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The importance of system configuration for distributed direct potable water reuse

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Water and wastewater infrastructure worldwide faces unprecedented demand and supply conflicts that require unconventional solutions. In this study, we develop a novel modelling framework to assess the environmental and economic implications of a hybrid water supply system that supplements a centralized surface water supply with distributed direct potable reuse (DPR) of municipal wastewater, as a strategy to address such challenges. The model is tested with real water and wastewater systems data from the City of Houston, Texas. Results show that supplementing the conventional centralized water supply with distributed DPR would reduce water age in the drinking-water distribution network and hence improve water quality; properly designed system configurations attain system-wide net energy savings even with the high energy consumption of existing technologies used for advanced treatment of the wastewater. A target energy efficiency for future advanced treatment technologies is identified to achieve net energy saving with all hybrid system configurations. Furthermore, distributed DPR remains financially competitive compared with other unconventional water supply solutions. The modelling framework and associated databases developed in this study serve an important research need for quantitatively characterizing distributed and hybrid water systems, laying the necessary foundation for rational design of integrated urban water systems.

Water and wastewater systems are critical infrastructure for cities. An urban water supply system consists of source waters, treatment plants, storage tanks, interconnected networks of pipes and other infrastructure, which together provide an uninterrupted supply of pressurized drinking water to end users. Wastewater collection and treatment systems remove contaminants from sewage before discharging it into natural water bodies. Most urban centres today rely on a centralized water supply system, which treats source water, typically a surface water, at a central facility and distributes it to each user through a massive distribution network[1]. However, such a system relies on complicated infrastructure and substantial energy use for delivery[2], suffers from water quality deterioration in the large distribution network[3] and has been shown to have little resilience to disruption (for example, impact by natural hazards) due to the large scale of impact and long recovery time[4]. In major cities throughout the world, such centralized water supply systems face unprecedented challenges: global climate change, which leads to large uncertainty in existing water sources; population growth and continuing urbanization, which drive rapid increases in water demand[1,5], intensifying competition for water among different sectors[6]; aging of the infrastructure and the lack of financial resources for related maintenance and upgrade[7].

Diversifying water sources and distributing water supply have emerged as a potential approach to enhance the resilience of urban water systems[8,9]. A distributed water supply system uses multiple water sources distributed throughout the service area. A feature of such distributed water supplies is the small distance to their points of use[8], which decreases conveyance needs[10] and minimizes water quality deterioration during transport, potentially reducing the economic and environmental costs of water supply[11]. Depending on local availability, alternative water sources, including seawater, brackish groundwater and municipal wastewater, can be used to supplement conventional sources, addressing shortage or uncertainty in conventional sources (for example, droughts). Municipal wastewater is considered the most reliable alternative source as its availability is independent of geographic location[12]. In addition to non-potable applications such as irrigation, reclaimed wastewater can be used as direct or indirect potable water sources. Direct potable reuse (DPR), also called pipe-to-pipe reuse, distributes wastewater treated to drinking-water quality directly to users through the same water distribution system used for conventional water sources[13]. DPR has been successfully applied in Windhoek, Namibia, since 1968[14]. Increasing interest in DPR has been seen in the United States in recent decades as new strategies have become needed to help meet future water demands and develop more sustainable water supplies[15–19]. With a distributed wastewater system, that is, multiple wastewater treatment plants (WWTPs) throughout the service area, treated wastewater can be reclaimed and used as distributed water supply sources through DPR.

Existing literature underscores the important role of distributed wastewater treatment and reuse systems in enhancing sustainability and resiliency of urban water infrastructure and has evolved from proposing decentralized systems (see the Decentralized versus distributed section in Methods) based on anticipated and qualitatively described benefits to a more quantitative and objective approach to assessing the costs and benefits. Gikas and Tchobanoglous[10] discussed the different types of decentralized wastewater management systems and examined two cases[10]. Zodrow et al.[20] envisioned a hybrid centralized/distributed urban water system that enhances efficiency and resiliency, and discussed approaches and research needs for overcoming implementation challenges. However, only a limited number of studies[8,21,22] have quantified benefits and tradeoffs to justify investment and inform policymaking with analytical tools. For example, Kavvada et al.[21] compared a centralized

