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Journal
Journal of Water Resources Planning and Management, 144(8)

ISSN
0733-9496

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Publication Date
2018-08-01

DOI
10.1061/(asce)wr.1943-5452.0000949

Peer reviewed

Groundwater Exchange Pools and Urban Water Supply Sustainability: Modeling Directed and Undirected Networks

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Abstract: Groundwater basins are important sources of water supply and storage for many cities. Groundwater exchange pools offer additional opportunities for utilizing these common pool resources, but their potential role in urban water management is not clear, and modeling such exchanges can be challenging. This paper presents an analysis of the potential for groundwater basin exchange pools to contribute to urban water supply sustainability. Building on an existing model of urban water management in Los Angeles, the analysis assesses the potential for groundwater exchange pools to reduce scarcity and demonstrates a method for modeling two-way (undirected) flows within a directed-network model using linear programming. Results indicate that exchange pools can help alleviate shortages from operational changes (reduced imported water) in Los Angeles, but providing more parties with access to storage improves their effectiveness. Exchange pools could potentially provide 6–12% of total supplies and reduce shortages as much as 86%. Considerations for organizing exchange pools are discussed to explore policy implications for managing common pool resources. The analytical method for embedding undirected network flows within a larger directed-network model has wide applicability for water resource systems analysis applications, including modeling water markets and interbasin transfers. **DOI: 10.1061/(ASCE)WR.1943-5452.0000949.** © *2018 American Society of Civil Engineers.*

Author keywords: Aquifer; Recharge; Undirected network; Directed network; Los Angeles; California.

Introduction

Groundwater is an important resource for many cities (Foster et al. 2010; Howard 2015). Groundwater basins provide both clean water supply and local storage capacity. Managing groundwater resources conjunctively with other available supplies supports their long-term preservation (Blomquist et al. 2001, 2004; Hill et al. 1946; Todd and Priestadt 1997; Trelease 1982). But urban watersheds are also connected to upstream water resources outside their jurisdictions when utilities import water from distant watersheds. Better management of local groundwater resources in cities can have widespread effects for connected landscapes and watersheds.

Organizing the sustainable use of water resources, including groundwater, across local or regional systems is a complicated management challenge with significant implications (Blomquist 1992; Brown and Farrelly 2009; Kiparsky et al. 2013; Marsalek et al. 2001; Wolfe and Brooks 2003). Groundwater is often considered a common pool resource (CPR). CPRs have several key defining characteristics. First, they are nonexcludable but rival. All users are affected when one or more users overexploit the resource (Hardin 1968). Second, many CPRs are renewable but can be depleted (Ludwig et al. 1993; Ostrom 1990). Third, they can be managed through cooperative, noncooperative, or external governance structures (Madani and Dinar 2012; Ostrom et al. 1994). CPRs can be openly accessible, or access can be controlled by government agencies and other organizations. Management agreements allocate access and usage rights, but codified arrangements may exclude some entrants and convert a CPR into the property of certain participants (Ostrom and Hess 2000; Wade 1986). Managing CPRs sustainably often requires both controlling the appropriation of the resource and taking actions to protect and improve its yield.

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Note. This manuscript was submitted on August 2, 2017; approved on January 17, 2018; published online on May 26, 2018. Discussion period open until October 26, 2018; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Water Resources Planning and Management***, © ASCE, ISSN 0733-9496.

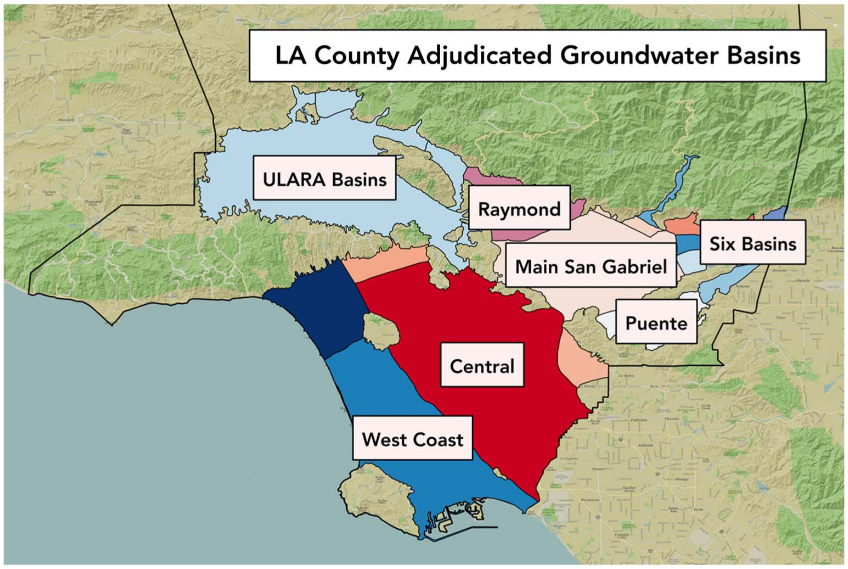


Fig. 1. Groundwater basins of Los Angeles. Basin boundaries are delineated according to historic adjudicated agreements. (Data from DWR 2003; LACDPW 2012; ULARA Watermaster 2013; MSG Watermaster 2013; Six Basins Watermaster 2013; WRD 2014b; Map data from iPhoto, OpenLayers.)

Groundwater management agreements typically outline procedures for managing basin yields, including allocating and restricting pumping rights (Gardner et al. 1990; Ostrom et al. 1994). But groundwater basins are an example of a CPR with storage capacity, which presents alternative management options (Schlager et al. 1994). Groundwater management actions can include allocating annual pumping yields as well as regulating storage capacity among pumpers. Moreover, groundwater resources and groundwater storage can be managed as separate common pool assets, with different parties participating in the management and use of each. In practice, arrangements for managing groundwater storage are less frequent (Blomquist et al. 2001, 2004).

In Los Angeles (LA) County, agreements to manage groundwater basin CPRs have incorporated all these tactics to varying degrees. Los Angeles groundwater basins are seminal historic examples of CPR governance, serving as foundational studies to understand how groups of users can assemble and devise lasting management agreements (Ostrom 1965). Across LA County, legal agreements have outlined procedures for managing seven groundwater basins (Fig. 1), which aggregate 23 distinct basins or subbasins. Each basin has a separate codified agreement, called an adjudication, which describes procedures for managing groundwater resources among dozens or hundreds of pumpers (Blomquist 1992; Porse et al. 2015). The agreements incorporate various schemes to restrict pumping yields, increase natural recharge, allocate basin storage capacity, and address surface and groundwater linkages. The agreements primarily arose to deal with overextractions during early eras of urban growth in Southern California, but they indelibly shaped the future of Los Angeles water management. A network of regional water agencies evolved to organize the acquisition of imported water and preserve local groundwater resources. Adjudications have allowed hundreds of public and private parties varying access (Blomquist 1992; Erie and Brackman 2006; Ostrom 1965). Many types of agencies supply water to end users, comprising a network of water utilities within the hierarchy of Los Angeles water management, which is depicted in Fig. 2 (Ostrom 1962; Pincetl et al. 2016).

