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Adapting Urban Water Systems to Manage Scarcity in the 21st Century: The Case of Los Angeles

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Abstract

Acute water shortages for large metropolitan regions are likely to become more frequent as climate changes impact historic precipitation levels and urban population grows. California and Los Angeles County have just experienced a severe four year drought followed by a year of high precipitation, and likely drought conditions again in Southern California. We show how the embedded preferences for distant sources, and their local manifestations, have created and/or exacerbated fluctuations in local water availability and suboptimal management. As a socio technical system, water management in the Los Angeles metropolitan region has created a kind of scarcity lock-in in years of low rainfall. We come to this through a decade of coupled research examining landscapes and water use, the development of the complex institutional water management infrastructure, hydrology and a systems network model. Such integrated research is a model for other regions to unpack and understand the actual water resources of a metropolitan region, how it is managed and potential ability to become more water self reliant if the institutions collaborate and manage the resource both parsimoniously, but also in an integrated and conjunctive manner. The Los Angeles County metropolitan region, we find, could transition to a nearly water self sufficient system.

Keywords Water scarcity · Socio-technical systems · Integrated water management · Water self-reliance

Introduction

The 2018 water supply crisis in Cape Town, South Africa, once again focused attention on the acute consequences of failing to plan for future water needs in cities. Throughout the globe, many urban areas face water scarcity in coming decades. Cities in Mediterranean climates, which experience highly seasonal precipitation, have particular challenges to meet year-round water demands and growing populations (Padowski and Jawitz 2012; McDonald et al. 2014; Padowski and Gorelick 2014).

This is not a new challenge. Cities in many types of climates have long imported water from distant watersheds to provide clean and reliable supplies (Baker 1948; Tarr et al. 1984; Melosi 2001). In the arid regions of western North America, such imports occur at grand scales. The

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prospect of accessing readily available freshwater sources in faraway places led cities in California, Arizona, and Nevada to build pipelines over long distances to deal with regular seasonal scarcity. Such actions, undertaken in the early and mid-twentieth century, helped mitigate regular water shortages and set the stage for long-term growth in the regions (Davis 1993; Reisner 1993; Hundley 2001).

But during drought, available water in these semiarid and arid regions is especially limited. In California, for instance, urban population growth through the mid-twentieth century was enabled by vastly expanded water transfer infrastructure. But severe droughts in the 1970s and 1990s showed that many cities were unprepared for the water cutbacks resulting from water shortages. Cities instituted emergency measures and imposed significant cutbacks, reinforcing rationing as a standard approach to periodic drought[1] (Bruvold 1979; Shaw et al. 1992; Dixon and Pint 1996; Mitchell et al. 2017).

California cities have made progress in the past decades to promote conservation and diversify supply sources, but they once again faced challenges during the 2011–2016 drought, the most severe on record. Larger cities fared better, though they were still mandated to cut water up to nearly 40% of 2013 consumption, depending on prior conservation actions (Office of the Governor of California 2016). But smaller communities with limited supply sources, such as Healdsburg and Cloverdale in Sonoma County, faced the risk of running out of water in 2014 (Gore and Bourbeau 2014).

Expectations of water availability for all these urban areas will likely continue to change in coming years, with more cities spending more money to ameliorate the effects of drought (MacDonald 2007; McDonald et al. 2014). But emphasizing the role of climatic drought, or the high variability in rainfall, as a driver of scarcity (both current periodic drought and future more prolonged events with climate change) misses the important role of societal expectations of water availability. In particular, engineered water conveyance systems bred confidence in in the availability of nearly unlimited water supplies for many end-uses, despite a historic record that clearly shows long periods of aridity in the southwest US. In cities, this translated to security of indoor, commercial and industrial uses, but especially supported highly irrigated landscapes full of nonnative species. Perceiving water shortages as caused by natural events like *drought* deflects attention from the ways that current conceptions of scarcity has been constructed over many decades, driven by the reliability of infrastructure that facilitates continued water use.

Modern water management systems are comprised of both technical systems and organizational hierarchies. Within social science literature, such combinations of human social structures and technologies are characterized as *sociotechnical systems* (Pincetl et al. 2016a). For urban water management, sociotechnical systems include municipal governments and regulatory organizations, associated rules, regulations, codes and procedures, and the technical systems comprised of dams, reservoirs, pipes, and water treatment plants. Sociotechnical systems interact with environmental resources, such as groundwater basins that provide water storage (Foster et al. 1999; Gelo and Howard 2002). These in turn connect to larger systems of dams and water conveyance, along with the rules that regulate how those systems operate. Understanding water systems in cities as comprised of both social and technical aspects reveals how periodic water scarcity may result from existing management systems, rather than solely attributable to climatic drought. Many problems of urban water management result from governance failures at multiple levels, rather than scarcity of the resource itself (Pahl-Wostl 2017). Such governance failures are inscribed in the operation of infrastructure systems that reflect assumptions about water quantity and distribution. Policy innovations must engage with historically developed hard infrastructure and its management (Kiparsky et al. 2013).

This paper examines the social and technical adaptations necessary for one Mediterranean-climate urban region, Los Angeles County (LA), to adapt to future water management challenges. Like many modern cities, LA's water management systems were designed to exploit highly available imported water from remote places to supplement regional water sources such as groundwater. Such local sources, while long-utilized, have not necessarily been managed to ensure long-term sustainability (Blomquist 1992). Summarizing results from research spanning a decade, we synthesize the findings of empirical investigations into the sociotechnical water system, elucidating potential actions for long-term water reliability in LA. We show how the embedded preferences for distant sources—and their local manifestations—have created and/or exacerbated fluctuations in local water availability due to changes in climate. This case study offers insights for other cities across the globe about sociotechnical system lock-in that creates water scarcity, and also pathways forward toward potential water self-reliance.

Sociotechnical systems

Urban infrastructure, and how it is connected to supply chain infrastructures, is critical to providing necessary

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[1] Drought is, of course, a term that implies a kind of referent of about rainfall normalcy. In the US southwest, dry periods are not uncommon historically. We use the terms shortage, scarcity, or aridity in some places to convey this concept.

goods and services to urban populations. Cities are products of complex interactions between sociopolitical, cultural, institutional, and technical networks, which are all dependent on infrastructures that can be configured in different ways (Swilling 2011). Sociotechnical systems co-produce each other (Trist 1981), and rely on an elaborated social network of agencies for structure and organization. Pahl-Wostl (2017) argues that the understanding of water governance is underdeveloped, with much work being descriptive. This is, in part, due to a failure to recognize how decisions, agency networks, and other social factors intimately influence the evolution of the physical infrastructure network. Early work in sociotechnical systems was developed for energy systems, such as the grid (Hughes 1993), which pointed to the importance of institutions and people in determining the trajectory of infrastructure development.

