Optimal designs for urban groundwater recharge systems that infiltrate both stormwater and recycled water through spreading basins

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Abstract

Increasing pressures on existing water supply systems are leading urban water managers to explore new options for diversifying water portfolios. Infrastructure systems that use stormwater and recycled water to augment groundwater recharge through spreading basins represent cost-effective opportunities to diversify water supplies. However, technical questions remain about how these types of managed aquifer recharge (MAR) systems should be designed; furthermore, existing planning tools are insufficient for performing robust design comparisons. To address this need, this study presents a novel model that describes these MAR systems and optimizes them by life cycle costs and recycled water deliveries. Through a case study of Los Angeles, California, this study illustrates how infiltrating stormwater and advanced treated recycled water through spreading basins could be optimally implemented in this example of a semi-arid city. Case study results illustrate how, compared to centralized

systems, decentralized recycled water systems could offer greater cost savings over their range of available capacities. Compared to existing methods, our model, which can be adapted to other contexts, produces results that allow for a more comprehensive and precise analysis of the tradeoffs between different design scenarios, e.g., centralized vs. decentralized recycled water configurations, and conveyance options to utilize excess capacity in spreading basins. Water management planners can use our model to inform decisions about developing new water supplies to meet future demands.

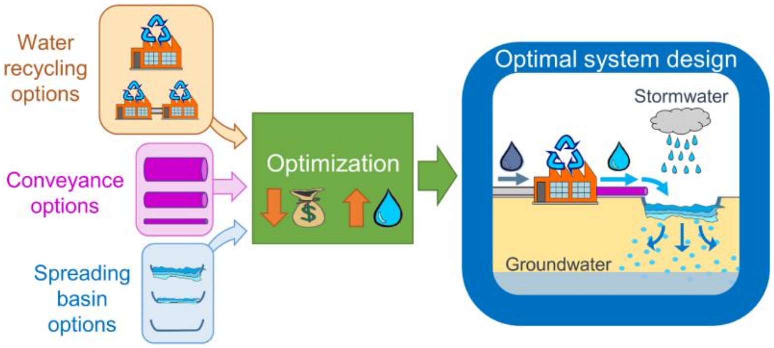

Figure 0. Abstract/ Table of Contents art

1 Introduction

In many regions of the world, groundwater reliability is at risk due to overdraft, reduced natural recharge due to urbanization, and changing precipitation patterns due to climate change.[1] This risk is amplified for cities in dry climates, which are more prone to drought and water shortages. To augment groundwater supplies and enhance drought resilience, one increasingly popular approach is managed aquifer recharge (MAR). In this approach, water—often captured stormwater or diverted surface water—is intentionally percolated through surface spreading or injected underground.[2,3] MAR projects have been developed in over 50 countries, representing every populated continent.[4] However, modern MAR projects have generally been planned without considering how innovative water sources, such as recycled water, can be combined with stormwater to augment groundwater recharge. Despite this general trend, there are a limited number of specially permitted systems that successfully augment MAR with recycled water. Notably, in Southern California, to supplement other MAR water sources, Orange County’s Groundwater Replenishment System produces 100 million gallons per day (MGD; one MGD is approximately 3.785 megaliters per day) of advanced treated recycled water, thereby meeting the annual water needs of nearly 850,000 residents at costs competitive with existing water imports.[5]

Concerns about growing water insecurity—highlighted by the multi-year California drought beginning in the 2012 water year—have generated more widespread interest in MAR with recycled water as a means of indirect potable reuse (IPR) for municipal water supplies. However, the lack of general design and operational guidance for such systems is an impediment to greater adoption.[1,6] Unit costs for spreading basin MAR systems (i.e., monetary costs per unit of water infiltrated) can vary by an order of magnitude depending on system features.[7] Moreover, water managers commonly cite infrastructure costs as the primary barrier to implementation of recycled water projects.[8,9] Consequently, planning tools that can optimize system costs and performance can be used to help cities make more informed decisions about how MAR could fit into their water management strategies. Furthermore, the need for infrastructure optimization is gaining recognition in the engineering field: the American Society of Civil Engineers’ ongoing Grand Challenge program encourages the development and use of optimization methods to reduce infrastructure life cycle costs 50% by 2025.[10]

Although designing and optimizing various water infrastructure components are long-standing subjects of research and professional practice, existing optimization studies have not investigated spreading basin MAR systems that combine stormwater and recycled water. Representative recent design and optimization studies have focused on optimizing the use of existing water infrastructure systems,[11,12] evaluating tradeoffs between centralized and decentralized wastewater treatment configurations,[12–14] designing direct potable reuse (DPR) systems,[15] siting and costing new recharge facilities,[16–19] designing injection systems that use a single source of water,[20,21] or optimizing new recycled water distribution systems.[16,22–24] While informative, these studies,[11–24] collectively, do not include several considerations relevant to spreading basins systems infiltrating both stormwater and recycled water. Specifically, these studies

- Did not consider costs for full advanced treatment (FAT). FAT—which commonly consists of microfiltration (MF), reverse osmosis (RO), and ultraviolet light with hydrogen peroxide (UV/H_2O_2)—is the standard water recycling process planned for new IPR projects in California,[25] and it requires fewer restrictions for recharge under California IPR regulations.[26] IPR projects in Singapore (NEWater[27]) and Australia (e.g., Groundwater Replenishment Scheme in Perth[28] and Western Corridor Recycled Water Scheme in South East Queensland[29]) apply a similar treatment process. FAT costs can be significant; for example, FAT accounts for approximately 85% of costs in Orange County’s Groundwater Replenishment System.[30]

- Optimized either infrastructure costs or recycled water deliveries, potentially resulting in sub-optimal systems when both objectives are considered.
- Optimized recycled water infrastructure based on prescribed average and peak annual demands at the destinations. While this basis is appropriate for recycled water deliveries to a residence or business, it is less fitting for deliveries to a stormwater spreading basin, which may have dynamic unused capacity due to seasonal precipitation patterns. Consequently, an MAR model that prescribes average and peak deliveries may not result in optimal infrastructure designs.
- Did not consider how recycled water infrastructure designs may be constrained by the supply of recycled water to meet potential demands.
- Optimized infrastructure systems where recycled water destinations are connected to a single water recycling facility (WRF), without assessing the potential benefits of multiple, decentralized WRFs that share destinations.