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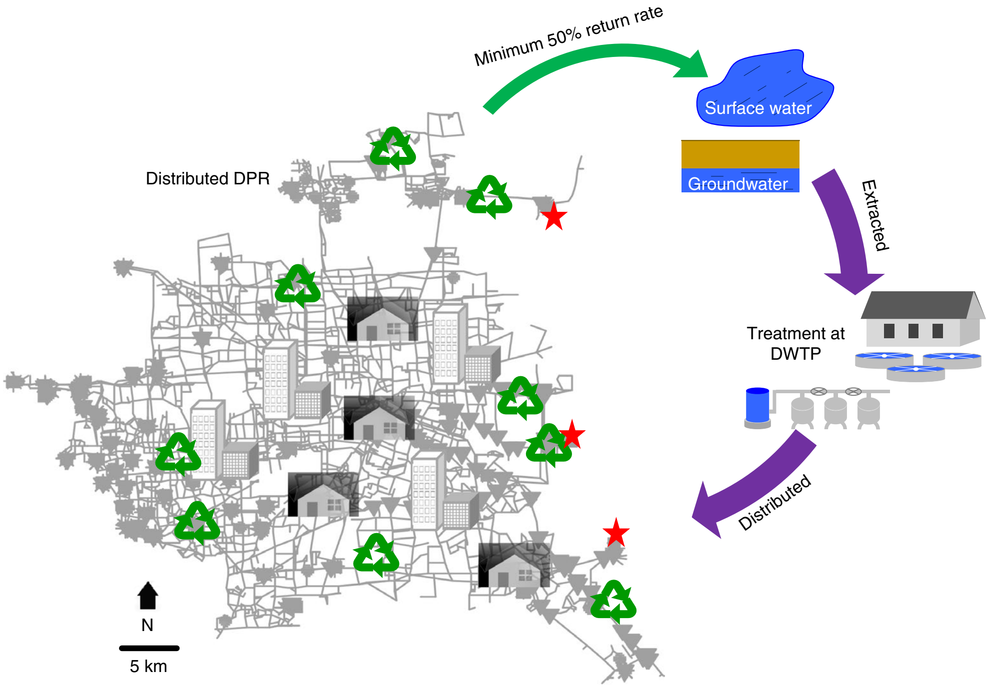

Fig. 1 | Schematic representation of the modelled water and wastewater system. Arrows indicate process flow. Stars indicate the locations of three centralized drinking-water treatment plants (DWTPs). Green recycle triangles indicate DPR. Wastewater is treated at nine WWTPs across the network (green recycle symbols). Background image in grey is Houston's water distribution network.

non-potable reuse (NPR) system with decentralized NPR systems over a range of scales and spatial and demographic conditions in San Francisco, California. They outlined a planning support tool that can reveal the environmental impact of integrating building-scale NPR with existing centralized infrastructure. They also presented a decision-support platform to assess and visualize on-site NPR system design and to explore the optimal system size on the basis of building layout[8]. Recently, Lee et al.[22] developed a decision-making toolkit that designs reclaimed water infrastructure and identifies preferred configurations of hybrid water reuse on the basis of a set of criteria determined by decision makers' preferences. However, no studies have systematically investigated the quantitative impacts of system configuration/topology (for example, number and locations of the wastewater reuse plants) on costs and benefits of integrating distributed wastewater reuse with existing water infrastructure[20]. The knowledge gap between site-based pilot experimental studies and system-level implementation of distributed systems calls for holistic, quantitative analysis of system configurations for distributed urban water supply systems.

This study aimed to assess the techno-economic impact of distributed treatment and direct potable reuse of wastewater using a modelling framework that was validated with data obtained from Houston Public Works. The two main objectives of this study were to:

1. Evaluate the cost–benefit of distributed DPR strategies on the basis of the existing water infrastructure and multiple alternative system configurations
2. Provide data-supported decision-making guidelines for future distributed system design

The study is innovative in the following aspects. First, our modelling framework considered DPR in the context of actual, existing water infrastructure and analysed the impact of the resulting distributed system on the existing infrastructure. We performed computations guided by a full factorial experimental design that covers all possible system configurations to reveal desirable and practical strategies. Hence, variables such as degree and strategy of distribution and treatment technologies can be systematically analysed within the same model with high computational efficiency. Second, most previous studies focused on NPR and evaluated site-specific reuse strategies. These reuse strategies require matching the non-potable demand with the reclamation capacity with a separate, new distribution system. The current study evaluates pipe-to-pipe DPR, which can use the existing distribution system. Furthermore, although the modelling framework is built and evaluated for one city, this approach is applicable to other water systems and can be tailored to different water supply configurations.