A sociotechnical perspective highlights that systems are not only comprised of technical artifacts, but also include economic, political, scientific and legislative components (Hughes 1993). Together, the social and technological elements form a web of interactions that contribute to the process of system building. The technological parameters and rules devised as part of system operations create a kind of "lock-in" (Unruh 2000), which is not only physical and regulatory, but also conceptual. That is, once systems are in place, patterns of expectations and notions of possibility also become fixed, limiting opportunities for system change even in the face of significant evidence. Aspects of this concept of lock-in, where previously-taken actions affect future decisions, are noted across many disciplines, including innovation economics (Liebowitz and Margolis 1995). Institutions build expertize that grows obdurate. Funded projects become sunk investments, perpetuating them as they are generally cheaper to use over short-term planning horizons. This pattern is often reinforced by budgetary rules. Legal and regulatory frameworks develop and generally solidify current practices.

Established practices within resource-exploiting sociotechnical systems may also mask potential resource availability, despite the paradox of over-allocated systems—that is a resource may be available that is obscured by established measurement or allocations. Existing laws, rules, and expertize can also inhibit opportunities for doing things differently—a simple self-censorship in seeing other ways of constructing the future and systems of implementation. Another way of stating this concept is to understand that information incorporated by sociotechnical systems is the result of a process of selection by which the system decides what is meaningful and what is disregarded; sociotechnical systems create a set of implicit filters (Luhmann 1984).

Water Systems in Los Angeles County

In 2015, Los Angeles County and its 10.5 million people used approximately 810 million cubic meters (1.4 million acre-feet) of water. Over the past decade, over half LA County's demands (55–60%) were consistently met by imported water from three main import infrastructures: reservoirs that store water from the Colorado River Basin that spans western North America, the California State Water Project (SWP) that brings water from mountain rivers in northern California, and finally the Los Angeles Aqueduct that brings water from the Owens Valley to the City of Los Angeles (Fig. 1). These water conveyance systems were built in a time of confidence in climate patterns—primarily the predictable presence of alpine snow pack that, melting slowly through spring and early summer months, is captured and dispatched through the drier summer and fall months to support the state's agricultural regions and its cities. Paleo and historic records of precipitation were either unavailable or ignored in these twentieth century infrastructure development projects.

In Southern California, the primary water importer, the Metropolitan Water District of Southern California (MWD), was created through state legislation in 1927 and approved by local voters to import water to the region, first from the Colorado River federal complex and subsequently from California's SWP. MWD distributes imported water to over 100 different water delivery entities within a hierarchy of agencies in LA County (Pincetl et al. 2016b). In addition, there is one area of the county with its own water district organized to also contract with the SWP for water imports.

For local sources of supply and water storage, LA County benefits from significant groundwater resources. The basins were adjudicated through agreements that set pumping rights, established governance structures, and guided long-term management actions to maintain yield (Ostrom 1990; Blomquist 1992; Porse et al. 2015). In support of the agreements, considerable investigations of hydrogeology and capacity were undertaken, though many of the findings upon which the adjudications were based are now likely out-of-date, as the LA metropolitan area overlying the basins has grown more urbanized. Reduced imported availability also led MWD to significantly cut its allocation of imported water for basin recharge. In response to such changes, pumpers, and groundwater managers in several basins have recently taken actions to incentivize recharge through groundwater storage pools or collectively limit pumping (ULARA Watermaster 2013; CB/WCB Amended Judgment 2013; LADWP 2015).

The modernist-era water infrastructure that currently supplies much of urban California will be strained as future climate change reduces seasonal snowpack storage

Fig. 1 Major conveyance systems for importing water to the Los Angeles metropolitan region. Two aqueducts, the Colorado River Aqueduct and the California Aqueduct, serve the greater Southern California region

(Diffenbaugh et al. 2015; Berg and Hall 2017). The severe multiyear drought showed vulnerabilities of reliance on imported water. In Los Angeles, the availability of imported water affects not only direct water supplies, but also groundwater recharge in LA's groundwater basins that provide critical sources for many communities. Increased conservation over recent decades has allowed the city and county populations to grow without increasing total water use, but such conservation—over time—may reduce the viability of acute water use restrictions alone to deal with dry climate cycles over time (Mitchell et al. 2017).

In the past 2 decades, new water awareness has been building in the region, urging better water management (Green 2007), including distributed stormwater infiltration zones, water recycling and reuse, water conservation and turf removal, and greater use of groundwater basin storage potential (Hughes and Pincetl 2014; Porse et al. 2015; Mika et al. 2017a). But these strategies must take hold across a highly diverse, fragmented, and complex water management system that combines natural features, such as the groundwater basins, rivers and run-off, and human-created institutions such as water districts and groundwater adjudications. These are all interconnected by technical infrastructure like pumps, pipes, and filters. There exist multiple human, engineered, and environmental systems that overlap to form hierarchical structures and interact in distinct ways that solidify dependent relationships between natural and human systems (Fig. 2).

The LA metropolitan region spans five major watersheds and over twenty groundwater basins with significant storage capacity (MWD 2007). Management decisions are dispersed among hundreds of agencies who lack