To advance the state of MAR and water reuse planning, this paper introduces and demonstrates a novel method for identifying the best-case design and operation schedule for infrastructure systems that infiltrate both stormwater and advanced treated recycled water through surface spreading basins. Extending previous studies by incorporating the above considerations, we developed a production cost model for FAT recycled water and an optimization process that satisfies the dual objectives of simultaneously minimizing life cycle infrastructure costs and maximizing recycled water deliveries to spreading basins. Our study applies to infrastructure systems with existing separate stormwater and wastewater conveyance, which are often prevalent in relatively recently developed urban areas, including the western United States.

To demonstrate how this model could be used to inform water infrastructure planning decisions in a real-world setting, this work features a case study of Los Angeles, California, (LA) a drought-prone city that plans to expand its use of recycled water to meet future water needs while decreasing reliance on water imports.[31,32] The metropolitan LA region is well-suited for a spreading basin MAR case study given its existing network of approximately 30 existing spreading basins and 10 potential WRFs facilities (Figure 1). Currently, these spreading basins are an underused asset, largely because of LA's Mediterranean climate: on average, LA receives approximately 38 centimeters of precipitation per year, approximately 80% of which occurs during the months of December through March.[33,34] As a result of this strong seasonality, spreading basins that only receive stormwater are underused outside the winter months. Historical data suggest that these spreading basins have received approximately 12% of their theoretical infiltration capacity.[33] Furthermore, groundwater management officials report the aquifers underlying the spreading basins contain substantial available storage, which could potentially be exploited for MAR.[34–38]

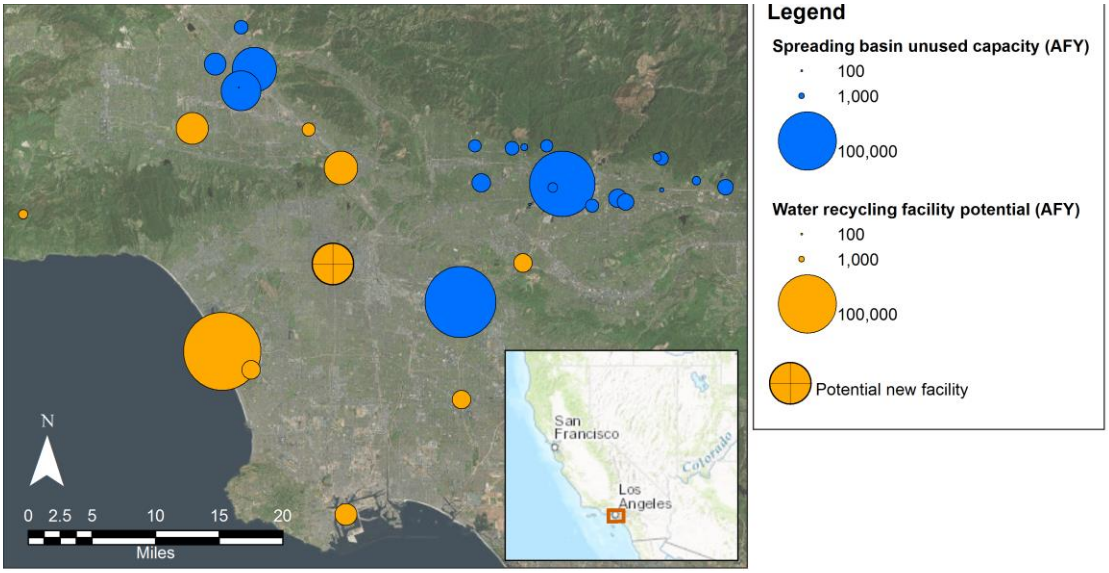

Figure 1. Potential water recycling facilities and existing spreading basins in metropolitan Los Angeles. Spreading basin unused capacity estimates are based on historical infiltration data. Water recycling potential is shown for facilities discussed in the City of Los Angeles recycled water master planning documents. One acre-foot per year (AFY) is approximately 1.23 megaliters per year. Data sources: [33,35,39,40].

2 Methods

This section summarizes our MAR system model and case study, highlighting the model's original contributions and critical differences from existing methods. For the purposes of this study, our MAR system consists of three stages: production of recycled water, conveyance of recycled water to the spreading grounds, and replenishment of groundwater through the infiltration of stormwater and recycled water at existing spreading basins. This section first discusses our modelling and optimization of the whole MAR system, considering both engineering and economic components. Then, our application of the model to a case study of LA is discussed. A more detailed explanation of our model's mechanics and the case study is presented in this paper's Supporting Information (SI).

2.1 Engineering and economic modelling

This subsection details how we modelled the three MAR stages, i.e., production, conveyance, and replenishment. In contrast to existing methods (e.g.,[13,14,16,22–24]), our model considers both engineering and life cycle economic considerations to describe feasible MAR system designs. Of particular relevance to engineering considerations, conservation of mass and energy are explicitly modeled using conventional mass balance and energy loss equations. Moreover, the model includes constraints on operating pipelines (e.g., hydraulic constraints) as well as scheduling recycled water production and delivery. To describe other engineering and economic components, our model generally follows the framework described in the City of Los Angeles's recycled water master planning documents (LA RWMPD).[41]

To comprehensively account for the monetary costs of the MAR infrastructure system, our model uses a life cycle cost (LCC) method. While some prior recycled water design and conveyance optimization studies[15,22–24] account for capital and operation and maintenance (O&M) costs, a LCC method that additionally includes replacement costs and salvage value can more comprehensively represent the true cost over the project's assessment period. A LCC method is especially relevant because the various infrastructure components (e.g., treatment facilities, pump stations, pipelines) have different replacement requirements and useful lives.[41]

2.1.1 Production

For the production stage, our model describes the incremental addition of the FAT process to produce recycled water. We did not explicitly model the costs associated with processes upstream of FAT (e.g., municipal wastewater treatment to produce the FAT influent). Upstream treatment is usually required by regulations or local policies governing wastewater discharges and, consequently, is typically excluded from the cost consideration of recycled water projects. Nevertheless, our model implicitly includes some of the limitations of upstream treatment by incorporating spatial and temporal constraints on the availability of influent for the FAT process.