Description of the modelling framework

The water and wastewater system considered in this study is illustrated in Fig. 1. Details of Houston's existing water and wastewater infrastructure and model assumptions about advanced treatment (AT) processes are provided in Methods. Freshwater is extracted from surface and ground sources and treated to potable standards before being distributed to residential and commercial users. Wastewater is treated at nine existing WWTPs. To meet the water quality standards required for DPR, wastewater treated by conventional means (that is, secondary treatment) undergoes advanced treatment (see the Assumptions about AT processes section in Methods).

Reclaimed water from the nine WWTPs was included as additional drinking-water supply through the existing water distribution network. Assumptions including energy consumption of AT processes and other adjustable model parameters are described in the Model setup and output analysis section in Methods. Guided by a full factorial design, the model considered $2^9 = 512$ different system configurations with all possible combinations of the nine WWTPs as DPR water sources, from status quo (that is, no DPR) to full reuse ('All open' scenario in this study) capacity at all nine WWTPs (see the Scenario configurations section in Methods).

Long water-residence time alleviated by distributed DPR

Drinking water in distribution pipes undergoes various physical, chemical and biological transformations that often negatively affect

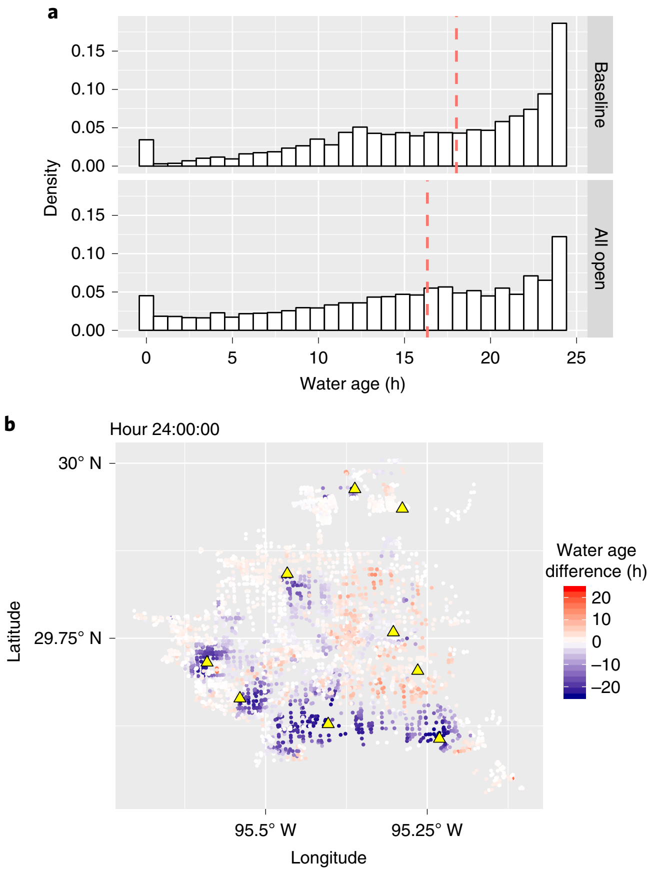

Fig. 2 | Water age difference between no water reuse (Baseline) and full implementation (All open). a, Probability mass function of water age at hour 24:00:00 for Baseline and All open scenarios (dashed line indicates median water age). **b**, Water age spatial difference at hour 24:00:00 between All open and Baseline scenarios.

water quality[23]. Water age is the time it takes for water to travel from the source to the consumer and is generally used as an indicator of water quality. The specific relationship between water age and water quality is complex, depending on the water flow rate, finished water quality, pipe materials and deposits on the pipe wall. However, it is generally accepted that microbial growth and toxic disinfection byproducts formation are strongly affected by water age; excessive water age may lead to formation of harmful disinfection byproducts (for example, trihalomethanes) as well as potential microbial pathogen growth[24,25]. Excessive water age would also lead to consumption of more chemical disinfectants and hence require a higher disinfectant dose and/or the construction of disinfectant-boosting facilities.