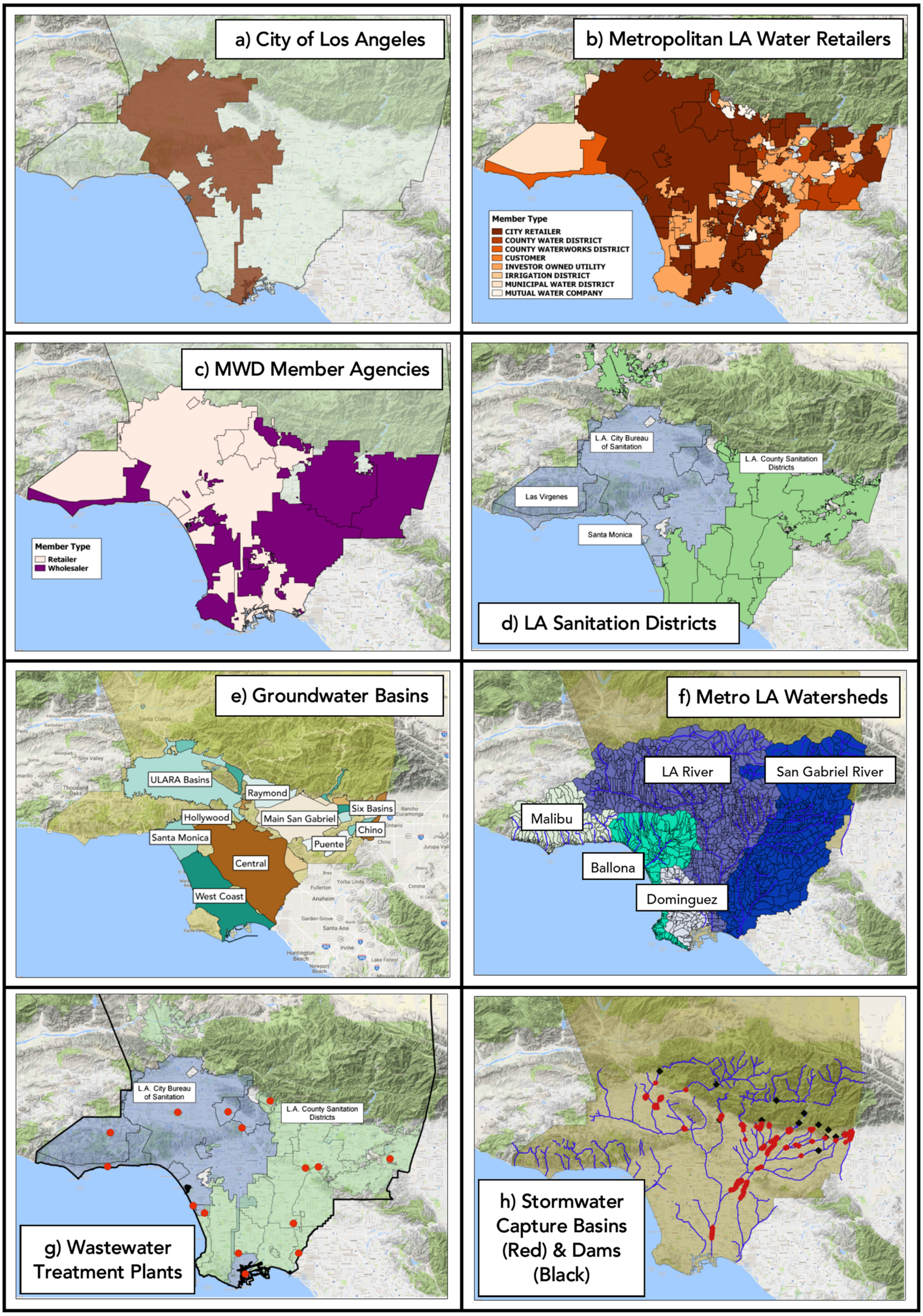

Fig. 2 Visualizing the layers of water management in Los Angeles. Each layer, including social, environmental, and engineered systems, is represented and linked through modeling

comprehensive region-wide quantifications of local water reliance potential (Supplemental Data File). Historic and contemporary ways of thinking, the disjointed institutional architecture of water management, and successful reliance on water imports, has meant the development of region-wide water resources quantification, has not been undertaken; it has not been seen, or perceived, as necessary. The most recent 4-year dry period points to the need for better quantification and modeling of this system under different scenarios and flows. We suggest the same applies to most urban areas across the globe with high reliance on imported water and poor understanding of local water flows.

Constructing the Empirical Basis for Change in LA Water Management

Analyzing complex systems driven by both human and environmental factors often requires composite assessments that draw on multiple modeling approaches based on extensive empirical data. To this end, we compiled methods and findings via a decade of interdisciplinary research to systematically deconstruct the complex and layered water system in the county metropolitan area using modeling, data collection and interviews, and field studies. Methods and key findings are summarized below. Full descriptions of the new modeling methods and results are provided in the Supplemental Data section.

Study Methods

We integrated operations research modeling, urban hydrologic modeling, field experiments, interviews and stakeholder outreach, policy and scenario analysis, historical and institutional analysis, and program evaluation to assemble a comprehensive understanding of the potential for local water reliance in the Los Angeles metropolitan area. Studies focused on LA City and LA County. The sections below briefly summarize key methods. Further details are included in the appendix and associated references.

(1) *Field experiments and program evaluations of tree and turf water use in Southern California:* Tree and turf water needs in LA were estimated based on experimental measurements taken between 2010–2011 (Litvak et al. 2012, 2017a, 2017b; Litvak and Pataki 2016). In particular, evapotranspiration (ET) in urban landscapes during pre-drought conditions (before the 2011–2016 record drought) was systematically estimated. For lawns, ET of irrigated turf lawns was measured using small chambers across lawns with varying levels of shading and irrigation (Litvak et al. 2013). For trees, transpiration rates, a reasonable proxy for tree ET in LA, was measured using thermal dissipation probes (Granier 1987) that recorded sap flux in urban tree species common in LA (Pataki et al. 2011). The experiments sampled trees of varying species across a variety of land use types, working with public and private landowners to gain access. These experiments provided an empirical basis for understanding landscape water conservation potential through a water budgeting approach for urban retailers.

Additionally, we evaluated the effectiveness of turf replacement programs in LA County through work funded by MWD. We examined participation trends in MWD's 2014–2016 turf replacement program and developed a landscape classification typology using openly-available imagery to evaluate changed landscapes (Pincetl et al. 2018). The findings from this project provide important context to understand whether turf replacement programs can be a successful strategy for promote landscape change and outdoor conservation to reduce urban demand.

(2) *Urban hydrology modeling to understand stormwater and water quality actions:* Through a multiyear project funded by the LA Bureau of Sanitation, we performed watershed-by-watershed analysis of stormwater capture potential from distributed green infrastructure to assess potential water supply benefits and water quality implications. Results from calibrated models, built using the US EPA's SUSTAIN modeling platform that supports multi-objective optimization (Lai et al. 2007), we investigated the maximal potential for stormwater capture via distributed stormwater control measures to augment groundwater recharge given available data. Associated effects on key surrogate pollutants were also examined to understand water quality outcomes and potential pollutant load reductions (Read et al. 2018; Mika et al. 2017b) (Mika et al. 2017a–2017c).