Our discussions with recycled water design professionals and a comprehensive review of publicly available studies and reports did not reveal any standardized, publicly available methods for estimating the costs of FAT facilities. While Guo et al.[42] provides cost equations for various water recycling technologies, including MF and RO, that study does not include the UV/H_2O_2 process within FAT. Moreover, their equations are fitted from a data series with limited coverage within our WRF capacity range of interest; specifically, for capacities between 1 and 100 MGD, Guo et al. features three and four data points for MF/ultrafiltration and RO, respectively. We aimed to develop a more comprehensive FAT cost model. For reports that include original FAT cost data, estimating practices appear to fall into two categories: some reports[41,43,44] use proprietary methods (e.g., parametric models) to estimate costs for a project based on the itemized costs of required components, e.g., equipment, labor, and chemicals; other reports[45,46] evidently assumed that costs scale linearly with treatment facility capacity relative to some baseline facility.

To address the absence of suitable production cost methods, we developed a mathematical model that predicts FAT costs based on facility capacity. To develop this model, we compiled predicted costs from utility and consultant reports for recycled water projects in California.[41,43,44,47–51] Additionally, we compiled observed cost data for completed projects from other publicly available documents[30,44,52,53] and from our inquiries to water utilities.[54–57] Because these compiled data represent projects in different years and regions, they may incorporate regional or temporal cost differences. To make these data more comparable, we adjusted all costs to 2015 values using the Engineering News-Record Construction Cost Index[58] and the California Consumer Price Index[59] for the Los Angeles-Anaheim region, an approach similar to that followed by other California recycled water cost studies.[13,22,41,60,61] The adjusted data are presented in Figure 2, which illustrates how FAT facility capacity is a predictor of both capital and O&M costs, following a power law relationship. While this is a typical relationship found in process engineering,[62,63] including conventional wastewater treatment technologies,[14] to the best of our knowledge, this relationship has not been reported for the FAT process; moreover, this finding contradicts the practice of assuming that production costs scale linearly with capacity.

These power law relationships form the basis for our production cost model. The equations of the fitted lines in Figure 2 describe FAT capital and O&M costs. Following the LA RWMPD framework, we compute the remaining LCC components (i.e., replacement costs and salvage value) as functions of the capital cost.

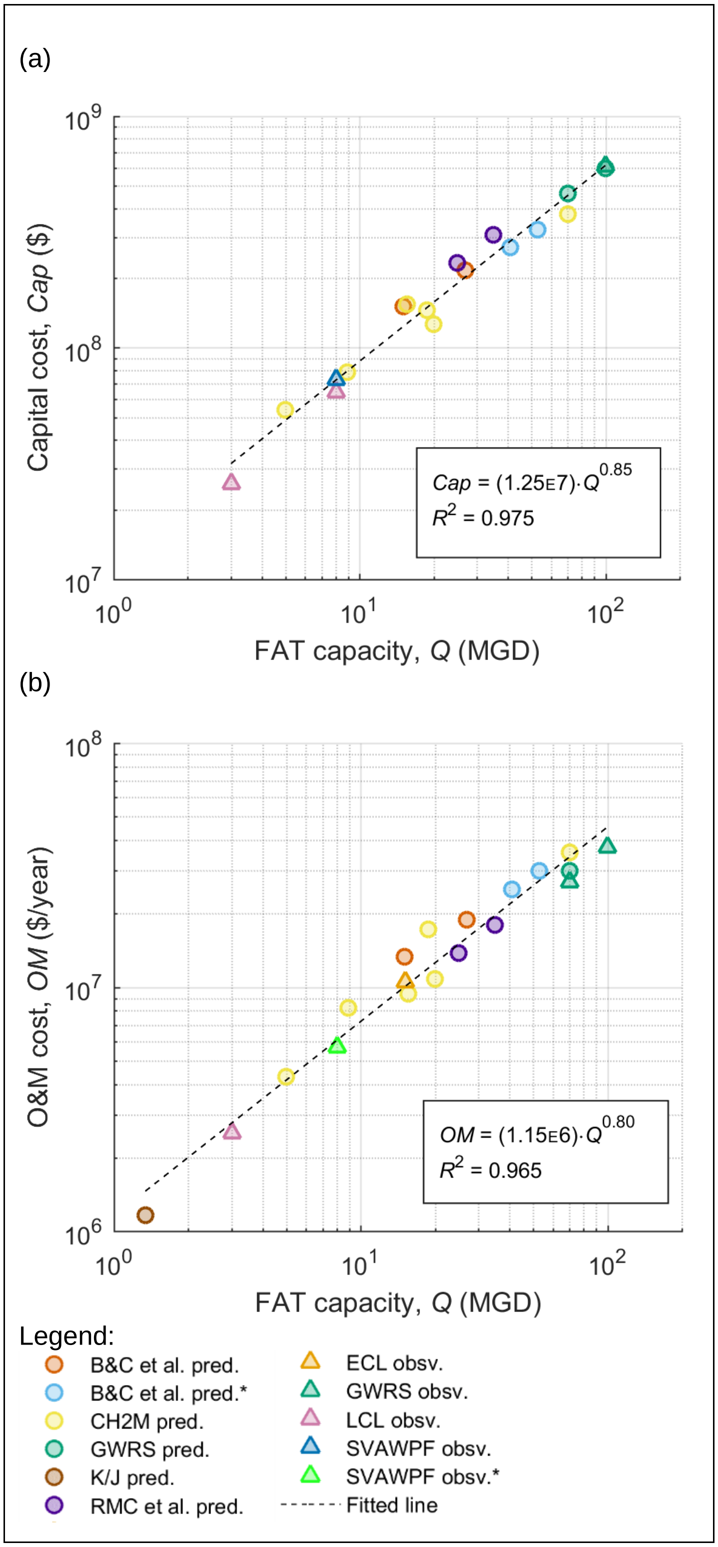
(a)
10^9
10^8
10^7
Capital cost, *Cap* ($)
$Cap = (1.25\text{E}7) \cdot Q^{0.85}$
$R^2 = 0.975$
10^0
10^1
10^2
FAT capacity, *Q* (MGD)
(b)
10^8
10^7
10^6
O&M cost, *OM* ($/year)
$OM = (1.15\text{E}6) \cdot Q^{0.80}$
$R^2 = 0.965$
10^0
10^1
10^2
FAT capacity, *Q* (MGD)
Legend:
B&C et al. pred.
B&C et al. pred.*
CH2M pred.
GWRS pred.
K/J pred.
RMC et al. pred.
ECL obsv.
GWRS obsv.
LCL obsv.
SVAWPF obsv.
SVAWPF obsv.*
Fitted line