Today, a diversity of pumpers, including water utilities, individuals, and private companies, all hold rights to pump groundwater based on their participation decades ago in extended adjudication processes (Porse et al. 2015). Groundwater comprises 40% of annual regional supplies for metropolitan LA County and its 10 million people, with some water utilities entirely dependent on groundwater resources (Gold et al. 2015; Pincetl et al. 2016). But increased risk of water shortages, resulting from reduced availability of imported water, is driving new approaches to future urban water supply reliability. Regional agencies look to capture more stormwater, increase reuse, promote conservation, and build distributed groundwater recharge, all with a goal of local resiliency and self-reliance (Johnson and Hevesi 2016; LADWP 2015c, b; USBR 2014). Such discussions take place within an existing groundwater management structure that allocated pumping rights to users based on the adjudicated agreements. The agreements codified pumping rights, but also provided mechanisms for water transfers via bilateral agreements between rights-holding parties (Blomquist 1992; Ostrom 1990). Adjudication processes to devise and certify agreements among parties lasted years or decades.

Despite the significant accomplishments of the adjudications, their ability to evolve with changing conditions is uncertain. Groundwater basins in Southern California have traditionally relied in part on imported water for recharge, supplemented by stormwater capture and recycled water (Allen and Elser 1979; Mills et al. 1998), but changing conditions have stressed current aquifers. Imported water for recharge is scarcer and more expensive, forcing basin managers to primarily rely on stormwater capture and indirect potable reuse as supply for spreading basins that annually infiltrate 246 million m^3, or 200,000 acre-ft, on average (LACDPW n.d.; Water Replenishment District of Southern California 2014a). Regional water managers around LA County have responded by outlining plans to increase centralized and distributed stormwater recharge, pump and treat contaminated aquifers, expand indirect potable reuse, and modify adjudications to increase storage in vacated aquifers (*Central and West Basin Water Replenishment District v. Charles E. Adams et al: Third Amended Judgment*; LADWP 2015c).

Groundwater storage and exchange pools, in particular, are currently being considered or implemented for key basins in the region. But the capacity for exchange pools to increase water

J. Water Resour. Plann. Manage., 2018, 144(8): 04018040

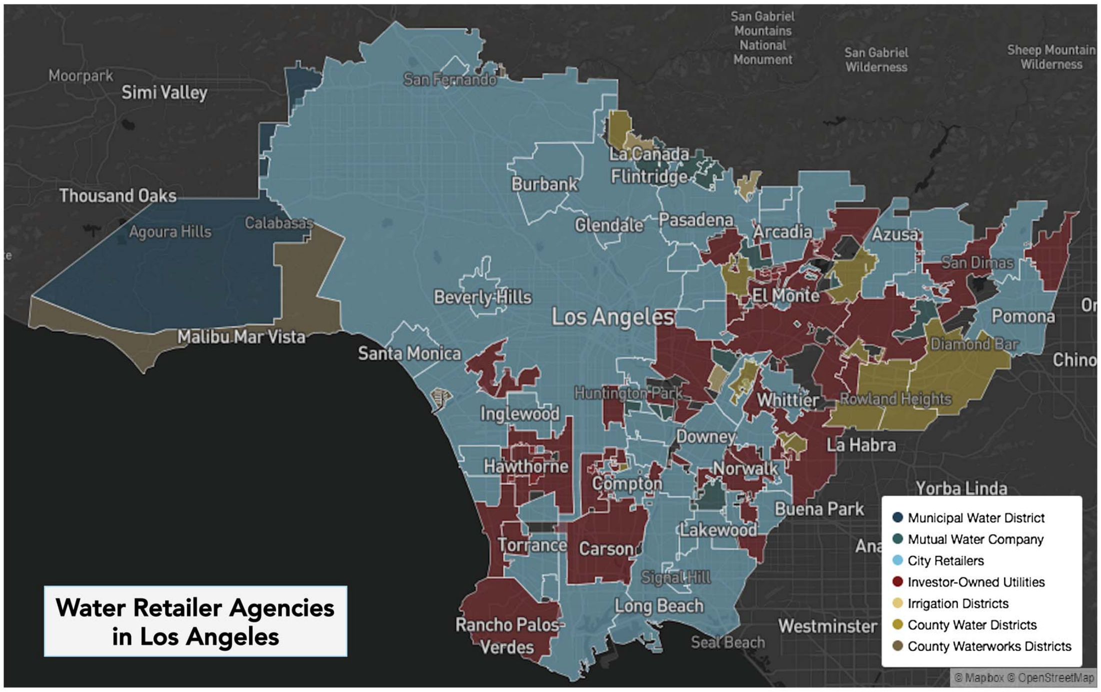


Fig. 2. Mapping retail water agencies in Los Angeles. (Data from CCSC 2017; Map data © Mapbox, © OpenStreetMap contributors.)

supply reliability and reduce shortages, given the region's highly complex water agency network, is not clear. Key theoretical and applied questions need to be explored. For instance, how much can storage pools help to alleviate shortages and promote local water supply reliance? Should allocations of common pool storage resources necessarily go to the same parties as the groundwater itself? And finally, how can arrangements help promote flexibility for managing regional urban water supplies given likely changes in climate and population? Devising modeling procedures to answer these questions presents a challenge for current water resource systems analysis.

Purpose

This paper presents an analysis of the potential for groundwater exchange pools in a metropolitan area to contribute to regional water supply sustainability. The study assesses how groundwater exchange pools in Los Angeles, which would allow transfers of stored groundwater within a basin, could maximally mitigate shortages from reduced imported water availability. It incorporates a novel formulation using linear programming to model an undirected network within a larger directed network, which is applicable to many water resource modeling tasks, yet has received limited attention in literature (Tu et al. 2005). An existing network flow model of water resources in metropolitan LA County (Artes) was modified to include the embedded undirected networks that simulate exchange pools for adjudicated groundwater basins (Porse et al. 2017).

The analysis also contributes to applied policy outcomes for understanding how the underlying organization of exchanges influences their potential success. It assesses two cases of CPR management with (1) groundwater storage pool access available only to existing pumpers in a basin, and (2) groundwater storage pool access offered to all parties that overlie a basin. Together, the methods assess the maximal potential for groundwater exchange pools to contribute to long-term supplies given current rules, as well as the role that more openly accessible rights might have in reducing water scarcity. The paper concludes with a discussion of the policy implications of the results in the context of CPR governance.

