tools for the region[12]. For this analysis, we additionally collected data on economic benefits and costs, as available, for regional water supply alternatives, along with estimated monetary consequences (economic losses) of residential outdoor water use cutbacks, which is described in detail below.

The collection of data and models supporting water management in Los Angeles is constantly evolving. We intentionally developed Artes to minimize assumptions of existing conditions, which can reinforce status quo practices, and to be flexible to incorporate newly available tools. Linear programming models with optimization use a specified mathematical objective function that minimizes or maximizes outcomes of one or more stated model objectives that are optimized through calculations. The optimization function in Artes is tailored to address the specific question of future water supply planning in a huge and complex metropolis. But we take advantage of flexible software and new modeling packages that enable developers to more rapidly convert a model's formulation, constraints, goals, underlying network structure simulating the system and outcomes. To date, we have used multiple objective functions to support simulation optimization procedures in Artes. For instance, objective functions have alternatively minimized or maximized outcomes over a given time period, as well as combined directed and undirected network flows using linear programming. Additionally, we have developed algorithms for optimizing flows over *annual* (12 month) time periods or the entire period being modelled (15–25 years in Artes), which is sometimes differentiated as modeling with *limited* or *perfect* foresight[12].

Hydroeconomic modelling. Incorporating economics into Artes required enhancing the model. Specifically, analysing economic implications of local water supply based on a hydroeconomic framework involved modifying the objective function in Artes. Past studies have outlined procedures for hydroeconomic analysis and various methods to assess costs and benefits of urban water supply options, including demand functions to estimate losses from water shortages, contingent valuation to assess consumer willingness-to-pay for various outcomes, and assessments of water utility costs associated with conservation[32,37]. These procedures have been alternatively applied for decades to assess economic losses from water scarcity, but with varying levels of detail[38,50,52–55].

We used an objective function that minimized a total value of costs for water supply and economic losses from residential outdoor water use reductions when considering potential benefits associated with large stormwater capture basins:

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

where Z is the difference between the sum of total economic costs and benefits of flows. The total costs include costs of water supply (C) and the sum of assessed economic losses of from reduced deliveries (L), and accrued benefits (B) reduce costs. The formulation in equation (1) assumes that the total system-wide costs are larger than the total potential benefits. Operations and maintenance costs were not added, as it was assumed that these are built, at least in part, into pricing structures.

We calculated economic losses associated with reductions in outdoor water use (changing irrigation habits and replacing lawns in urban Los Angeles) based on a linear demand function procedure with estimated elasticities of demand and water prices derived from existing sources (discussed below). We did not include revenue losses to utilities or expenses incurred by residents in replacing landscapes as part of the objective function, though some portion of the replacement costs to residents could be considered part of the economic loss calculation. Benefits are limited to assessed benefits associated with large-scale stormwater capture derived from existing regional sources.

In the model, the Los Angeles water system, including engineered, natural, and institutional features, is represented as a network of links and nodes where each distinct link k connects nodes i and j within the set of all nodes. Total costs become the product of the volume of flow across link k (Q_{ijk}) and the specified unit cost of flows across link k (c_{ijk}) from Table 2:

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

Economic impacts of reduced residential outdoor water demand were calculated as the product of the volume of reduced deliveries, or shortages (S) to node j, and the unit cost associated with assessed economic losses for node j (d_j):

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

Economic benefits of water supplies B are calculated for all nodes as the product of the total flows to a node and the unit value of benefits for that node:

$$B = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} b_j Q_{ijk} \tag{4}$$

Economic losses associated with shortages, which are the difference in stated and modelled flows to a node (equation (5)), are limited solely to reductions in residential outdoor water use. To estimate this, we calculated the minimum demands for each water retailer service area associated with (1) indoor residential populations that use 50 gallons per capita per day, and (2) reported commercial and industrial uses[12,40]. We refer to these as minimum health, safety, and industry demands (HSI_j) that must be met (equation (6)).

$$S_j = \sum_{i=1}^{I} \sum_{k=1}^{K} (D_j - Q_{ijk}) \tag{5}$$

$$Q_{ijk} \geq \text{HSI}_j \tag{6}$$

In practice, model results do not always meet the constraint in equation 6 when, for example, the sources remaining to a retailer after imported water cuts are too small to meet HSI demands. Remaining constraints are similar to previously published versions of Artes and detailed in the Supplementry Information.

Economic parameters. We collected economic data from multiple sources to populate model parameters for costs of water supply (Table 1). Costs of imported water from MWD were based on the published price for tier 1 treated water, and costs for Los Angeles Aqueduct imports were derived from previously reported work[21,56]. The model did not explicitly include MWD prices for untreated (raw) water, which some utilities purchase and treat locally. We estimated costs for groundwater pumping, including water treatment, are based on published data for the region's largest retailer, LADWP[21,57]. The estimated value did not include variations in pumping costs due to geography (across groundwater basin areas) or groundwater depth, whereby pumping from deeper wells increases costs. Recycled water costs were extracted from reports published by Los Angeles County and LADWP. These were based on reported sale prices specific to each water reclamation plant and end-use as available[57,58]. Finally, costs for capturing stormwater in large basins were collected from published sources, personal communications with regional managers and documentation from LADWP (L. Alexanderson, personal communication)[15,57,59]. Costs associated with constructing distributed stormwater capture basins were not included. As such, simulation of distributed recharge does not significantly contribute to aquifer replenishment in the model results, which corresponds with recent analytical findings for the region[60]. Taking this approach in the model ultimately yields a more conservative estimate of available groundwater and regional potential for local water supplies. But many regional groundwater basins, operated based on historic estimates of recharge, are drawn down, so a conservative approach is highly useful. Future analysis with additional modeling of surface-to-groundwater linkages should address the challenge of integrating aquifer recharge from landscape infiltration and distributed stormwater capture.