Figure 2. Recycled water production cost model developed for this study. Capital costs (a) and operation & maintenance costs (b) are plotted as a function of full advanced treatment capacity. Legend symbols, representing different data sources, are explained in Table S3.1.

2.1.2 Conveyance and replenishment

To describe the conveyance system costs, we applied the methods presented in the LA RWMPD, which are detailed in the SI. To summarize, the costs depend on several variables: the length of the pipeline, the pipe diameter, the velocity of water in the pipe, the elevation profile along the pipeline route, and the pumping requirements, the last of which depend on all the preceding variables.

We considered negligible the life cycle costs of the replenishment stage. Similar to our rationale for excluding production costs associated with processes upstream of FAT, the scope of our analysis includes only the incremental cost of supplying recycled water to existing stormwater spreading basins. As further detailed in the SI, connecting FAT recycled water to existing spreading basins is not expected to substantially increase the life cycle cost of the spreading basin.

While our model considers negligible spreading basins costs, it explicitly quantifies spreading basins' performance, namely, unused capacity (the potential to infiltrate additional water volumes). Although several possible ways exist to quantify unused capacity, our method follows the LA RWMPD framework, which is consistent with LA's policy of prioritizing the infiltration stormwater over recycled water.[50] Using site-specific performance and hydrologic data, our model allocates each spreading basin's finite infiltration capacity between existing spreading basin water sources (primarily stormwater) and potential new sources of recycled water. In this study, we identified each basin's maximum observed recharge volume for each calendar month using historical spreading basin performance data, as explained below. We then computed each month's unused capacity as the difference between this monthly maximum observed recharge volume and the hydraulic loading rate (long-term infiltration rate).[64] The resulting unused capacity measure represents a conservative upper limit for additional water deliveries.

Our model applies the assumption that, at a systems level, any water entering a spreading basin becomes groundwater recharge. This assumption is commonly applied in engineering practice,[33,50] and it is also appropriate given our conservative measure of unused capacity, which limits recycled water delivery rates to less than the hydraulic loading rates. Moreover, the assumption is appropriate for our case study given regional conditions: potential evaporation losses in the metropolitan LA area are negligibly small (on average, less than 0.5 centimeters of reference evapotranspiration per dayr[65]) compared to theoretical hydraulic loading rates (on the order of tens of centimeters per day or more for nearly all LA spreading basins[33]). This assumption also applies in other dry regions. Scanlon et al.[2] report estimated evaporative losses of less than 1% and approximately 1% of delivered water volumes for spreading basin systems in California's Central Valley and Tucson, Arizona, respectively. In Australia, Dillon and Arshad[19] report that MAR can result in low or no evaporative losses, and they assume 5% losses in a case study in New South Wales, Australia.

2.2 Optimization

Using the modelling principles described above, we formulated an optimization problem to describe a spreading basin system that infiltrates both stormwater and recycled water. This problem describes the costs and performance of the system subject to constraints on the availability of recycled water, WRF operations, spreading basin unused capacity, conservation of mass and energy, and pipeline hydraulic constraints. A detailed problem formulation is presented in the SI.

For these MAR systems, reliably optimizing the dual objectives of minimal life cycle costs and maximal recycled water deliveries required a new method. To weigh these objectives equally, our strategy was to transform this dual-objective program into a single-objective program that minimizes the unit life cycle cost, defined as the ratio of life cycle costs to recycled water deliveries over the project's assessment period. This optimization problem is classified as a mixed integer nonlinear program (MINLP), and the non-linear terms are non-convex, signifying that conventional, gradient-based optimization techniques cannot be used to find a global optimum. As other studies (e.g., [23,24]) have noted, although stochastic approaches or approximation algorithms are popular techniques for finding near-optimum solutions to this kind of water infrastructure MINLP, these techniques are limited because they often cannot guarantee finding the global optimum.

In contrast to existing methods, our optimization method reliably converges to the global solution for systems featuring a single WRF. We applied a strategy of reduction and iteration that identifies the solution without material losses in solution precision. Although our MINLP can be described with many decision variables, through dependent relationships it can ultimately be reduced to consist of two continuous variables (WRF production capacity and recycled water production schedule) and two integer variables (conveyance pipeline diameter and conveyance pump station locations). Our method exploits two properties of this reduced program to find a global solution. First, for a fixed production capacity value, the non-linear terms in our MINLP become convex. Second, for a fixed pipeline diameter value, the remaining integer terms can be efficiently minimized though a separate optimization subroutine. Consequently, iterating through production capacity values and pipeline diameters allows us to find the global optimum using proven convex optimization techniques, such as the interior-point methods we selected and implemented using MATLAB.[66]

Applying this optimization strategy also allows us to find the near-optimal solution for systems with multiple WRFs in series, a design not demonstrated in previous studies and potentially not possible with the methods used in those studies. In contrast to existing recycled water studies, which often do not discuss the error associated with their approximation methods, the error for our method can be bounded by comparing results between two separate methods that respectively over-estimate and under-estimate the optimum. As further discussed in Section 3, this error in our case study was immaterial. The SI contains additional details on the optimization and error-estimation process.