Methods

The analysis used a previously published network flow model of Los Angeles water management (Artes). The model was developed to understand the potential to maximize local water supplies to meet demands for more than one hundred retail water utilities in LA County. It uses optimization and a flexible architecture to support contemporary water planning needs in Los Angeles (Porse et al. 2017). Artes incorporates data from hundreds of sources on water utility operations, surface hydrology, climate, hydrogeology, wastewater operations, and stormwater infrastructure. It includes a central database and open-source software framework that supports analysis at multiple geographic and temporal scales in LA. Model outputs quantify water flows and potential shortages, calculated as the difference between expected demands and available supplies, for all water agencies, while also reporting aggregated annual volumes to understand regional water supply portfolios given assumptions of conservation and imported water availability. Detailed documentation, data, and source code are available (CCSC 2017; Porse 2017).

For this analysis, similar to prior published work, the primary objective function [Eq. (1)] maximizes the difference (Z) of the sum of flows from local sources, Q_a, and the sum of shortages S (multiplied by an arbitrary constant c):

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

The constant c was set to minimize shortages in the baseline case and kept constant throughout model runs. Practically, the objective function above incorporates shortages to provide a driver for meeting demands within the mathematical optimization using maximization and prevents unrealistic solution sets. The total volume of water from local sources during a given time step is the sum of flows from local source i to demand node j over link k [Eq. (2)]. Shortages are calculated as the difference between demands and water deliveries [Eq. (3)]:

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

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

A continuity equation preserves flows into and out of each node [Eq. (4)]:

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

For this analysis, the Artes network was altered to include groundwater exchanges. The network was expanded to include simulated groundwater storage pool nodes. Pumpers in a basin could potentially access supplies in these storage pools to exchange water. The groundwater exchange pools were explicitly incorporated for each adjudicated groundwater basin i_b, which is a subset of the set of all nodes. Pumper j_b can contribute or extract water to the storage pool in basin i_b at an amount less than or equal to p annual extraction rights, while they can annually extract up to double their allocations [Eq. (5)]. The formulation included the assumption that contributors could extract more than their allocated volume to quantify potential needs for redistributing water in the region

$$Q_{ji_bk} \le p, \qquad Q_{i_bjk} \le 2p \tag{5}$$

where $j_b \in \{\text{pumpers with rights in } i_b\}$ or $j_b \in \{\text{suppliers within boundaries of } i_b\}$.

But incorporating undirected network flows for exchange pools into the directed network flow model required additional constraints. To preserve the continuity of flows across the network with exchange pools, the model algorithm included additional constraints for flows into and out of the exchange pools. Undirected networks have been assessed in only a few studies for water resources, including Deuerlein (2008) and Tu et al. (2005), using evolutionary algorithms or by transforming undirected paths into a directed graph (digraph) of a water distribution network.

The revised formulation in Artes modeled undirected subnetworks for each exchange pool using the transformation method that separated exchange pool flows into two nodes for inflows ($i_{b_{in}}$) and outflows ($i_{b_{out}}$) (Ahuja et al. 1995). This is necessary because the same party can dually contribute or extract from a single exchange pool node. The result is parallel, but opposite, links between exchange pool node pairs, with the net balance of the exchange pool (P_{j_bt}) [Eq. (6)] for a given demand node j_b given as

$$P_{j_bt} = \sum_{i_b}^{I_b}\sum_{k}^{K}(Q_{j_bi_{b_{in}}kt} - Q_{i_{b_{out}}j_bkt}) \tag{6}$$

For the subset of nodes with exchange pool connections, a separate continuity equation was included as a constraint to calculate the balance of contributions or extractions to exchange pools [Eq. (7)]:

$$\sum_{i=1}^{I}\sum_{k=1}^{K} Q_{ij_bkt} + I_{j_bt} = \sum_{i=1}^{I}\sum_{k=1}^{K} Q_{j_bikt} + R_{j_bt} + L_{j_bt} + P_{j_bt} \tag{7}$$

Finally, for each exchange pool, contributions must equal extractions over the entire time period [Eq. (8)]:

$$\sum_{i_b=1}^{I_b}\sum_{j_b=1}^{J_b}\sum_{k=1}^{K}\sum_{t=1}^{T} Q_{i_bj_bkt} - \sum_{j_b=1}^{J_b}\sum_{i_b=1}^{I_b}\sum_{k=1}^{K}\sum_{t=1}^{T} Q_{j_bi_bkt} = 0 \tag{8}$$

The analysis assessed varied scenarios of groundwater exchange pool existence and organization to understand how alternative arrangements affect exchange pool success. In particular, resulting urban water supply portfolios and shortages were compared for (1) model runs with and without storage pool arrangements, and (2) in scenarios where exchange pools do exist, two options for organizing exchange pools where either existing pumpers in a basin or all parties that overlie a basin can access the storage pool. As noted previously, the first situation simulates exchange pools managed as a single CPR with pumping and storage rights shared among participating parties, while the second simulates exchange pools managed as separate CPRs. Modeling the two cases of groundwater storage pool organization, in which either an existing or an expanded set of pumpers have rights to access storage pools, required slightly different sets of nodes for pumpers in j_b [Eq. (5)].

The network flow optimization (including groundwater exchange pools) was run over scenarios that varied system-wide demands and available imported water. Demands were derived from available sources, including 2010 Urban Water Management Plans (UWMPs) and reports from LA County. The mix of current supply sources and associated allocations for a given retailer was compiled from numerous sources, including UWMPs, engineering reports, groundwater adjudications, and recycled water master plans (Pincetl et al. 2016). Scenarios of input parameters included varying levels of imported water availability (50 or 0% of historic inputs) and demands (100 or 80% of 2010 demands). Model results simulated monthly flows over 15 years (1996–2010) using historic data for imported water supplies and modeled hydrology as included in Artes. Imported water flows were based on historic data provided by the Metropolitan Water District of Southern California and the Los Angeles Department of Water and Power, in which inputs for fully available imported water were 100% of historic monthly inflows to LA County (LADWP 2015a; Metropolitan Water District of Southern California 2015). Table 1 summarizes the model input parameters and exchange pool options that comprise the scenarios.

Model results quantified the volume of flows for each retailer to and from exchange pools, which was analyzed and interpreted according to several metrics. To determine the extent to which exchange pools contributed to urban water supply portfolios, the quantity of supplies coming from exchange pools was compared to other water sources (stormwater infrastructure, groundwater pumping from main basins, and recycled water as nonpotable or indirect potable reuse). To determine effects on long-term groundwater preservation, net extractions of groundwater were quantified over the time series to identify long-term overdraft. Finally, to determine if exchange pools reduce shortages, the average volume of shortages for a retailer across demand scenarios was analyzed and mapped.