In this study, we showed that implementing DPR from the nine WWTPs reduced the average water age in the distribution network. In the 'All open' scenario, the median water age of the distribution network decreased by 2 h. This may not appear substantial, but distributed DPR had the greatest impact on users who previously had a long water age, as shown in Fig. 2a. Reduced water age is particularly prominent for consumers located close to the WWTPs and consumers on the west side of the city, who experienced a long water age previously (Fig. 2b and Supplementary Fig. 5). Communities previously experiencing excessive water age (20+ h) had 20 h reductions in water age; an improvement in water quality is expected for these communities[23,24]. Although consumers close to the three DWTPs experienced a small increase in water age, water age at these locations was short to begin with. At the same time, water pressure in the distribution network was not substantially different from that in the 'Baseline' scenario (Supplementary Fig. 6), which means that the system's stability and reliability are intact with the introduction of distributed DPR.

Variability of system-level electric energy consumption

The DPR reduced the City's dependency on conventional freshwater supply and resulted in a reduction in the energy required to treat and transport surface water and groundwater. However, additional energy is needed for the treatment and distribution of reclaimed wastewater. We estimated energy consumption per unit volume of water for treatment of surface water, groundwater and wastewater on the basis of the city's actual operation data in conjunction with estimates from the literature and calculated energy consumption for water distribution using EPANET (Supplementary Note 2). As energy intensity for AT processes varies widely, three representative energy intensities for DPR were used in the model: 1 kWh m^{-3}, 1.5 kWh m^{-3}, and 2 kWh m^{-3}, which are denoted as low, mid, and high cases. These values are comparable to those reported in the literature for pilot-scale systems (Supplementary Table 3). We assumed constant energy intensity of DPR regardless of flow and capacity due to the scarcity of available data for full-scale systems. At this time, insufficient information is available to determine whether economies of scale are still important for the size of treatment plants considered in this modelling (3.6–92 MGD, or 13,627–348,257 m^3 d^{-1}).

Electric energy consumed by the treatment plants under each scenario was computed and compared with the Baseline scenario for all possible system configurations (Supplementary Note 2). As expected, electric energy consumption by both the groundwater and surface water treatment plants decreases as more wastewater is reused (Fig. 3a, b), and energy consumed by WWTPs increases with more WWTPs adding AT to produce potable water (Fig. 3c).

Figure 3d shows that the overall system energy consumption may be either higher or lower than the Baseline, depending on the specific system configuration, even though AT processes consume substantially more energy than conventional treatment to provide the extremely high water quality desired. This is because the amount of energy saved in distributing surface water and groundwater may outweigh the amount of energy consumed in treating and distributing reclaimed water (Supplementary Fig. 14). In fact, there are system configurations that provide a net energy saving even with up to five WWTPs providing DPR at a mid-case energy intensity of 1.5 kWh m^{-3}. Implementing more DPR plants leads to an increase in energy consumption compared with the Baseline. Since our approach considers all possible permutations of WWTPs implementing water reuse, we can identify specific configurations that result in system-wide energy reductions. Out of the 511 system configurations (excluding Baseline), the number of configurations with net energy saving is plotted as a function of AT energy intensity in Fig. 4. The percentage of system configurations that yield net energy savings decreases as energy intensity for DPR increases. At ~1.04 kWh m^{-3}, almost all system configurations will result in net energy saving compared with the Baseline, while AT technologies with energy intensity higher than ~1.8 kWh m^{-3} will inevitably result in higher overall energy consumption. This gives us an important guideline in choosing and developing AT technologies for DPR.

Financial costs

Financial costs to implement DPR include capital investment for infrastructure (for example, addition of pipes and pump stations) and treatment equipment (for example, AT technologies), operational and maintenance (O&M) costs for electricity, chemicals and materials, and labour costs. Costs were amortized to an annual basis with exogenous assumptions. Details of the calculation are provided in Supplementary Note 3.