Our optimization process differs in another significant way by requiring that potential pipeline paths are specified. That is, our model's user must specify candidate pipeline routes to evaluate. This feature differs from other recent recycled water distribution optimization studies solving MINLPs, e.g., Lee et al.,[22] in which an approximation method identifies a pipeline route within a factor of 11/6 of the global optimum. An advantage of our process is that it permits convergence to a global solution, thereby reducing the uncertainty of the results. This method's application to our case study is further discussed in the subsection below and the SI. In professional practice, we expect that the water utility or consulting engineers designing the recycled water system would identify multiple candidate pipeline routes based on various site-specific social and technical considerations, such as potential impacts on traffic, existing subsurface infrastructure and right-of-way, and environmental impacts. These engineers could then use our method to compute and compare the globally optimal design for each candidate route.

2.3 Los Angeles Case Study

Based on proposed scenarios within the LA recycled water master planning documents, our case study illustrates several potential options for connecting WRFs to two existing spreading basins. We examined options for connection the Hansen Spreading Grounds (Hansen) to three potential WRFs—the Donald C. Tillman (Tillman), LA-Glendale, and Hyperion facilities—all of which are existing wastewater treatment plants that could hypothetically be upgraded to include FAT. Additionally, we assessed the option of connecting LA-Glendale and Tillman in a serial configuration (Tillman+LA-Glendale system). Under this scheme, treated wastewater effluent could be conveyed from LA-Glendale to Tillman, where treated effluent from either LA-Glendale or Tillman could undergo FAT and be conveyed to Hansen. We also examined options for connecting the Rio Hondo Spreading Grounds (Rio Hondo) to Hyperion and a potential new satellite wastewater treatment facility proposed for downtown LA, referred to as the New Metro Satellite facility. These different scenarios are depicted in Figure 3.

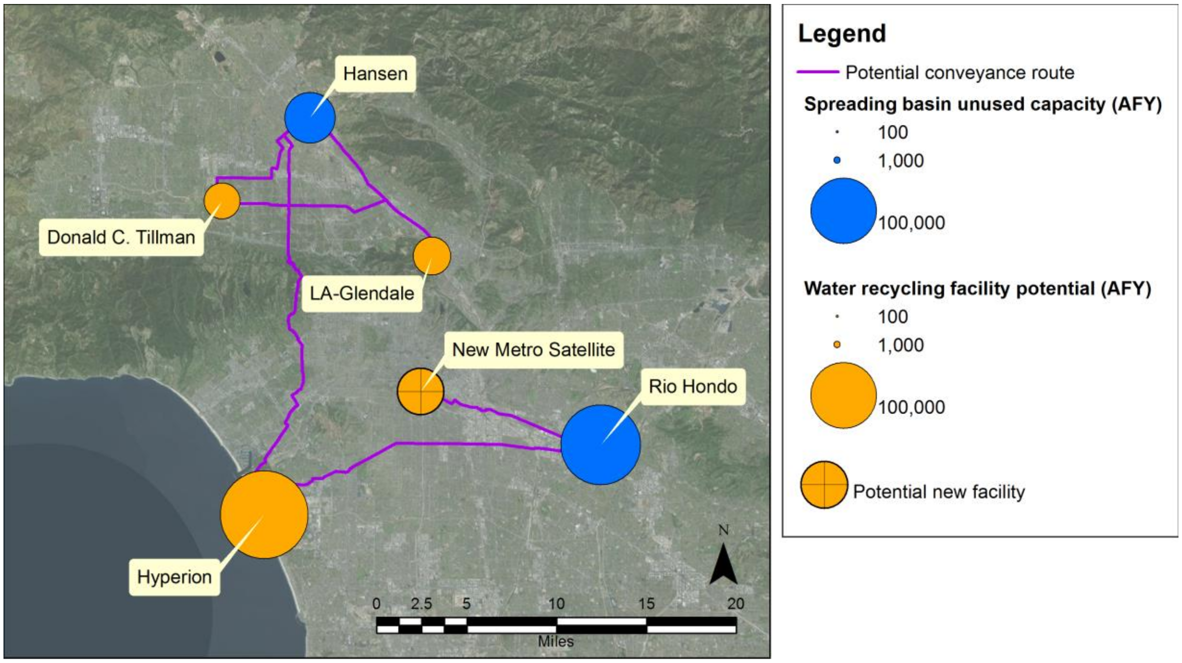

Figure 3. Map of MAR system scenarios evaluated in LA case study. Data sources: [33,35,39,40].

The range of our case study's design scenarios aids in evaluating the tradeoffs associated with varying levels of recycled water centralization. Connecting spreading basins to Hyperion, LA's terminal wastewater treatment facility, is consistent with the centralized water infrastructure paradigm conventionally practiced in the developed world. In contrast, connections to smaller, satellite WRFs represent more decentralized systems, which are an ongoing focus of research (e.g., [12,13,15,67,68]).

Although typically excluded in existing optimization studies, production and replenishment facilities have physical upper limits to their use that are advantageous to incorporate into a practical system analysis. As discussed above, spreading basins' unused capacities represent the upper limit for additional water deliveries; to estimate unused capacity, we compiled historical spreading basin performance data provided by municipal agencies and regional watermasters for Hansen (from water years 1979 to 2008)[69,70] and Rio Hondo (from water years 1989 to 2014, earlier data unavailable).[70] Discussed further in the SI, the resulting unused capacities are represented on an annual basis in Figures 1 and 3.

For production, each potential WRF has an upper limit of FAT recycled water that could be produced for MAR based on factors such as temporal fluctuations of treated wastewater effluent flows and the need for in-stream flows throughout the year. For our case study, we used the limits presented in the LA RWMPD, and we assume that each WRF could potentially construct FAT capacity up to this prescribed upper limit. Notably, the LA RWMPD specifies that LA-Glendale's potential to produce recycled water for MAR is capped at 20 MGD during summer—compared to 40 MGD during winter—due to existing recycled water commitments. As discussed in the results section below, this feature leads to unique behavior compared to systems with the other WRFs, which could produce a constant upper limit of recycled water year-round.