Artes uses the optimization software package Gurobi Optimization as a solver, while data processing and input/output operations are performed using Python (JetBrains PyCharm Community Edition). Model parameters were extensively calibrated to quantify surface flows across the natural and engineered systems, within a range of tolerance, to historic hydrologic conditions, using

Table 1. Description of options for model scenarios reported in results

Model scenario option	Description
Water demand	Demands for each water agency used in a model scenario, quantified as a percentage (100 or 80%) of historic (2010) demands. Demands are specified for each month and agency.
Imported water supply	Available imported water used for a model scenario for each of the three primary sources of imports. The values included in the scenario are a percentage (100, 50, or 0%) of historic availability. Available imports are specified for each month and water source.
Existence of exchange pools	For each modeled scenario of supply and demand, the model was run with and without groundwater exchange pools to facilitate comparisons.
Organization of exchange pools	For model scenarios with exchange pools, two ways or organizing exchange pools were compared: (1) exchange pools only accessible to existing pumpers in a basin, and (2) exchange pools accessible to all parties that overlie a basin.

spatially-explicit surface flow records from an existing, high-detail regional model, the Watershed Management Modeling System (WMMS) (LACDPW 2013). A multistep calibration process was described in detail in previous research and supporting documentation (Porse 2017; Porse et al. 2017).

Groundwater basin flows and exchange pool operations were simulated using a bucket approach. No detailed groundwater model exists for the entire metropolitan area; there is a model only for a subset of the regional groundwater basins that are interconnected. This limitation was previously documented and identified as a goal for regional water management to support future sustainable urban water supply regimes (Mika et al. 2018; Porse et al. 2017).

Results

The following results compare scenarios with and without exchange pools, including the instances of exchange pools that are either accessible only by existing pumpers in a basin or are open to all pumpers that overlie a basin.

Exchange Pools with Limited Access

When only current rights-holders in a basin can access storage and exchange pools, so that the groundwater and storage in a basin are treated as a single CPR, results indicate that exchange pools operations can reduce system wide water shortages by 13–39%. The percentage of total supply from exchange pools varied across scenarios (Tables 2 and S1 in the Supplemental Data). Annual net contributions across all pumpers are either positive (net contributions to storage) or negative (net pumping extractions). Scenarios with more available imported water (50% of historic demands) show increased storage pool activity in terms of both volume (contributions and extractions) and number of participating parties [Fig. 3(a)]. Scenarios with no available imported water show smaller, more consistent annual net contributions to and extractions from exchange pools.

The assumptions for available imported water and demands influence storage pool operations (Table 3). As noted, more available imported water results in greater use of exchange pools when measured in terms of volume (Scenarios C and G). Similarly, for scenarios of both higher and lower regional demand, storage pools are more effective at reducing shortages when imported water is available (Scenarios D and H). The presence of imported water also results in a larger variation of net contributions and extractions to pools because retailers have more water for participating in exchanges [Fig. 3(a)]. Scenarios without imported water show smaller and less variable operations, as seen in the graphs of linear net contributions [Fig. 3(a)] and ranked distribution [Fig. 3(b)] across scenarios. Without imported water (Scenarios D and H), a majority of years see net extractions from storage pools, with balances made up in a few wetter years.

The use of storage pools varied by basin, likely due to real-world constraints on pumping as well as the intricacies of management across different basins. The number of pumpers and average monthly extractions vary widely, as shown in Table 4 for one scenario. The Central Basin in the lower coastal plain, which receives flows from upper groundwater basins in the region, has the largest number of average and maximum monthly storage pool participants. The Central and Main San Gabriel Basins, which are large but located in different parts of the region with distinct surface and subsurface hydrologic processes, also have high maximum

Table 2. Comparing supply portfolios across scenarios of demand (% of 2010) and imported water supply (% of historic), with and without groundwater exchange pools

	Scenario							
	No exchange pools		With exchange pools		No exchange pools		With exchange pools	
Statistics	A	B	C	D	E	F	G	H
Demand (%)	100	100	100	100	80	80	80	80
Imported water supply (%)	50	0	50	0	50	0	50	0
Portion of total annual supply (%)								
Imported	41	0	40	0	40	0	43	0
Groundwater	47	80	51	85	48	81	51	89
Storage pools (in years with net pumping)	N/A	N/A	12	6	N/A	N/A	8	3
Reuse (IPR or nonpotable)	11	18	9	14	11	17	6	11
Surface water	1	2	1	2	1	1	0	1
Potential stormwater capture	40	43	62	61	52	54	70	75
Shortages	41	56	2	34	13	47	0	23

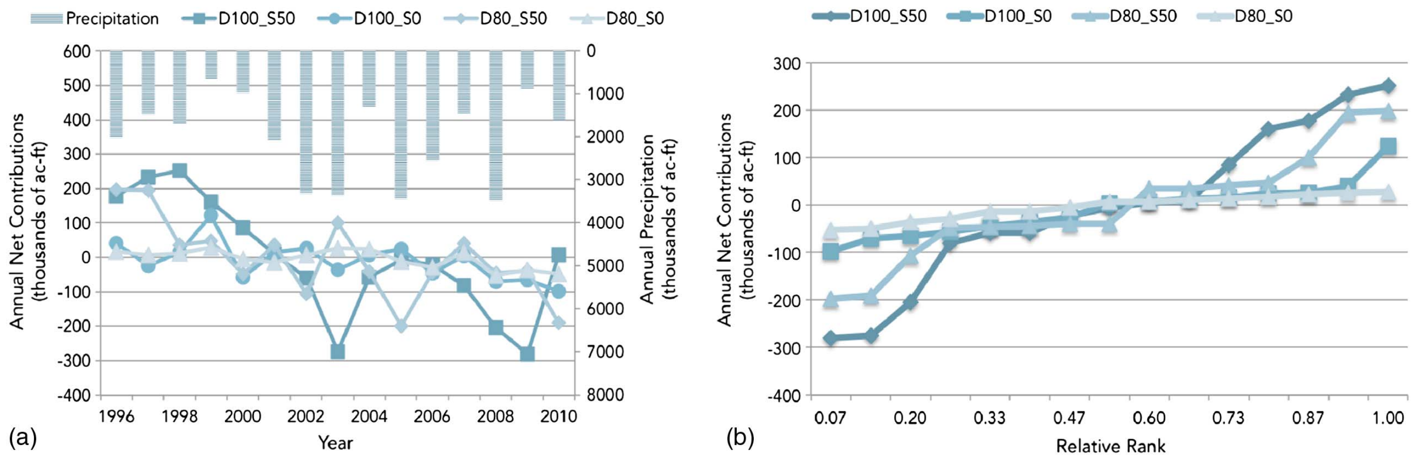


Fig. 3. Modeled annual groundwater exchange pool operations, by scenario, for (a) annual net contributions; and (b) rank-order distribution of annual net contributions.