(3) *Systems analysis with optimization for integrated water management:* For both LA City and LA County, integrated systems analyses with quantitative and qualitative assessments were developed to understand relationships among water supply reliability, water conservation, alternative supply sources, current policy goals, and existing regulations. For the city of LA, results from the urban hydrology modeling with SUSTAIN were combined with systematic data collection and analysis of groundwater pumping, wastewater treatment, and water supply operations. The potential role of stormwater and recycled water to augment existing supplies was evaluated in the context of stated goals for local water reliance in LA City (Mika et al. 2017a). For the county of LA, a comprehensive network flow model of water management (*Artes*) was developed to simulate and optimize promising actions (and associated tradeoffs) for local water supply across more than a hundred institutions with existing allocations and water rights, environmental features, and engineered infrastructure (Porse 2017; Porse et al. 2017). For both study areas, economic

Table 1 Nine themes toward water self reliance for semi-arid cities

Theme 1.	Use Scientific Knowledge for Outdoor Water Conservation	Measure water use for outside vegetation, including, for each, trees, shrubs and lawns
Theme 2.	Maximize Use of Groundwater Basins	This includes detailed hydrologic analysis, recharge capacity and users
Theme 3.	Upgrade Wastewater Systems for Water Quality and Reuse	Wastewater is a misnomer going forward in the 21st century. This is important water supply.
Theme 4.	Emphasize New Water Cycles	Develop closed loop systems where water is reused and kept in the urban system, including groundwater.
Theme 5.	Import Water only in Wet Years	Many semi-arid regions do have high rainfall years. Maximize storage to take advantage of those years.
Theme 6.	Capture Stormwater in Large and Small Infrastructure	Stormwater is an important water supply that needs space to infiltrate. Maximize that capacity throughout the urban system.
Theme 7.	Recognize Tradeoffs in Water Uses	Instream flows versus infiltration is an issue that can have esthetic and recreational implications.
Theme 8.	Integrate Old and New Infrastructure	Take advantage of existing infrastructure, adapt and reoperate as well as create new infrastructure.
Theme 9.	Recapitalize and Consolidate Retailers	In places where there is a proliferation of small providers and fragmented systems, cost effectiveness and coordination is enhanced by consolidation.

effects were examined and implications for current water supply and groundwater management institutions were evaluated (Mika et al. 2017a; Porse et al. 2018b).

(4) *Interviews and stakeholder outreach:* Across water management institutions in LA County, we worked with regional agencies to collect key data for modeling, such as water treatment plant outflows and historic imported supplies. We conducted interviews for two additional purposes. First, we interviewed regional managers and experts to capture and understand views on local water reliance potential. Second, we conducted interviews with key regional experts to understand operations of key system components that informed the systems analysis. Assistance from and collaboration with regional water managers was critical to the success of the multi-year research agenda (Hughes and Pincetl 2014). We interviewed approximately 20 persons, spanning groundwater masters that manage regulated basins, water utilities, local elected officials, environmental nonprofit staff, and scientists.

Key Findings

Findings from the research (Table 1) detail the changes in system governance, along with the investments in existing infrastructure, which will be necessary to achieve water self-reliance in a region such as Los Angeles. Additionally, such changes are not without potential consequences that must be considered in advance to understand ripple effects throughout the system. The findings are organized into key themes below.

Theme 1: Use Scientific Knowledge for Outdoor Water Conservation

Urban vegetation of Los Angeles, like most of Southern California, is predominantly characterized by lawns and plants from more humid parts of the world. Substituting this vegetation for California/Mediterranean ecosystem plants that are adapted to dry summers and extended dry periods would potentially reduce regional water use by 30% (Litvak et al. 2011, 2012, 2013, 2017b; Litvak and Pataki 2016).

Field experiments derived a dataset of tree water use by particular species, including variance within a single species across locations and water availability. Such pertinent scientific knowledge can help drive regional tree planting and landscape conversion programs. In particular, to maintain LA's urban tree canopy in a future locally reliant water supply regime, the current canopy composition must be converted to trees that are adapted to Mediterranean climate conditions (winter precipitation and dry, hot summers) that are also drought-tolerant (can survive arid periods), a long-term conversion process. Additionally, this will involve not only changing perceptions of what an attractive yard looks like, but plant offerings of local nurseries will need to evolve so as to support a change toward different resident decisions (Pincetl et al. 2013). For example, promoting wider availability of native plants can provide options for changing decades-old landscape types.

But regional water managers have limited understanding of species-specific water use by trees in LA and other landscape elements. Landscapes are outside of the domain of responsibility and expertize, though multiple agencies offer turf replacement incentive funding. Some agencies, notably the City of Long Beach, provide more robust guidance in good designs for replacement landscapes, but resident and contractor expertize is scarce. To date, a few local nonprofits have spearheaded the task of piloting programs that engage residents in the process of remaking the urban landscape of Southern California cities. Much more needs done in transforming water agency practices to recognize the value of promoting landscapes that are appropriate to the region in partnership with property owners.

Theme 2: Maximize Use of Groundwater Basins

The groundwater basins of LA currently provide up to 40% of annual supplies across the county. The adjudicated basins have a pumping limit of approximately 555 million cubic meters (mcm, or 450,000 acre-feet) annually and are LA's most critical natural resource for achieving local water reliance. Groundwater basins provide readily available local storage capacity that would otherwise not exist in a highly urbanized basin where land prices outstrip the value of building reservoirs. Urban areas without such groundwater basins face greater challenges from imported water reductions.

But current groundwater management practices must adapt to future conditions. Recent assessments have estimated that 985mcm (800,000acre-ft) of unutilized available storage capacity exist in three of the region's larger basins: The Central and West Coast Basins 407mcm (330,000acre-ft) and the San Fernando Basin 555mcm (450,000acre-ft) (ULARA Watermaster 2013; CB/WCB Amended Judgment 2013). This constitutes approximately half of the LA metropolitan region's historic annual water use, which has been approximately 2000mcm (1.6 million acre-feet), but less during drought. Additional storage may be available in other groundwater basins as well. In the Central and West Coast Basins, the new groundwater master for the basins, the Water Replenishment District of Southern California, led basin stakeholders to develop a regional storage pool, whereby infiltrated water could fill the depleted void and provide pumpers over-year storage capacity. Such agreements can encourage greater utilization of local groundwater basin resources, bringing back into production depleted aquifers to offer pumping rights to more parties, though current adjudications will need to be significantly revised to do so.

Many retailers throughout the county do not have current rights to pump or store groundwater in underlying basins (Porse et al. 2015). To benefit the region, current management regimes with adjudicated storage and pumping rights need updating. Restructuring groundwater pumping rights can provide greater access to groundwater resources among agencies, especially those that have no existing rights and would suffer significant supply shortages with imported water cutbacks. In addition, implementing groundwater storage pools that open up water rights to more parties could significantly reduce the effects of imported water cutbacks by allowing vulnerable retailers access to alternative sources of supply (Porse et al. 2018a). Yet, even as key regional agencies are promoting more recharge to address overdraft, past industrial operations have also left many parts of LA with underlying contaminated groundwater plumes. Pumping, treating, and using or reinjecting water from these plumes will be critical in opening up greater access to available groundwater resources.

The state of current groundwater basins is also a challenge. A number of aquifers in the metropolitan region are contaminated, a legacy of past industrial practices from aerospace and other industries that disposed of chemicals on-site. In some areas, such as the upstream San Gabriel Valley, remediation activities have taken place for years. But much more needs done. Groundwater basin managers are concerned about disturbing current contaminant plumes, which restricts wider pumping (ULARA Watermaster 2013). New "pump-and-treat" technology investments will be necessary to remediate contaminated groundwater pockets and mitigate risks of spreading plumes (Mika et al. 2017a). Such actions could help open more groundwater areas to active management, supported by robust modeling to ensure that infiltration and pumping activities do not pose undue risks for water supplies.