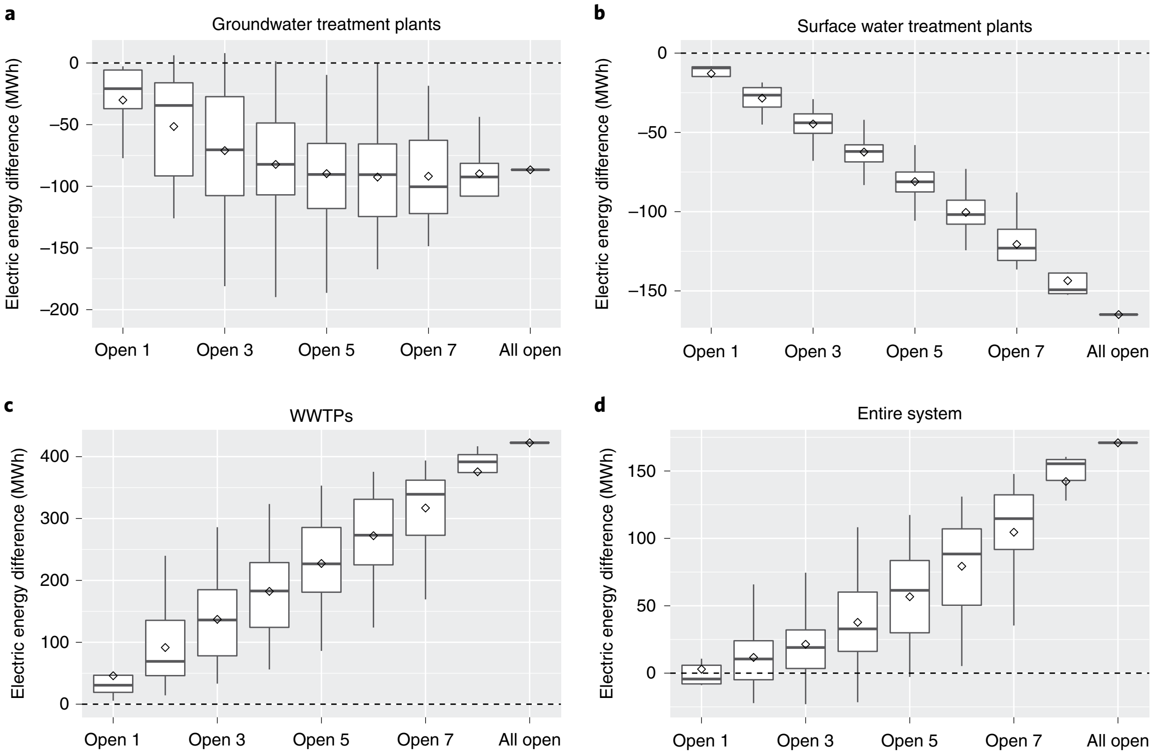

Fig. 3 | Changes in electric energy consumption (mid case) from the Baseline over a 24 h simulation period. a, Groundwater treatment plants. **b**, Surface water treatment plants. **c**, WWTPs. **d**, The entire system. Boxes encompass 25th and 75th percentiles of all possible system configurations under mid-case scenario, black vertical lines extend to minimum/maximum values, diamonds are mean values, and black horizontal lines are median values. Mid-case energy intensity for AT is assumed.

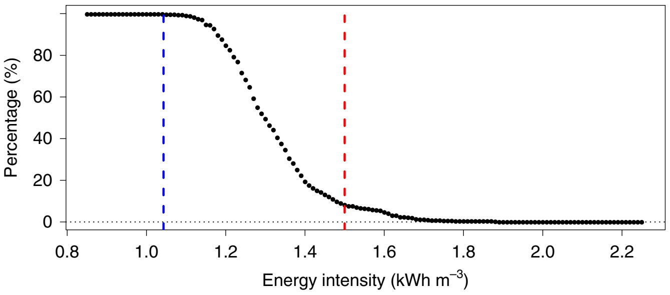

Fig. 4 | Percentage of distributed DPR system configurations that keep energy consumption lower than Baseline as a function of WWTP energy intensity. Red dashed line indicates mid-case energy intensity of 1.5 kWh m^{-3} considered in this study. Blue dashed line indicates the energy intensity below which 100% of the configurations achieve net energy saving.