The potential pipeline routes we identified (Figure 3) represent actual routes specified in the LA RWMPD and hypothetical routes that we developed for the purposes of our case study. While the LA RWMPD provides a specific route connecting Tillman to Hansen, it does not provide route details for any of the other design scenarios investigated in our case study. For all other design scenarios, we developed hypothetical, best-case pipeline routes by finding the shortest feasible pipeline route. Extending Lee et al.'s[13] routing method, we defined a path as feasible if it followed major roads (excluding freeways, which are more likely than other roads to be elevated) or other public rights-of-way. Using Dijkstra's algorithm, we identified the shortest path along these transportation corridors as defined and categorized by the County of Los Angeles.[40] This analysis was performed using ArcGIS.[39] As Lee et al.[22] observed, restricting pipeline routes to feasible corridors differs from existing studies that commonly assume pipelines could be installed along the Euclidean distances between facilities, an assumption that is often unrealistic in densely-developed, urban settings.

Following the methods outlined above, the primary production and conveyance parameters used in the LA case study are summarized in Table 1.

Table 1. Summary of case study design scenario parameters.

Case study	**Scenario name**	**Production parameters [a]**		**Conveyance parameters [b]**	
		Winter maximum potential capacity, MGD (ML/d)	Summer maximum potential capacity, MGD (ML/d)	Pipeline distance, miles (km)	Net elevation change, feet (m)
Hansen Spreading Grounds	Hyperion system	160 (606)	160 (606)	27 (43)	910 (277)
	LA-Glendale system	40 (151)	20 (76)	11 (18)	520 (158)
	Tillman system	27 (102)	27 (102)	11 (18)	250 (76)
	Tillman+LA-Glendale sys.	67 (254)	47 (178)	25 (40)	520 (158)
Rio Hondo Spreading Grounds	Hyperion system	160 (606)	160 (606)	23 (37)	130 (40)
	New Metro System	45 (170)	45 (170)	11 (18)	-26 (-7.9)

[a] Production parameters, representing the potential to produce recycled water for MAR, were provided in the LA RWMPD.

[b] Conveyance parameters were computed using ArcGIS

3 Results and Discussion

This section discusses how our model can inform plans to connect WRFs to spreading grounds and improve urban water management. Specifically, it examines the results of our case study and how this work contributes to a greater understanding of urban MAR systems that combine stormwater and recycled water. The subsections are organized to discuss connection options for the Hansen Spreading Grounds and the Rio Hondo Spreading Grounds individually before this section concludes with general lessons from this study and opportunities for future research.

3.1 Hansen Spreading Grounds

Our Hansen Spreading Grounds study addresses questions related to the optimal scale of water recycling operations and opportunities for wastewater treatment plants to work together to deliver recycled water. Figure 4 plots the results of the different Hansen design scenarios, which include a centralized paradigm design (Hyperion system) and several decentralized options. Although most design variables are not explicitly displayed in this figure, each point on the curves represents the best-case design for production (i.e., WRF capacity and production schedule), conveyance (i.e., pipeline and pump stations), and replenishment systems. The data series labeled “Idealized production” represents the optimal design solution for a FAT facility operating year-round at full capacity with no conveyance costs. This series’ inclusion facilitates comparisons between the MAR system designs we assessed and an idealized FAT facility. Each systems’ minimum delivery value is based on a 3 MGD capacity, the smallest facility for which both capital and O&M production cost data were available; note that to enhance figure clarity, the Hyperion system scenarios presented in Figures 4–6 are truncated, with a minimum capacity of 4 MGD. Maximum delivery values are determined by the point where either (a) the capacity to infiltrate recycled water is exhausted for all months or (b) recycled water production is equal to the WRF potential capacity or 100 MGD (the largest facility for which production cost data were available). Between these minimum and maximum delivery values, each series is composed of the optimal solutions computed using production capacity increments between 0.02 and 0.05 MGD.

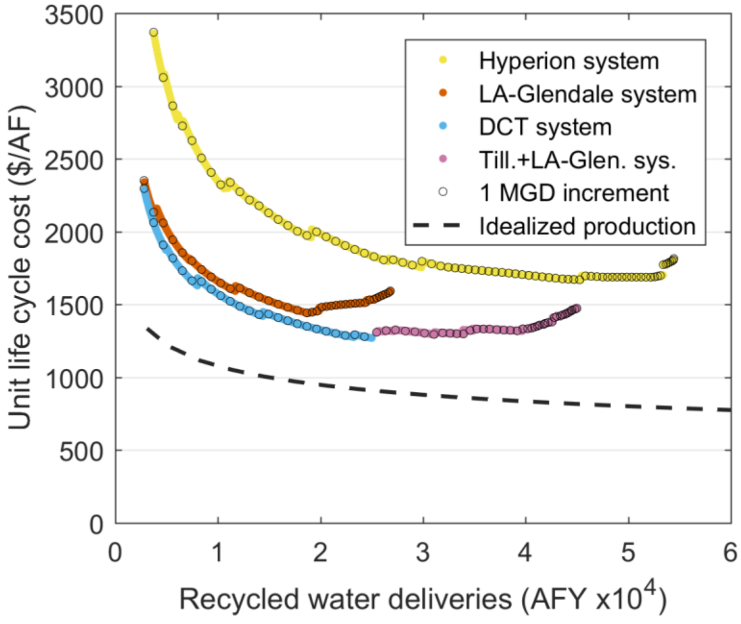

Figure 4. Optimal unit life cycle costs for case study design scenarios connecting recycled water to Hansen Spreading Grounds. The "1 MGD increment" series tracks how the optimum solution changes with a 1 MGD change in FAT capacity. The "idealized production" series represents the optimal design solution for a FAT facility operating year-round at full capacity with no conveyance costs.

The curves in Figure 4 exhibit some expected behaviors. First, they generally demonstrate the economies of scale effect, with unit life cycle costs decreasing with greater recycled water deliveries and corresponding increases in WRF capacity. The curves also include discontinuities, which are a result of the conveyance systems' integer variables: when a marginal increase in recycled water deliveries necessitates installing a new pump station, selecting a larger pipe size, or changing the installation technique for large pipes, these features sharply increase costs.