Theme 3: Upgrade Wastewater Systems for Water Quality and Reuse

Recycled water (treated and disinfected to regulatory standards) comprises approximately 10% of current supplies in LA County. But this source is only for non-potable uses (e.g., outdoor irrigation) or indirect potable reuse (groundwater recharge). Due to its consistent output, recycled water provides critical reliability in a future water regime dependent on local sources. New water reuse projects are already underway throughout the county, (detailed in the Supplemental Data section), but could be vastly expanded as sewage flows and water treatment capacity are relatively predictable and could thus be a stable source of water going forward.

Current recycled water operations deliver nonpotable water at affordable prices in comparison to the rising cost of imported water supplies (Mika et al. 2017a; Porse et al. 2018b). Storing recycled water in LA's substantial groundwater resource capacity provides a critical supply chain for future water management in LA. Direct potable reuse, which is the subject of statewide policy development proceedings in California, would provide, if enacted, additional options for creating closed loop urban water management (SWRCB 2016).

Water reuse is an important emerging supply source that requires new infrastructure, but the changing dynamics of urban water in Southern California will affect current systems. The large existing wastewater treatment plants in LA, in particular, will see lower inflows as a result of water conservation and reduced imports. This serves to concentrate waste streams, leading to increased costs of treatment. Results of our systems modeling in LA County showed that this prospect would likely continue if advancing goals of local water supply and increased conservation (Fig. 3). This phenomenon represents one of the perhaps

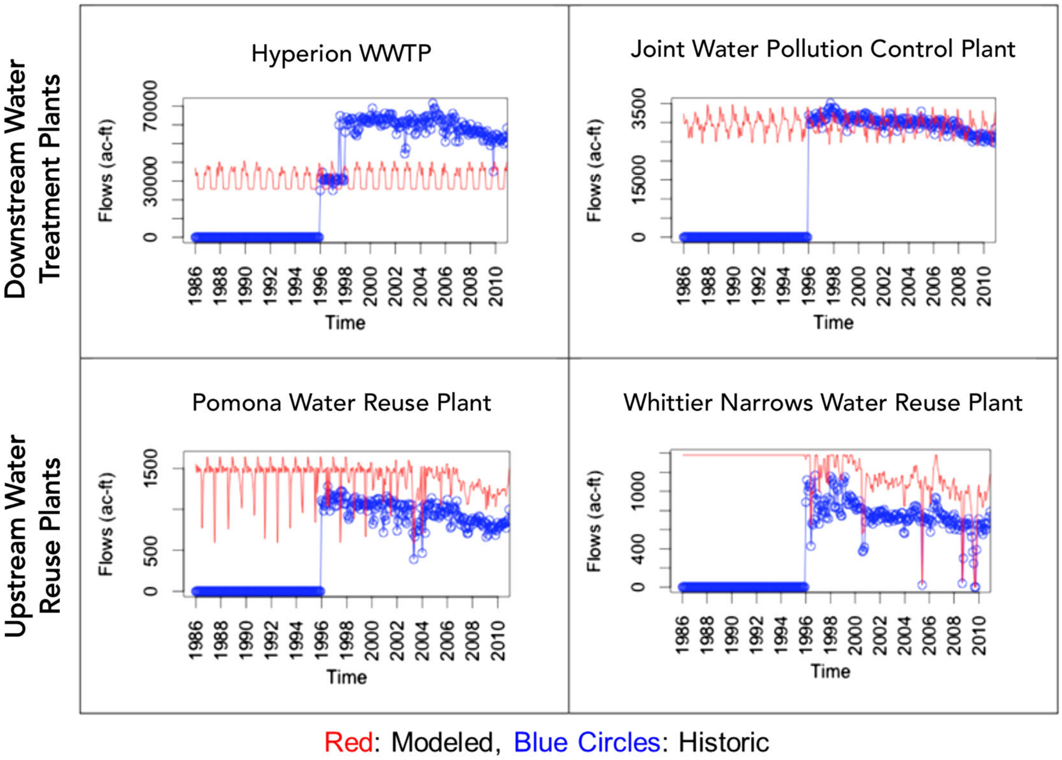

Fig. 3 Modeled inflows to selected wastewater treatment plants in the Metropolitan LA region. Downstream wastewater treatment plants (top row) see much lower inflows due to conservation and stormwater capture, while upstream indirect potable reuse plants (bottom row) see greater inflows, as imported water cutbacks emphasize alternative sources

undesired, but predictable, outcomes of changing the urban water systems of coastal Southern California. Additionally, the increasing concentration of effluent waste streams flowing into treatment plants, resulting from less dilution from imported water and stormwater, will also require new investments in aging facilities. But while these issues are definitely challenges for future infrastructure management, in the context of historical actions to bring water to the region, they seem manageable given the economic prowess of the region.

Theme 4: Emphasize New Urban Water Cycles

A water supply regime more dependent on local sources requires reconfiguring the ways regional agencies conceive of and manage supply sources and the cycles of water management in LA. Most water is predominantly imported, used, treated, and disposed to the ocean. In the future, flows need to form closed loops, with in-basin or imported sources undergoing treatment and reuse that retain much more of the volume within the basin, either through direct use or recharge. Moving towards a greater closed loop perspective of urban water management is a significant change in historic operating practices and is known as *One Water*. It means the development of a new sociotechnical system with integrated planning at the watershed scale and regional institutions and/or collaborations, transcending the fragmented historical system. The network flows, illustrated in Fig. 4 for a modeled scenario with significantly reduced imported water, would change current operations significantly.

Within the complex water management regime in LA, with its many agencies and bureaucratic silos, closed loop projects can be accomplished through either: (1) laboriously negotiated, bilateral agreements among agencies with detailed plans for funding new infrastructure, or (2) systematic, multilateral, and regional strategies that aim to create a water system that relies on local water resources by water recapture and reuse. This latter approach would entail crafting new regional water analysis for optimizing reuse, reinjection and treatment and management structures to ensure full use of groundwater basins with equitable access to water by all areas in the urbanized Los Angeles basin. The regional *Artes* model provides a heretofore inexistent platform for doing so.