Benefits included in the analysis were limited to large-scale capture basins and adapted from existing Los Angeles County studies[59]. The assessment also limited benefits to the Los Angeles County metropolitan area alone. To limit uncertainties and assumptions in the modeling, it did not include any estimated benefits to ecosystems or agricultural production that could result from reducing imported water diversions from upstream areas such as Owens Valley or the Sacramento–San Joaquin Delta.

As noted, economic losses (welfare losses as defined by a changed landscape away from lawns) were calculated using a linear demand function method. Demand elasticity was specified for water supply agencies at the wholesaler level (municipal water districts) using recently published values, which were reported in a comprehensive study based on survey data and accounts for heterogeneity in varying water prices as well as median resident income across water agencies[38]. In the Los Angeles water system, wholesaler agencies receive imported water from water importing agencies, primarily MWD, and resell this water to retailer agencies that provide it to end-users. For each wholesaler, the published elasticity of demand was applied to all retailer agencies in the wholesaler service territory. We used estimates of retailer populations derived from the existing Artes model and Los Angeles County water rates from an existing database[39]. Insufficient data were available to estimate seasonal changes in price elasticity. Although these are likely to be higher in the summer months with the demand for irrigation, this issue is a notable gap in data availability for a large metropolitan region such as Los Angeles[50]. Moreover, the linear function may underestimate unit costs associated with significant cutbacks. We compared estimates of economic losses from reduced irrigation associated with residential outdoor demand reductions based on several reported procedures[38,50], including heterogeneity in prices and income that yields larger estimates.

We incorporated the need for an extended planning period using annualized costs of water supply, losses, and benefits. For costs with current prices (imported water, groundwater, current stormwater capture, and recycled water), we extrapolated future prices (adjusted for inflation) associated with historic reported rate increases[56] and estimates based on higher energy prices for groundwater pumping. As noted, rates for imported water have increased on average 5–6% over the past decade and upcoming infrastructure projects are likely to further increase this value. For some water supply sources, such as proposed stormwater capture basins, reported unit costs are already amortized and we did not adjust these values. The longer period for annualizing costs (typically 50 years) reported for such projects in previous studies was compared with a shorter period of annualized costs for imported, groundwater and recycled water sources (20 years), resulting in a conservative outcome that could underestimate their competitiveness, especially given that imported water is likely to experience the most significant long-term annual price increases.

Notably, the objective function does not resemble an entirely traditional benefit–cost assessment, as the costs of water supply from various sources do not always equate to fixed and variable costs. The costs for large stormwater capture basins, for instance, are likely to include both fixed and variable costs. The costs for water supply are assessed at the level of water retailers that supply water to end-users. These agencies would assess costs of purchasing imported water across seasons as variable depending on the volume needed each year. The water price used to derive willingness to pay, on the other hand, represents retailer costs of sale and would include fixed and variable costs. For these reasons, we do not report the total system costs throughout the production chain, instead trying to count costs (fixed + variable) only once throughout the supply chain using retail prices.

This may differ from how utilities approach finances and accounting, but was done to assemble a longer-term view of the trajectory of system changes and associated financial or policy challenges.

Demand and supply parameters. For the economic analysis, we included current and proposed supply options as detailed in the Supplementary Information. This includes many new reuse and stormwater capture projects. For imported water, however, available supplies in the model scenario were limited to 50% of historic deliveries. This constraint was imposed to understand the effects of water shortages through a scenario that simulates an imposed long-term dry period.

Finally, water demands were set at a minimum baseline, which we refer to as health, safety and industry (HSI). Baseline water demands were set according to a municipal budgeting procedure that yielded a regional target of approximately 302 lpd (80 gpd). This value was previously shown to be a reasonable regional conservation target that could still maintain businesses, trees and low-water landscapes[40]. The HSI demands are critical needs that served as a lower constraint for minimum deliveries in the model. Thus, any results with regional consumption below the baseline target, but still meeting HSI levels, stem from economically efficient outdoor water use reductions as part of the objective function losses variable (L).

Implementation and software. Calculations are performed using custom software that includes a commercial optimization package (Gurobi) and open-source code for data operations and formatting. Python scripts manage inputs and outputs from spreadsheets and text files, and constructs the model objective function and constraints[61,62]. The Gurobi optimization engine performs the calculations for optimization with linear programming[63]. Post processing from output text files was performed using spreadsheet software and custom scripts developed in Python and R.

Data availability. Data and software for Artes, including the new data and modifications that supported this analysis, are published in an open-source repository (https://erikporse.github.io/artes/). Multiple versions of the data and software are available in the repository, corresponding to this analysis and associated studies. For each, the software includes source code used to run the model, along with intermediary scripts used in processing pre- and post-analysis data. Data in the repository include model inputs, aggregated flows from the regional watershed model, and GIS files, as well as datasets collected in support of contributing studies. Calculations used to estimate economic values for this analysis are provided in worksheets. The repository includes documentation for using or adapting the model and underlying data.

Received: 6 December 2017; Accepted: 18 April 2018;

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Acknowledgements

This research was supported by the John Randolph Haynes and Dora Haynes Foundation, the National Science Foundation's Water, Sustainability, and Climate program (NSF WSC #1204235), and the Los Angeles Bureau of Sanitation. M. Glickfeld, K. Naik, D. Cheng, P. Cleland and J. Rodriguez all contributed to supporting research.

Author contributions

E.P. and S.P. conceived of the study. E.P. and K.B.M. collected data, performed modelling and analysed results. E.L. performed field experiments and estimated tree canopy water needs. S.P., T.H., D.P. and M.G. were primary investigators of research projects that funded this work. All authors were involved in writing and editing.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41893-018-0068-2.

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