Beyond exhibiting expected system behaviors, the curves also provide insights into this system that are otherwise unavailable using existing MAR or recycled water network design methods. In particular, the differences between the MAR system and ideal production curves are a result of two factors: conveyance costs and system inefficiencies. These roles of these factors are clearer in Figure 5, which illustrate the contributions of production and conveyances costs to the unit life cycle cost for the Hyperion and Tillman systems.

Conveyance costs, the first factor, are expensive in a highly developed urban area like LA. The City of LA estimates the capital cost of installing recycled water pipeline ranges from approximately 1 to 30 million United States dollars per mile (a mile is approximately 1.6 kilometers), depending on the pipe diameter.[41] In addition, as summarized in Table 1, all of the WRFs in this study are located downgradient from Hansen, so pumping requirements add costs. Because the centralized system design requires pumping from Hyperion, which is both farther away and further downgradient from Hansen, the Hyperion system has substantially higher costs than the decentralized options. As seen in Figure 5, conveyance costs constitute approximately half of the Hyperion system’s unit life cycle cost; in contrast, conveyance costs are much less for decentralized designs, e.g., the Tillman system.

The second factor, system inefficiencies, refers to factors that limit WRFs from operating at full capacity. For example, because seasonal precipitation patterns leave spreading basins with less unused capacity in winter, a large capacity WRF may operate under-capacity during the winter. In Figure 5, production costs above the “idealized production” line represent these production inefficiencies. Production and conveyance inefficiencies also explain why unit life cycle costs for the LA-Glendale system and Hyperion system increase when delivering more than approximately 19,000 acre-feet per year (AFY; an acre-foot is approximately 1.23 megaliters) and 50,000 AFY, respectively: delivering recycled water volumes above those values requires adding infrastructure capacity that proportionally increases costs more than water deliveries. The increase is amplified in the LA-Glendale system because of its reduced potential to produce recycled water during summer, as described in Section 2.3.

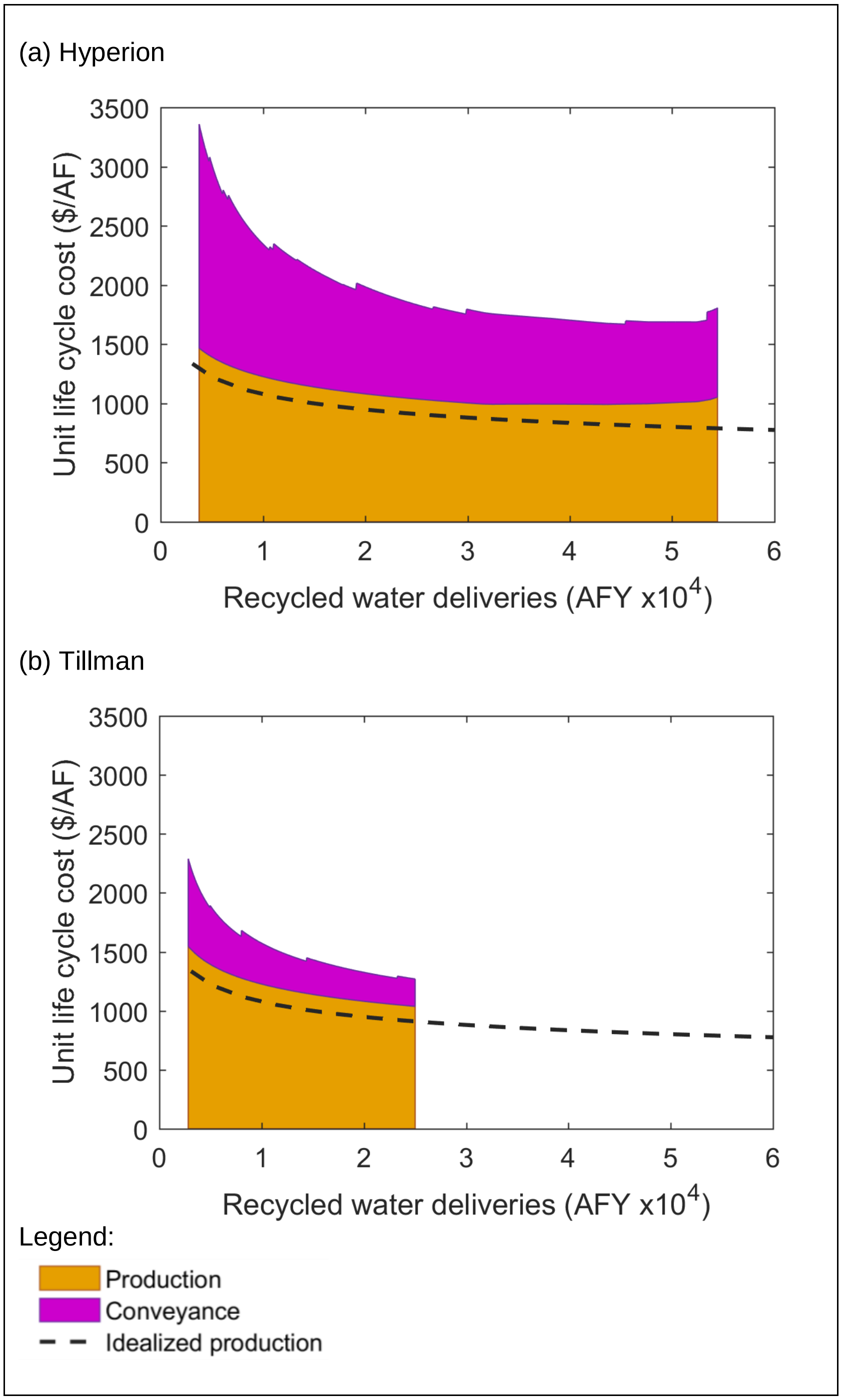

Figure 5. Optimal unit life cycle costs for connecting recycled water to Hansen Spreading Grounds for (a) the Hyperion system and (b) the Tillman system. Costs are

apportioned according to contributions of production and conveyance stages. The "idealized production" series represents the optimal design solution for a FAT facility operating year-round at full capacity with no conveyance costs.