Reduced dependency on surface water and groundwater leads to reduced costs at the DWTPs. With full implementation, the amount of electricity saved annually is equivalent to ~$9.1 million. Total annual savings from DWTP, including electricity, chemicals, labour, materials and maintenance, are estimated to nearly $30 million under the ‘All open’ scenario (Fig. 5a). Overall, the additional financial cost for implementing DPR increases with more WWTPs providing DPR (Fig. 5b, c). In the ‘All open’ scenario, $136 million per year is needed to implement DPR at all nine WWTPs (Supplementary Fig. 7). The cost is dominated by the O&M cost for AT (63%), followed by the capital cost for AT (35.3%). Note that the capital cost for new pipes and pump stations is minimal (0.4%) for DPR; however, this cost would be substantial for non-potable reuse due to separate piping requirements. The unit O&M cost for AT processes used in our calculation was \$0.47 m^{-3}, notably higher than that for conventional WWTP[26] and DWTP[27] (——\$0.11 m^{-3} and \$0.16 m^{-3}, respectively) but comparable to reported seawater desalination O&M costs (\$0.14 m^{-3}—\$0.64 m^{-3})[28] in the Middle East and North Africa region, cheaper than seawater desalination O&M costs in Texas (\$0.95 m^{-3}—\$1.53 m^{-3})[29], and consistent with available data on actual DPR plant operating costs (\$0.4 m^{-3}—\$0.74 m^{-3})[17,30]. Overall, the net additional financial cost is about $106 million per year for the ‘All open’ scenario (Fig. 5d). It is worth noting that DWTPs worldwide are implementing more AT for better water quality. In that scenario, DPR would lead to more savings in the DWTPs.

Tradeoffs in performance metrics

Our results show that different DPR strategies yield drastically different effects on system-wide energy consumption, financial costs and freshwater withdrawal, which has important implications for greenhouse gas emissions and groundwater depletion. To quantify potential benefits, we ran an analysis to identify DPR configurations that achieved three performance targets: (1) maximizing energy saving, (2) minimizing additional financial cost, and (3) minimizing freshwater withdrawal. Results showed that optimizing one criterion hinders the performance of another (Supplementary Table 7). System design is hence a complex multi-objective optimization problem. With the ‘All open’ scenario, freshwater withdrawal was minimized, with 28% of the freshwater supply replaced by DPR. The amount of additional energy required for full implementation is ~170 MWh d^{-1} for the mid-case scenario, which accounts