Theme 5: Import Water Only in Wet Years

Importing water during only “wet” years, used to supplement local water resources and recharge groundwater, is a novel strategy for mitigating potential shortages from over-reliance on continual imports. Such a configuration enables

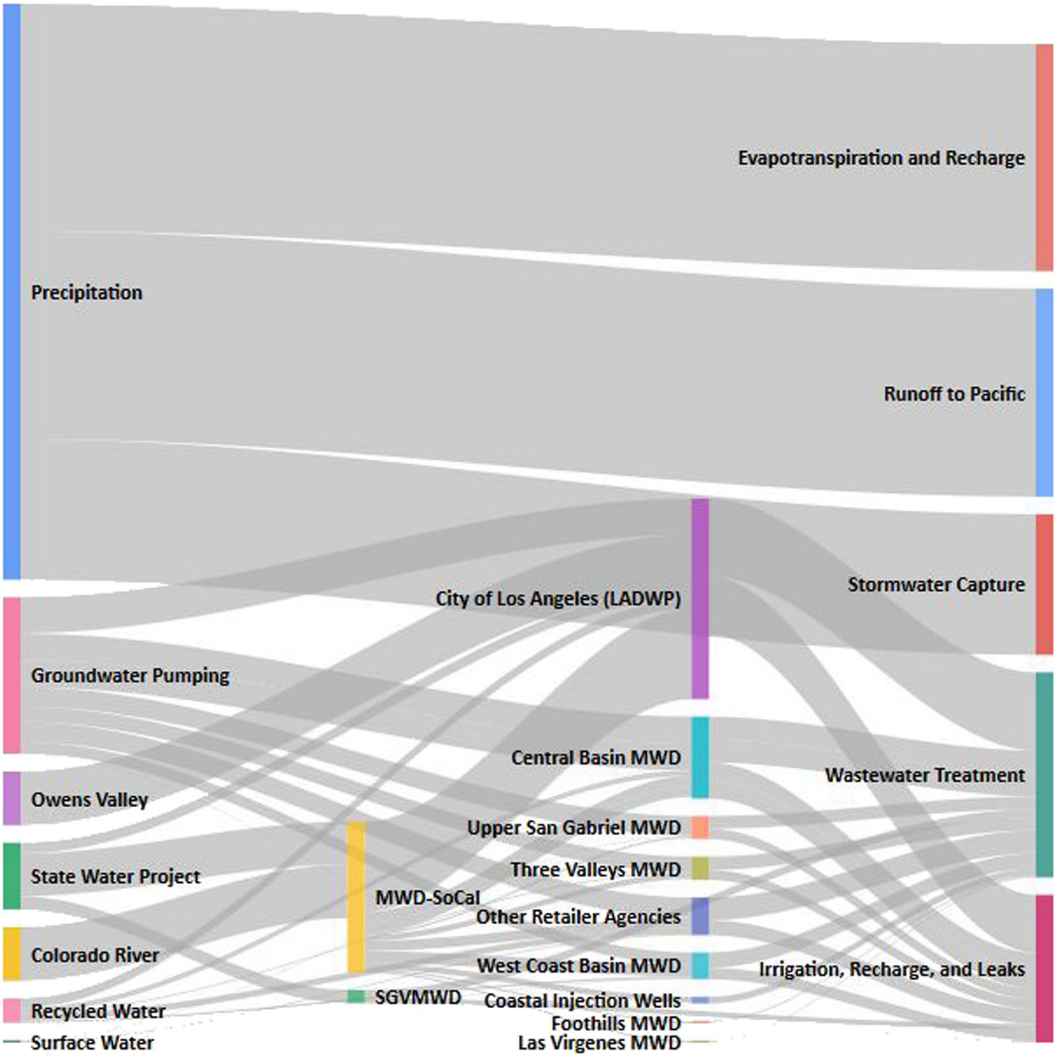

Fig. 4 Sankey diagram of system flows for a model scenario with 50% reduction in historic imported water, using a cost-minimizing formulation. Wastewater treatment plant inflows, in particular, are far reduced from current levels. MWD Municipal Water District, MWD-SoCal Metropolitan Water District of Southern California, SGVMWD San Gabriel Valley Municipal Water District

conjunctive use strategies for jointly managing surface and groundwater supplies. In times of high statewide precipitation, water is imported and infiltrated into the basins and local surface water is deferred and water is infiltrated, maximizing water in basins for later use. When there is no precipitation, groundwater is pumped. But, in this scheme, groundwater recharge and storage allows for the imports that arrive only in wet years to be banked overall years. Agreements will need to be altered to increase storage and expand pumping rights to ensure management for long-term resource availability and equitable access. Currently, there are about 300 groundwater pumpers that have historic rights to the exclusion of all others and many cities have no groundwater rights.

The finding about the potential of groundwater to buffer drought, stems from previously unpublished modeling results, which are detailed in the Supplemental Data. We developed alternative models to create scenarios to help understand the balance between conservation potential and imported supply being cut back. Using several scenarios of imported water availability and water conservation. Reducing water use to 280–380l per capita per day (75–100 gallons per capita per day, gpd) across the county metropolitan area (total water use) would go far in promoting cutbacks in imported water (Porse et al. 2017, 2018b). With investments in infrastructure and landscape conversion to drought-tolerant species, this means importing water in only the 25% wettest years, which would significantly reduce upstream environmental impacts of water diversions (see Supplemental Data). Water conservation to achieve 75gpd is on par with other global industrialized cities, and would allow for completely cutting water imports in LA City (4 million inhabitants) when coupled with other infrastructure improvements (Mika et al. 2017a), though not for the rest of the region. Reconfiguring state agreements to use risk-based procedures that promote timely importation of water from distant sources during wet years, rather than consistent imports that are only curtailed by drought, would require significant changes in current operating conditions and agency practices, at all levels: federal to state and local. The primary purpose of the imported water would be to recharge regional groundwater basins and reservoirs, which would be carefully managed between years of high precipitation. The region would then be largely living within its means. This would have the additional benefit of alleviating ecosystem impacts in regions of origin.

Theme 6: Capture Stormwater in Large and Small Infrastructure

LA currently has an extensive network of large stormwater capture basins that capture 246mcm (200,000acre-ft) of runoff annually, and have captured as much as 800mcm (650,000acre-ft) in a year (LACDPW 2014). Agencies are looking at cost-effective and achievable options for increasing these values, including re-operating flood control release schedules, building new pipelines for recycled water, and even inflatable dams to temporarily capture runoff. Going forward, both regional and distributed stormwater capture systems will be necessary to promote reliability and achieve stringent Clean Water Act regulations that municipalities must current meet as part of regional stormwater discharge permits (LA RWQCB 2016).

The results from multiple models indicated that existing centralized stormwater recharge infrastructure is a key regional asset. It provides a cost-effective way to recharge a significant volume of water on an annual basis. Modeling indicated that they could infiltrate much more water with changes in land use, management practices, and additional infrastructure that connects recycled water facilities with recharge basins. But distributed stormwater capture facilities, including low-impact development strategies such as bioswales, retention basins, and others, can also significantly contribute to groundwater recharge. In three of the main riversheds, the Los Angeles River, Ballona Creek, and Dominguez Channel, runoff for potential capture totaled 121 mcm (150,000acre-ft) in a dry year and more than 810mcm (1 million acre-ft) in a wet year. This is before implementing any distributed BMPs to capture and retain runoff throughout the landscape, which can also significantly improve water quality.