Table 3. Summary statistics for model scenarios with exchange pools

	Model run			
Statistics	C	D	G	H
Demand (%)	100	100	80	80
Imported water supply (%)	50	0	50	0
Storage pool operation statistics				
Range, max pumping to max contributions, million m^3 (acre-ft)	662 (537,000)	289 (234,000)	497 (403,000)	113 (92,000)
Median annual pumping, million m^3 (acre-ft)	−12 (−10,000)	19 (15,000)	−38 (−31,000)	12 (10,000)
Max annual pumping, million m^3 (acre-ft)	318 (258,000)	168 (136,000)	254 (206,000)	47 (38,000)
Average supplies (%) from exchange pools (for years with net pumping)	12	6	8	3
Range of supplies (%) from exchange pools (for years with net pumping)	1–21	2–16	3–15	1–5
Number of years with net pumping (out of 15 total years)	6	8	7	8
Reduction in shortages (%) from equivalent case without exchange pools	39	22	13	24

Table 4. Comparing pumping operations across LA groundwater basins for the model scenario with 100% demands and 50% imported water supplies (Scenario C)

Groundwater basin	Average number of monthly pool participants	Maximum number of monthly pool participants	Max monthly pumping volume, million m^3 (acre-ft)	Max annual pumping volume, million m^3 (acre-ft)	Median annual pumping volume, million m^3 (acre-ft)
Central	19.8	26	1.1 (820)	62 (50,800)	13.6 (11,000)
Main San Gabriel	13.4	20	0.7 (560)	76 (61,300)	2.1 (1,700)
Puente	0.4	2	0.037 (30)	0.59 (480)	0.37 (300)
Raymond	5.1	9	0.27 (220)	24 (19,300)	−3.3 (−2,700)
San Fernando	2.0	3	0.23 (190)	67 (54,400)	22 (17,800)
Six Basins	0.5	3	0.23 (190)	142 (11,500)	1.06 (860)
Spadra	0.2	1	0.05 (40)	1.0 (850)	0.43 (350)
Sylmar	1.2	2	0.025 (20)	1.6 (1,300)	0.17 (140)
Verdugo	1.1	2	0.15 (120)	4.8 (3,900)	1.2 (1,000)
West Coast	4.7	7	0.33 (270)	33 (26,700)	−2.1 (−1,700)

monthly and annual pumping volumes. The largest pumping volumes, however, are in the San Fernando Basin. The San Fernando Basin belongs primarily to the City of Los Angeles, which is the biggest single user of groundwater in the metropolitan area and has the largest rights to pump from this basin.

The distribution of monthly participation by retailers in an exchange pool varies across basins and scenarios of imported water (Fig. 4). The San Fernando and Central Basins [Figs. 4(a and d)] show higher single-month volumes. The number of months with net pumping and extractions are evenly distributed in most basins [Figs. 4(a–c)]. In the San Fernando Basin, however, monthly participation varies significantly between scenarios, due to a lower number of participants and their large volumes of exchange pool rights [Fig. 4(d)]. The San Fernando Basin, as such, is likely a major driver of variations in total annual pumping. Seasonal differences also arise. Across model scenarios, there is a trend of

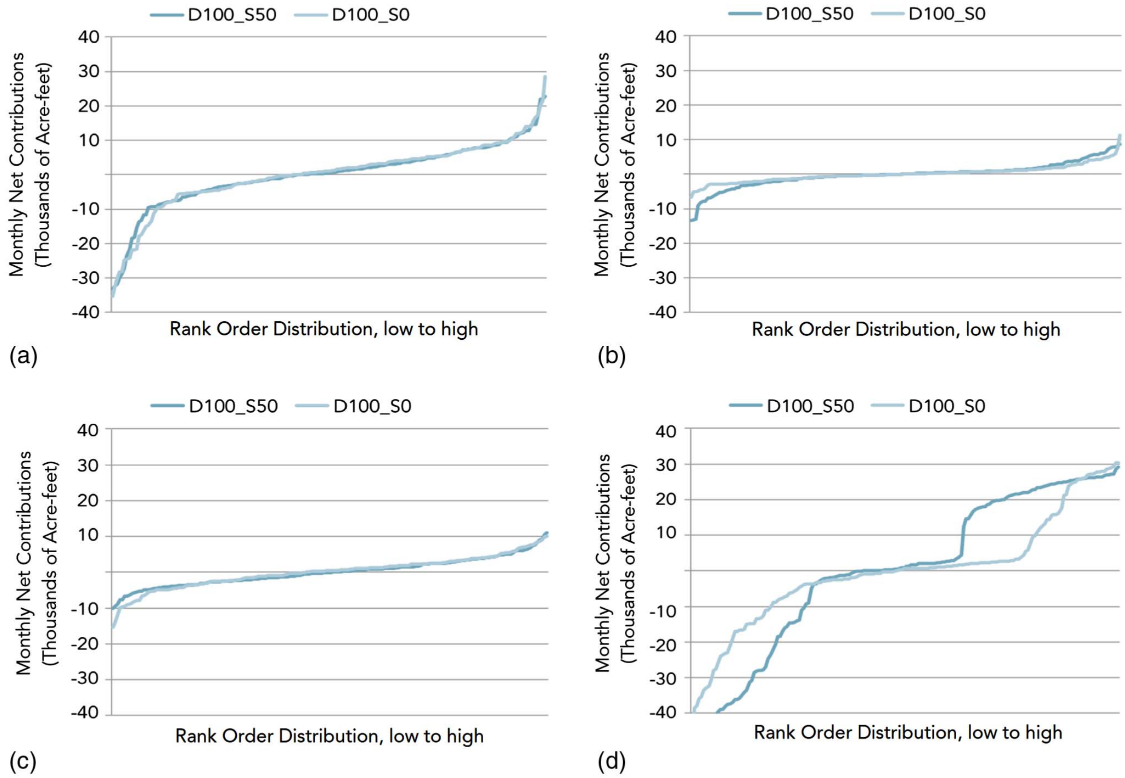


Fig. 4. Distribution of net exchange pool contributions by individual participants for largest groundwater basins in LA: (a) Central Basin; (b) West Coast Basin; (c) Main San Gabriel Basin; and (d) San Fernando Basin. For each basin, two model scenarios are presented, 100% demands and 50% imported water supplies (D100_S50), and 100% demands with no imported water (D100_S0).