These results also reveal new insights into the potential for WRFs operating in a serial configuration. Our model indicates the decentralized, Tillman+LA-Glendale system can deliver nearly 45,000 AFY with life cycle costs lower than the centralized Hyperion system (Figure 4). Although the results for the Tillman+LA-Glendale system represent a near-optimum—rather than the global optimum guaranteed for the other design scenarios—the error for this system is 3% or less, which is both a relatively small error for an approximation method and immaterial when comparing this design scenario to the others featured in our case study.

3.2 Rio Hondo Spreading Grounds

Our Rio Hondo Spreading Grounds case study addresses questions related to the opportunity for new decentralized wastewater treatment and recycled water production facilities. Figure 6 plots the results of two different design scenarios connecting WRFs to Rio Hondo. Like the Hansen case study, the Rio Hondo case study includes a centralized design (Hyperion system) and a decentralized design (New Metro Satellite system). Unlike the Hansen case study, in which only existing wastewater treatment facilities were evaluated, the Rio Hondo case study features a wastewater treatment facility, New Metro Satellite, that does not currently exist but was proposed in the LA

RWMPD. Consequently, our results help quantify the opportunity for this potential new WRF. Over its potential delivery range, the decentralized New Metro Satellite system offers lower unit life cycle costs than the centralized Hyperion system. These lower costs follow from a lower requirement for conveyance infrastructure. As shown in Table 1, the New Metro Satellite system requires less than half of the total pipeline of the Hyperion system; moreover, while Hyperion is located downgradient of Rio Hondo, the New Metro Satellite WRF would be located upgradient of Rio Hondo, thereby reducing pumping requirements.

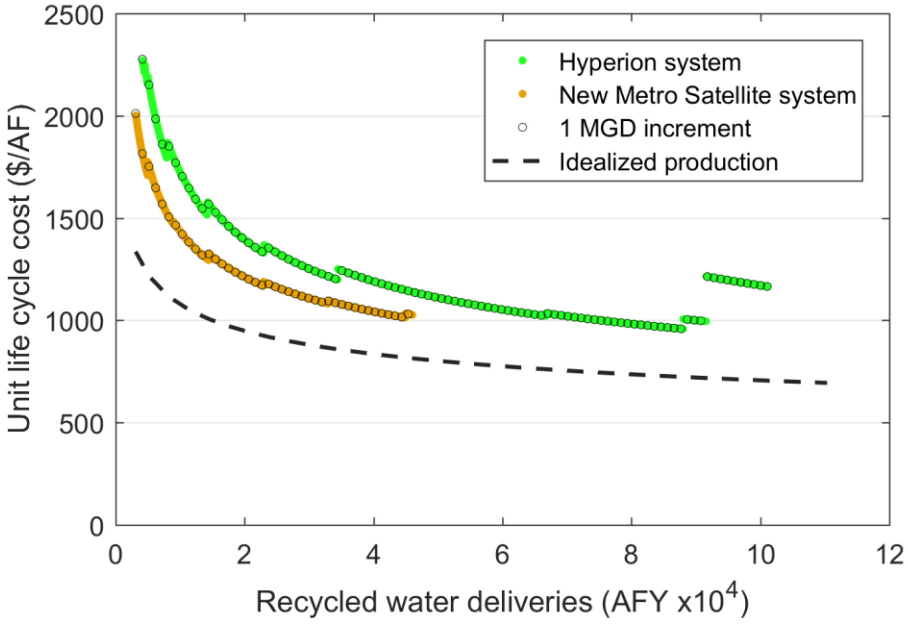

Figure 6. Optimal unit life cycle costs for connecting recycled water to Rio Hondo Spreading Grounds. The “1 MGD increment” series tracks how the optimum solution changes with a 1 MGD change in FAT capacity. The “idealized production” series represents the optimal design solution for a FAT facility operating year-round at full capacity with no conveyance costs.

3.3 Discussion

This study advances the state of modeling and optimization of urban MAR systems using stormwater and FAT recycled water. Specifically, this study incorporates new modelling and optimization features that extend existing studies to include several practical considerations to quantify infrastructure design tradeoffs more comprehensively and precisely. As illustrated through its application in our case study, our model provides unique insights into the tradeoffs associated with spreading basin

MAR designs of different scales, locations, and configurations in a semi-arid city. In particular, case study results illustrate how, compared to a centralized recycled water configuration, decentralized configurations could offer greater cost savings over their range of available capacities.

This paper argues the merits of our engineering and economic models—and their applicability to our LA case study. However, as with any model, our model should be understood as a decision support tool, results from which require a user’s thoughtful interpretation. In its current form as a systems-level model, our methods provide users with high-level insights about designs that optimize infrastructure costs and recycled water deliveries to spreading basins. With the level of complexity presented in our illustrative case study, modelling results would be especially useful in early-stage planning to identify which design ideas offer the greatest potential and deserve additional investigation. Nevertheless, our modelling framework is customizable, so users could modify underlying assumptions or parameters to better suit their specific context (e.g., climate and other hydrologic conditions, labor costs) or a different project scope.

After adapting our model to their specific context, urban water management planners can use this study and model to make more informed decisions about developing new water supplies to meet future demands. For example, this planning tool could be used to better assess the tradeoffs of MAR compared to other water reuse technologies or water management alternatives, such as seawater desalination.

This study can serve as the foundation for additional research into MAR systems or, more generally, water infrastructure systems. For example, researchers could use this study and life cycle assessment studies (e.g., [68,71,72]) to more holistically assess tradeoffs between optimal water recycling configurations at different scales, such as for the whole of Los Angeles County. Future research could also expand our modeling and optimization framework to consider more complex infrastructure configurations (e.g., multiple treatment plants in parallel) or advanced hydrogeologic behaviors. Moreover, additional research could investigate the extent to which modifying key policy parameters affect optimal MAR system designs. For example, our case study applies the City of LA’s method for computing spreading basin unused capacity, which prioritizes the infiltration of stormwater over recycled water. Considering the availability of recycled water can be more certain than the availability of stormwater, it is conceivable that a policy that instead more strongly emphasizes the role of recycled water could produce greater total recharge volumes and consequently improve the overall economics of an MAR system.

4 Supporting Information Description

The SI contains additional case study parameters and detailed explanations of our modelling and optimization methods.

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