However, many regional agencies view such distributed capture as too expensive and plagued with challenges regarding siting and maintenance. These management realities are valid. Promoting more broad-based accounting procedures for projects can help in this regard. As an example, stormwater projects that capture and infiltrate runoff to groundwater basin supplies can consider the averted costs of imported water as a project benefit. But stormwater utilities typically do not sell water and cannot directly include these benefits as part of project planning. In jurisdictions where stormwater and water supply agency boundaries differ, assembling projects becomes a complex negotiation that requires activities outside the norm of agency mandates. New accounting structures and multilateral agreements, such as large water supply agencies funding distributed stormwater capture that has both water quality and supply benefits, would help open latent investments in stormwater capture. Alternatively, as has been proposed, water retailer, stormwater and sanitation agency duties should be merged or better coordinated under one roof as a way to achieve goals of local "*One Water*" initiatives.

For many regional agencies, however, enhancing water supply through stormwater management is secondary to regulatory realities in the region. LA municipal agencies with stormwater management duties face steep bills to build new stormwater capture measures (SCMs) that meet water quality goals (Upper LA River Watershed Management Group 2015). Detailed plans outline millions of dollars of spending that will be necessary, according to modeling, to meet water quality targets in downstream watersheds. For these places, incorporating multibenefit accounting procedures, which recognize the benefits to social, economic, and environmental systems from better stormwater management, is a well-documented strategy, though its enactment has been slower to emerge.

But even if distributed SCMs became widespread, there is no single best type of stormwater capture device to use, and some water quality targets will be hard to meet, especially for some contaminants such as heavy metals (Mika et al. 2017a). For instance, the watershed modeling for LA City showed that scenarios with distributed SCMs could manage up to the "design storm" runoff (85th percentile of the historic distribution of precipitation events), but tradeoffs existed. Some SCMs achieved runoff mitigation targets more cheaply, while others were more effective at reducing water quality exceedances or peak flows. Still others provided greater water supply benefits. Modeling scenarios that emphasized SCMs that treated and released stormwater, such as vegetated swales and dry ponds, resulted in fewer exceedances of the regulatory stormwater exceedance limits for metals. But treat-and-release SCMs provided less potential recharge than those that emphasized infiltration to groundwater. Thus, both types of distributed infrastructure provided the most economical solution to achieving both water quality and supply goals for the region. Agencies with significant financial capacity are, at present, most likely to have sufficient capital to invest in such measures. Such trade-offs are likely in most regions, with or without strong water quality regulations.

Theme 7: Recognize Tradeoffs in Water Uses

Water supply regimes dependent on local sources can have many benefits. But tradeoffs exist. For instance, capturing, and using more stormwater for groundwater recharge may reduce flows in the highly channelized urban streams of LA County (Porse and Pincetl 2018). The LA River basin, in particular, is a useful case study in examining these tradeoffs. Currently, a broad planning process has been examining opportunities for the channelized Los Angeles River to promote economic development and multibenefit uses such as recreation. But water conservation and cuts to imported water reduce treatment plant outflows that constitute a significant percentage of the artificial summer stream flows, would be reduced (Manago and Hogue 2017). In addition, promoting more stormwater infiltration in upstream basins would decrease downstream urban stream flows across the county in most seasons and years (Porse and Pincetl 2018t; Mika et al. 2017b). These infiltration projects would recreate the historic predevelopment water regime in the region where water infiltrated rather than being captured by stormwater systems to send the storm flows out to sea.

Theme 8: Integrate Old and New Infrastructure

Existing infrastructure in LA will not go away. It will continue to be used and likely adapted and reoperated to meet current management needs. Current assets, such as LA City's Hyperion Water Treatment Plant or LA County's Joint Water Pollution Control Plant that provide sewage treatment and disposal, can be retrofitted to support greater water reuse. Yet, many assets key for a local water supply regime of urban water are not located in optimal locations. For instance, some of the regional sewage treatment plants lie in locations where water recycling opportunities would need new pumping infrastructure. Local applications—or decentralized infrastructure—may reduce the need for new construction or expensive retrofitting of recycled water distribution systems. A major question will be the scale (centralized, decentralized and size) and cost/benefit of such retrofits.

Additionally new areas for large-scale stormwater capture in the highly urbanized basin are limited. Public lands that are well situated can serve hybrid purposes, including stormwater retention and infiltration, will need to be identified and strategies developed to optimize the opportunity. New approaches will require shifting the modernist-era sociotechnical system toward gray/green infrastructures to enhance local sustainability and resilience. Opportunities for distributed stormwater infrastructure exist in stormwater channels (some of which are already soft bottomed, but others could be unpaved), parking lots, alleyways, parks and more, but have not been seen as such due to the lock-in thinking of the current system. The barriers to these alternative systems include cost, fear of failure in increased flooding risk, lack of experience in assessing the infiltration potential, and inadequate experience in such alternatives in the region. However, repurposing such areas for multiple use is an important component of achieving greater local water self-reliance (Gold et al. 2015; Mika et al. 2017a–2017c). This type of opportunity exists in cities throughout the globe, but requires new approaches and funding mechanisms.

Theme 9: Recapitalize and Consolidate Retailers

The complex hierarchy of water management agencies in LA developed slowly over time. It is not the result of any single act of planning. The agency network includes municipal utilities, special water districts, private investor-owned utilities, nonprofit landowner-controlled mutual water companies, and irrigation districts. The agency network spans over 100 sizeable water delivery entities and, when including extremely small retailers, more than 200 (Ostrom et al. 1961; DeShazo and McCann 2015; Pincetl et al. 2016b).

All of these agencies make policy and investment decisions based on an existing system, where revenues are predominantly tied to water sales (volumetric). This creates a structural disincentive for conservation, including turf removal. Some larger and more financially secure agencies have systematically invested in conservation, but not to the extent possible. But without long-term planning and changes in rate structures, conservation detracts from revenues, causing economic ramifications for risk-averse utilities.

The agencies most prone to status quo management serve hundreds of customers only and are managed by property owners who vote according to property share. Many of these are poorly capitalized and cannot finance basic infrastructure repairs such as leakage (Naik and Glickfeld 2017). Consolidating water utilities is seen as an enormous uphill battle and impossibly expensive. Small water utilities' infrastructure would have to be upgraded, and any private utilities would have to be purchased. Yet consolidation into regional utilities could be more effective at implementing wastewater reuse facilities, a systematic approach and funding of landscape change, and planning and implementation of stormwater capture and infiltration projects, in addition to infrastructure repair and upgrading. Such larger scale entities would also have greater capacity to revise revenues and strategies to decouple infrastructure funding needs from volumetric water sales, which has proven a significant constraint to investment. Going forward *one-water* agencies, combining stormwater, sanitation, supply and groundwater, are a strategy toward greater fiscal health and moving toward integrated water management.