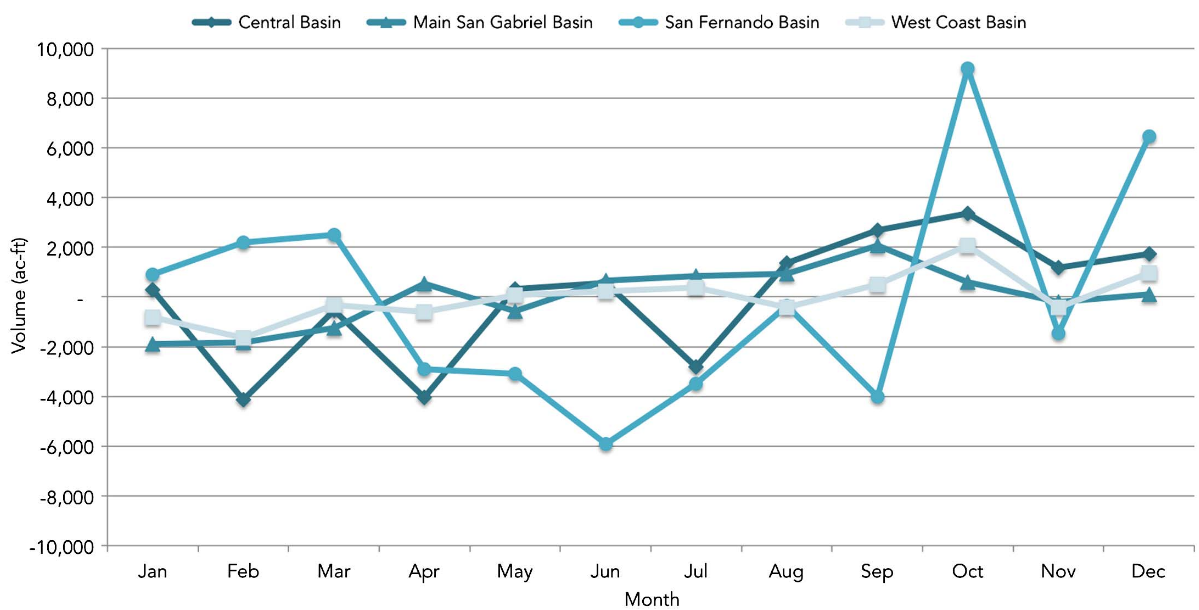
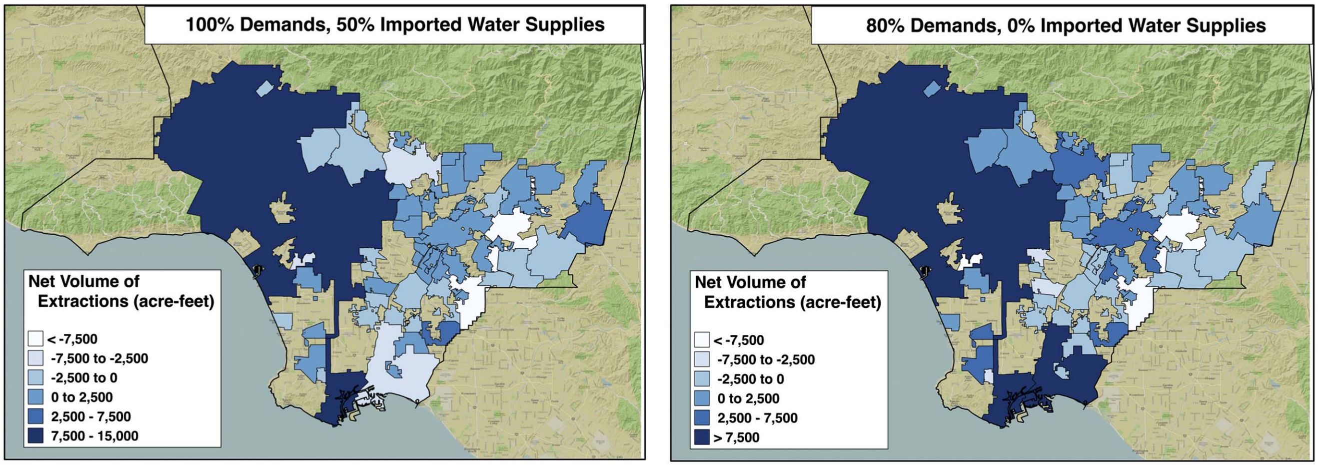


Fig. 5. Average monthly net contributions to exchange pools in the largest groundwater basin for the scenario with 100% demands and 50% imported water supplies.

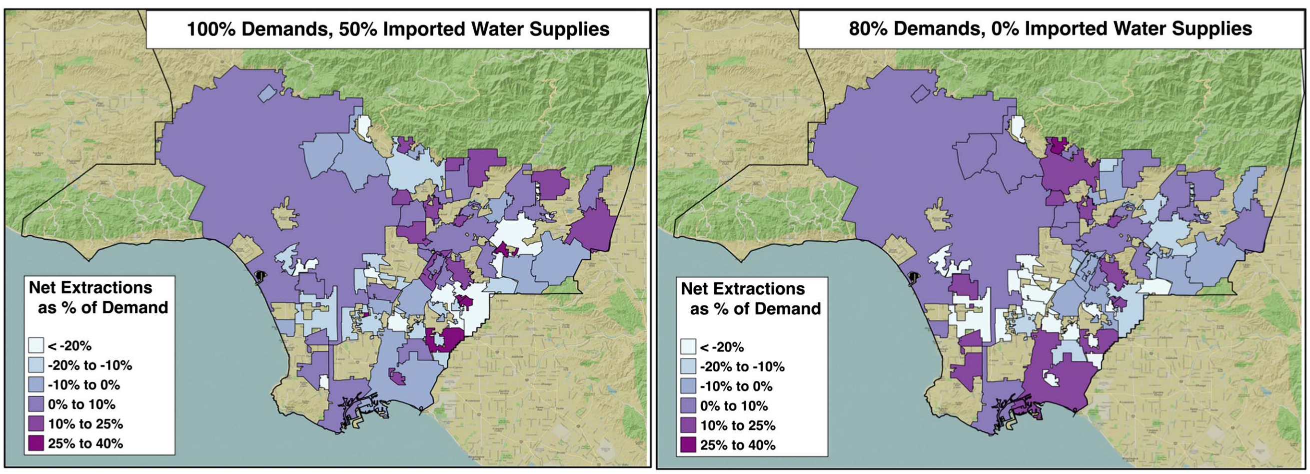
net contributions during winter months and net pumping during summer months, as shown in Fig. 5 for the case of 100% demands and 50% available water supplies (Scenario C).

Among pumpers, the average volume pumped by the largest extractor, the City of Los Angeles, is greater than the largest contributor for scenarios without imported water, but smaller in scenarios with 50% available imported water. The average pumping volumes for the City of Los Angeles were lower, ranging from 14 to 35 million m^3 per year (12,000–29,000 acre-ft) across scenarios. Notably, Los Angeles has the largest population and water demands among retailers in the county. But this indicates that when imported water must be used to meet demands, the many small- and



(a) (b)

Fig. 6. Volume of average annual net extractions by retailers to all groundwater storage pools by LA County water retailers (in acre-ft) for (a) 100% demands and 50% imported water supplies; and (b) 80% demands and 0% imported water supplies. Positive numbers indicate retailers that are pumping groundwater from pools for supplies. (Map data from iPhoto, OpenLayers.)



(a) (b)

Fig. 7. Average annual net extractions by LA County water retailers as a percentage of retailer demands for (a) 80% demands and 50% imported water supplies; and (b) 80% demands and 0% imported water supplies. Positive numbers indicate retailers that are pumping groundwater from pools for supplies. (Map data from iPhoto, OpenLayers.)

medium-sized retailers may be less able to contribute to exchange pools and support larger pumpers such as the City of Los Angeles. Investor-owned utilities are consistently large contributors to exchange pools, as many have dispersed service territories and access to groundwater from multiple basins. Other retailers are not consistent pumpers or contributors. For instance, the smaller cities of Burbank, Glendale, Pasadena, and Long Beach, all of which have municipal water utilities, alternate from being net contributors to being net extractors as imported water decreases [Figs. 6(a and b)]. Generally, reducing demand results in more use of exchange pools.

When considering net contributions as a percentage of demands, however, the picture changes. While the City of Los Angeles is a large extractor, other small regional water supply retailers obtain a larger percentage of supplies from exchange pools [Figs. 7(a and b)]. Retailers in the Upper Basin are large extractors from exchange pools when imported water is available. But across the region, cities such as Pasadena and Long Beach grow reliant on exchange pools to make up for imported water reductions. Notably, these municipal utilities are direct members of the regional agency, the Metropolitan Water District of Southern California, which is the primary water importer.

Exchange Pools with Greater Access

When access to storage pools is broadened to include all retailers that overlie a basin, exchange pools are even more effective at reducing shortages. Across scenarios, when storage and exchange rights are allocated according to geography and not coupled with existing pumping rights, total system shortages drop significantly. For instance, comparing the two scenarios of storage pool arrangements for 100% demands and 50% imported water supplies (Scenarios C and I), more broadly allocated storage pool rights are twice as effective at eliminating shortages. In general, imported water reductions again lead to more years with net pumping, while much larger single-year allocations are present in scenarios with some available imported water as retailers draw heavily in drought years. Exchange pools provide between 6 and 12% of total supplies

Table 5. Summary statistics comparing arrangements for managing common pool resources of groundwater and storage

Statistics	Model run					
	C	I	D	J	H	K
Storage pool arrangement	Existing rights	Geographic	Existing rights	Geographic	Existing rights	Geographic
Demand (%)	100	100	100	100	80	80
Imported water supply (%)	50	50	0	0	0	0
Storage pool operation statistics						
Range, million m^3 (acre-ft)	662 (537,000)	738 (599,000)	289 (234,000)	208 (169,000)	113 (92,000)	278 (225,000)
Median annual pumping, million m^3 (acre-ft)	−12 (−10,000)	−53 (−43,000)	19 (15,000)	−2.3 (−1.9)	12 (10,000)	11.7 (9.5)
Max annual contribution, million m^3 (acre-ft)	318 (258,000)	479 (388,000)	168 (136,000)	99 (80,000)	47 (38,000)	113 (92,000)
Average supplies (%) from exchange pools (for years with net pumping)	12	12	6	7	3	6
Range of supplies (%) from exchange pools (for years with net pumping)	1–21	2–28	2–16	2–12	1–5	1–11
Number of years with net pumping (out of 15 total years)	6	5	8	7	8	8
Reduction in shortages (%) from equivalent case without exchange pools	39	86	22	32	24	42

Note: Scenarios C, D, and H (also reported in Table 2) assume joint management of groundwater and groundwater pool CPRs. Scenarios I, J, and K assume storage pools are available to more retailers.

across agencies. Either having available imported water or reducing demand increases the usefulness of storage pools by allowing retailers more flexibility to participate. Table 5 shows equivalent scenarios of demand and imported water supplies for the two storage pool arrangements, while Table S2 in the Supplemental Data provides further data.

Discussion

The results demonstrate that groundwater exchange pools can be an important tool in managing long-term water scarcity and reduced imports for regional water management in places like Los Angeles. But organizing the governance structure of storage pools is just as important as their existence. Creating effective exchange pools in Los Angeles will require innovations to existing management schemes, much like the innovations that were part of the novel twentieth-century groundwater basin adjudications. Reducing demand by promoting urban water conservation, for instance, provides critical flexibility for local water utilities to participate in exchange pools. But results showed that arrangements allowing participation by more parties in groundwater storage and exchange performed better than arrangements with more restrictive access corresponding to existing agreements. In other words, broadening access to and utilization of groundwater basin storage can improve regional sustainability (Megdal et al. 2014; Shuster and Garmestani 2015). CPR arrangements should more explicitly outline how they allow for agreements to evolve over time to respond to changes in operating procedures such as reductions to imported water.

Considerations for Designing Exchange Pools

Groundwater exchanges can be mechanisms for reallocating water to areas of greater need or economic value. Such exchanges can be organized in many ways, including bilateral transfers, regulated storage pool contributions, or reallocations of groundwater rights based on evaluations of demand and equity. At present, many basins in Los Angeles allow direct, bilateral transfers between retailers, which tend to be smaller (by volume) than the modeled results from this study. A few new regional schemes are organizing broad exchange pools among many retailers. These can even include special dispensation and dedicated storage space for communities in need (*Central and West Basin Water Replenishment District v. Charles E. Adams et al.: Third Amended Judgment*). The future success of regional exchange pool arrangements is unclear and will depend on the implementation details.

Schemes for transferring water among agencies, including markets and exchange pools, typically include economic considerations. Pumping and recharging water costs energy and money, while the infrastructure to acquire, move, store, and recover water requires upkeep. This analysis examined the maximum potential for a likely exchange pool scheme to reduce shortages in an effort to understand the usefulness of such schemes. Details of exchange pool operations are still evolving. An exchange pool based on a water-marketing scheme would reallocate water from areas of availability to areas of higher economic value, assuming the presence of willing buyers and sellers. But such reallocations may not align with the ability of local utilities to pay for water that meets essential baseline health and safety allocations. For instance, undercapitalized water retailers in LA County that serve disadvantaged communities often have limited capital and technical capacity (DeShazo and McCann 2015). Transactions in a market-based groundwater exchange scheme would not necessarily address the poor access to water found in many Los Angeles communities. Thus, how to include economic considerations in exchange pools is a critical question. At minimum, operational procedures of an exchange pool must cover costs for basin management, program administration, and pumping and recharge operations. But exchange pools could go further by ensuring baseline access to water rights across the county, funding groundwater remediation, and promoting scientific data collection and monitoring.