Theme 10: Promote Openly Available Data and Models

Studies of water management in LA County, like many places, benefit from agencies that publish significant amounts of data. One example of openly available data in LA is LA County's hydrologic model, the Watershed Management Modeling System (LACDPW 2013). This open-source model and its underlying data has facilitated numerous studies for government planning processes and external research. LA-area agencies that publish data and models to date have significantly contributed to integrated water management in the region. Through this research, we similarly sought to contribute to available data by publishing reports and open-source repositories of results and contributing data, such as a *Github* repository with databases of countywide local water reliance analysis (Porse 2017). For other regions in the world, implementing and facilitating data collection and access will be important to addressing water planning for shortages.

Discussion

The key themes elaborated above offer a framework for policy goals and necessary actions to achieve greater local water supply reliance across LA County and can provide a template for replication. They draw on an integrated perspective of urban water management from a socio-technical systems perspective, to understand how infrastructure, management regimes, and behavior all interact to influence future trajectories.

The water supply regime transformation that emerges from the synthesized findings has the following key components: (1) Water conservation, supported by scientifically informed transformations of the urban landscape, is critical to reducing demand to levels that can be supplied locally; (2) groundwater basins have hundreds of thousands of acre-feet of capacity for additional water storage, but the current agreements for pumping are based on 20th century assumptions of imported water availability. Conjunctive use can be tied with timely storage of imported water in years of high rainfall to keep basins productive and adequately supplied; (3) water reuse, including wastewater and increased opportunities for stormwater infiltration are part of this trajectory toward regional water self-reliance; (4) transformation of current siloed water management systems toward a *One Water* management regime that integrates water supply, groundwater management, water infiltration and recycling will shift the system toward water self-reliance. This is likely the most difficult change of all, requiring overcoming the 20th century establishment of single-purpose agencies for each jurisdiction.

While the synthesized results from modeling, analysis, and interviews show the possibility for a regional future of water sufficiency, the sociotechnical system's lock-in makes the transition challenging. We suggest this is the case for many cities and regions that have developed over the course of the 20th century. Rules, codes and conventions, piping and infrastructure coupled with expectations of water use and landscapes, create obdurate circumstances that effectively create water shortages amidst the potential for there being enough water.

Current groundwater adjudications, in particular, are highly codified and pose challenges for quickly adapting LA's water systems. For example, if agencies without pumping rights invest in stormwater capture and recharge, they do not benefit from opportunities for seasonal or annual storage. Moreover, the status of captured stormwater in many adjudications is even in question. It is seen in some basins as part of the natural recharge regime, which is only available to pumpers with current rights. In this way, additional water storage, including the injection of treated sewage water in locations where groundwater basins are adjacent to those plants, faces a sociotechnical conundrum. This social construction of groundwater management and water rights, impedes the full utilization of the groundwater basins to their maximum potential for water storage and use. Thus they are a physical water resource in the region which the sociotechnical system has marginalized.

Planning for Climate Variability and Change

Climate change is often noted as a contributing driver of local water reliance efforts in LA, but precipitation in Los Angeles is already highly variable. In a given year, LA receives a handful of storms, often via large events driven by atmospheric rivers that inundate the Pacific Coast. This type of rainfall will likely grow in frequency and intensity in coming years (Dettinger et al. 2011; Warner et al. 2015; Gao et al. 2015). But climate change will also intensify drought in a region that already experiences seasonal and annual periods of extreme dryness (MacDonald 2007; Diffenbaugh et al. 2015; Allen and Luptowitz 2017). Studies indicate that the alpine sources of runoff in the Sierra Nevada that feed much of LA's imported water will likely experience decreased snowpack accumulations in future years. This increases spring runoff volumes and, without additional surface storage or groundwater recharge, changes the timing and availability of imported water during the late summer and early fall months (Costa-Cabral et al. 2013).

Within the LA basin, increases in mean surface temperatures associated with climate change will affect hydrologic cycles and water supplies that support aquatic habitat, irrigated landscapes, and protected areas. In particular, more extreme rainfall events will require infrastructure capable of capturing larger storms to recharge groundwater basins to meet future water supply goals (USBR 2015; Porse et al. 2017). Aquatic habitats and marshlands will be affected by water conservation, imported water losses, and precipitation changes that reduce runoff (Read et al. 2018; Thorne et al. 2016; Manago and Hogue 2017), themselves artifacts of the current engineered system. Urban trees may suffer in future years without conversion of the tree canopy to low-water species (Pataki et al. 2011; Litvak et al. 2013, 2017a, 2017b; Vahmani and Ban-Weiss 2016).

Many of the adaptation actions for dealing with the effects of climate change align with research findings for enhancing local reliance. First, promoting continued outdoor water use conservation is key. Residential lawns constitute half of all urban water use throughout much of California, including LA (Hanak and Davis 2006; Mini et al. 2014b). Some parts of LA, notably coastal areas with high-density urban development and small yards, have much lower use, while other parts of LA, especially inland areas and affluent neighborhoods with sizable well-irrigated yards, use more (Mini et al. 2014a; Litvak et al. 2017a, p 20; Porse et al. 2017). Smarter investments in lawn replacement programs, driven by scientific knowledge and community engagement, are the best strategies for achieving long-term water savings and enhanced urban landscapes. Second, agencies must enhance supplies that are resilient to climate change. This includes increasing groundwater recharge and storage capacity for drought contingency, reducing reliance on distant imported sources, enhancing investments in alternative sources, and promoting capacity for timely use or storage of distant water during wet years,

Conclusions

Going forward a closer understanding of the ways in which sociotechnical systems evolve to construct resource availability and/or scarcity and vulnerability in cities is called for (Pincetl et al. 2016a). The *idea* that Los Angeles or Cape Town face natural water shortages due to climate change, rather than ones that result from how these systems are constructed and managed over time, preclude the possibility of change. California's water systems, which are highly capital intensive, engineered, and technocratic, are similarly the products of expectations and rules constructed to support those systems and twentieth century modernist assumptions. Water was assumed to be plentiful, with the only obstacle being proper conveyance systems and management of the new engineered infrastructure. With the impacts of a shifting climate that result also from human decisions, we cannot afford to simply accept the conditions of those systems and must tackle unlocking them—rules, regulations and pipes and pumps. They are coupled and self-reinforcing and work together.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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