Current Governance and Future Conditions

The continued success of current adjudication schemes in Los Angeles groundwater basins is not guaranteed. The adjudications are seminal examples of CPR governance and have wide applicability to water management applications. The twentieth century adjudications were widely seen as critical innovations for long-term resource preservation, in contrast to most other parts of California, which had little oversight of groundwater pumping (Blomquist 1992). Adjudications emerged from collective concern regarding regional groundwater depletion. Each pumper's rights were inscribed in the adjudications, based on historic water extractions.

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Negotiations among pumpers used agreed-upon, but dated, engineered assessments of water supply. But adjudicated agreements are not easily changed to adapt to new conditions. The system of codified groundwater rights could constrain needed adaptations in regional groundwater basin management. It is critical that such agreements evolve to promote equitable access to water supplies. There are hopeful examples of change, such as the recent readjudication of the Central Basin that permits some new entrants (entities without any rights) to store additional water in that basin, with very specific requirements about year-over-year storage. But such changes are not yet ubiquitous across basins. Revising an adjudicated agreement is time consuming and expensive. Identifying new sources of groundwater recharge will be a continual challenge.

The current adjudications also resulted in detailed definitions that shape current practices. For instance, to get credit for storing water in groundwater basins, retailers must typically demonstrate that contributions are *new water*, that is, water newly imported into the basin or offset through reductions in other volumes. But if a utility invests in stormwater capture infrastructure to augment water supplies, it may not be considered *new water* for some basins, since it could be part of the adjudicated values of natural recharge. Such definitions may reduce incentives for agencies to improve infiltration and augment groundwater supplies. Future interpretations will have wide-ranging implications for water management in western North America.

Exchange Pools and Alternative Water Sources

Beyond direct retailer transactions, other policy mechanisms provide opportunities for exchanging groundwater. Conjunctive use of surface and groundwater supports recharge of surplus water during periods of availability (Blomquist et al. 2001, 2004). Los Angeles has over 20 existing large centralized groundwater recharge basins that can infiltrate water from multiple sources, including captured stormwater, recycled water, or even desalinated water. But optimizing the use of recharge basins requires interagency coordination, which is made more difficult because of current rules under each basin's adjudications. The current adjudications primarily assume available imported water for recharge and do not explicitly describe using alternative sources that are common today.

Recycled water presents additional opportunities for creative water exchange schemes. In addition to Indirect Potable Reuse (IPR), highly-treated nonpotable water can be used via in-lieu virtual transfers. When recycled water is too far from existing recharge zones but close to other end users that could utilize the supply, such as for industrial processes or commercial irrigation, a retailer can pursue a lease with customers that have existing groundwater pumping and storage rights, offering to supply the nonpotable recycled water in exchange for access to stored groundwater. For instance, in the West Coast and Central Basins of Los Angeles, there are approximately 35 million m^3 (29,000 acre-ft) per year of industrial rights, including 27 million m^3 (22,500 acre-ft) per year of unused industrial rights (WRD 2015). Retailers could even lease unused industrial rights without providing in-lieu recycled water, as such rights are not used in current operations.

For stormwater, too, communities in Los Angeles are examining ways to promote new capture and recharge capacity. This presents scientific and managerial challenges. Uncertainty surrounding surface-to-groundwater recharge and the volume of captured water that actually reaches drinking water aquifers inhibits water utilities from receiving monetary or storage credits for building infrastructure to enhance groundwater storage. Additionally, the presence of contaminated groundwater basins throughout LA County, a legacy of past industrial processes, means that water quality implications of recharge must be further studied and continuously monitored. Infiltrating water in one area could promote plume spreading. Despite these challenges, projects are moving forward, such as the Broadway Neighborhood Stormwater Greenway Project in Los Angeles, which is a collaborative project to operate a series of stormwater Best Management Practices (BMPs) across land-use types in the watershed of a local tributary to capture 0.4–0.5 million m^3 (30–50 acre-ft) per year. Coupled with remediation and better scientific tools to understand urban hydrogeologic processes, stormwater capture will continue to be an important source of indirect supply in Los Angeles.

Limitations and Extensions

The analysis is subject to several limitations. In the model, water is exchanged among storage pools without explicitly considering costs or energy for pumping. Exchanges, either bilateral or through market mechanisms, have costs and undercapitalized retailers would not necessarily have resources to access such water. Assessing the relationship between scarcity costs and costs of water supply—and whether this relationship even holds true in a semiarid basin with outdoor water use as a major driver of demand—is a topic of future work. In addition, the analysis assesses maximal potential for groundwater exchanges. The presence of existing bilateral agreements in some basins, which are approved by regulators, could affect the willingness of parties to participate in exchange pools. Also, the model does not include estimates of losses during injection, storage, or extraction. These could affect final quantifications, but in a large metropolitan system that uses 1,200–2,400 million m^3 (1–2 million acre-ft) of water annually, the values are not well-quantified. Finally, limitations of the modeling framework for Artes, described in previous work, are applicable here.

In addition to improving the analysis to better address these limitations, future research could more comprehensively survey existing exchange pool arrangements and analyze, using models and additional empirical techniques, how the structure of such arrangements influences economic and water supply outcomes.

Conclusions

This study assessed the role of groundwater exchange pools in supporting urban water supply sustainability. In Los Angeles, effectively organizing groundwater exchange schemes can help regional water supply agencies meet future demands. The study adapted an existing network flow model of water resources in metropolitan Los Angeles. It included a novel formulation with linear programming that incorporated undirected networks simulating groundwater exchanges, into the larger directed network model. Results showed that exchange pools could comprise 6–12% of total supplies and significantly decrease water shortages. The study also assessed two possible organizational arrangements of exchange pools that simulate when common pool resources of groundwater and groundwater storage are either managed together or separately. Results indicate that greater access to storage pools can go further in reducing water scarcity. Greater access occurs when pumping and storage rights are allocated and managed separately.

Building on the results, the paper discussed equity and economic considerations in organizing exchange pool operations. Exchanges can take many forms, including bilateral exchanges, regulated exchange pools across a basin, groundwater markets, or reallocated rights. We compared and contrasted implications for each of these schemes. As California embarks on developing regional groundwater management schemes through the Sustainable Groundwater

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Management Act (SGMA) passed in 2014, eloquent consideration of the implications of such exchange pool arrangements is highly relevant for both metropolitan and rural regions. The diversity and complexity of water management in Los Angeles is a microcosm of California and many other parts of western North America. Study results provide theory and methods for future water management schemes to deal with climate variability, population growth, and increased water scarcity.

Acknowledgments

This work was supported through grants from the US National Science Foundation Water, Sustainability, and Climate program (NSF Award No. 1204235) and the LA Bureau of Sanitation.

Supplemental Data

Tables S1 and S2 are available online in the ASCE Library (www.ascelibrary.org).

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