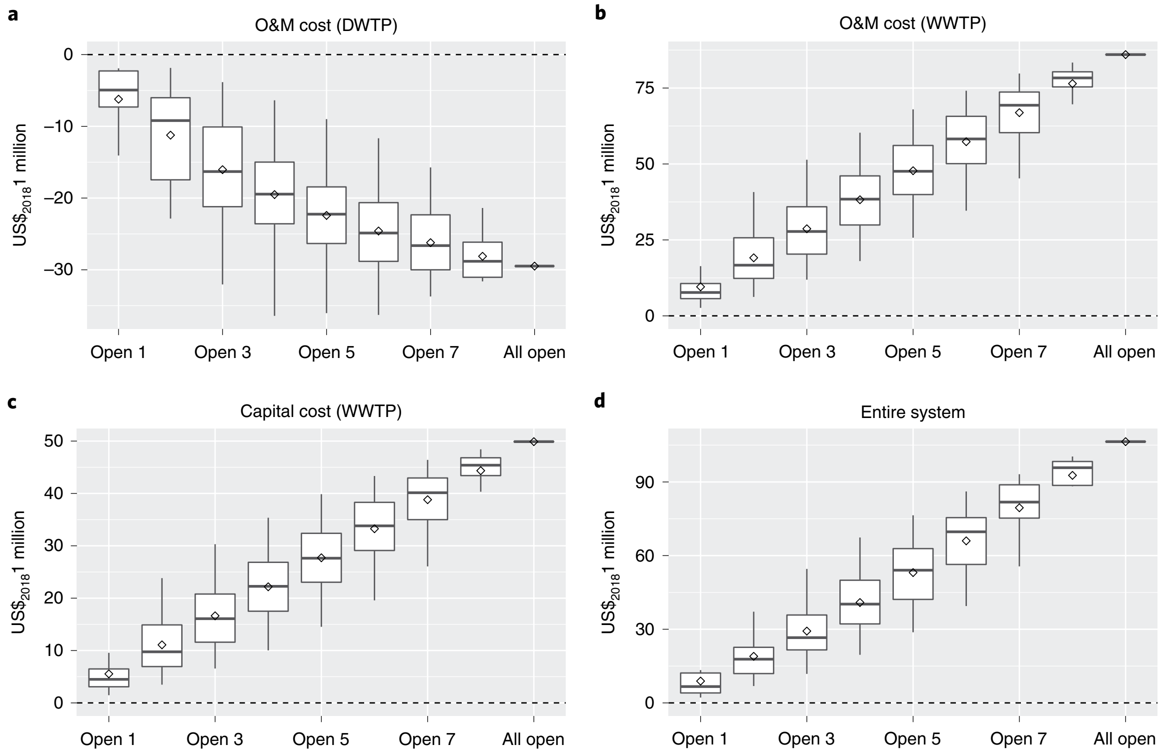

Fig. 5 | Changes in annual financial costs (US$$_{2018}$1 million) from the Baseline. a, The O&M cost for DWTP. **b**, The O&M cost for WWTPs. **c**, Capital cost for WWTPs. **d**, Overall cost for the entire system. Boxes encompass 25th and 75th percentiles of all possible system configurations under the mid-case scenario, black vertical lines extend to minimum/maximum values, diamonds are mean values, and black horizontal lines are median values. Mid-case energy intensity for AT is assumed.

for approximately 7.5% of Houston city government's daily average electricity consumption[31] (In 2017, electricity consumption by the three DWTPs accounted for ~14% of government's electricity consumption). The configuration that minimized annual financial costs constrained the use of reclaimed water. The configuration with maximized daily energy savings of 23 MWh exhibited a moderate cost increase of ~$15.7 million per year and ~25 MGD (94,635 $m^3 d^{-1}$) reduction in freshwater withdrawal. The associated changes in water age and water supply mix for the three DPR configurations are shown in Supplementary Figs. 8 and 9. The economic value of freshwater, which is important for decision making, was not considered in this modelling study. Nevertheless, our analysis suggests that if reduced freshwater use and its benefits on ecosystem can be monetized, a value of $106 million per year will completely offset the additional costs needed to fully implement DPR.

Figure 6 illustrates the tradeoffs among freshwater use, energy and cost under the assumption of mid-case energy intensity. In general, there is large variation in energy consumption and financial costs for a given capacity of DPR, underlining the importance of system configuration. Out of the 511 possible DPR configurations, about 8.8% of the configurations result in net energy savings. These hybrid configurations are able to reduce freshwater withdrawal by 0.4–13%, but increase financial costs by $2.1–38 million. Sensitivity analyses around energy intensities of AT technologies were conducted. With low-energy AT processes (1.0 kWh m^{-3}), all configurations can attain net energy saving, and the total additional financial cost for 'All open' is only 57% of the estimated cost for the mid-case scenario (Supplementary Fig. 10). More sensitivity analyses around other model assumptions are included in Supplementary Note 4. These insights stem from our proposed modelling approach (Supplementary Fig. 4), which considers all possible scenarios that span the full spectrum of costs and benefits from distributed DPR. With the help of this analytical model, the impact of distributed DPR can be evaluated across urban centres with needs prioritized by local stakeholders and decision makers. It is worth noting that these calculations do not consider the improved water quality resulting from the AT processes[32] and the shorter water age in the distribution network. Therefore, the analysis presented in this study does not include health or societal benefits.

Discussion and conclusions

This paper presents a quantitative model to comprehensively assess the environmental and economic impact/benefits of distributing and supplementing urban water supply through DPR of wastewater and exemplifies such impact with real system data from the City of Houston. Our results show that upgrading existing WWTPs to implement DPR can provide up to 28% of the city's water supply and reduce system-wide water age, which suggests improved water quality. The associated energy consumption and costs are strong functions of the system configuration, water volume reused and energy intensity/cost of advanced treatment technologies needed, with 8.8% of the possible system configurations achieving net energy savings. The additional O&M cost for AT processes is no more than $0.47 m^{-3}, which makes distributed DPR a competitive alternative water supply solution compared with desalination.

The degree of distribution has important implications for the system's overall performance. A greater degree of distribution, as represented by a higher percentage of water supply provided by distributed sources (that is, DPR at the WWPTs), requires more energy consumption and financial costs at the WWPTs for the AT processes, but a wide range of overall system performance exists at the same level of distribution, depending on the specific location and treatment capacity of the WWTPs providing DPR. Therefore, our results demonstrate that it is critical to evaluate each individual

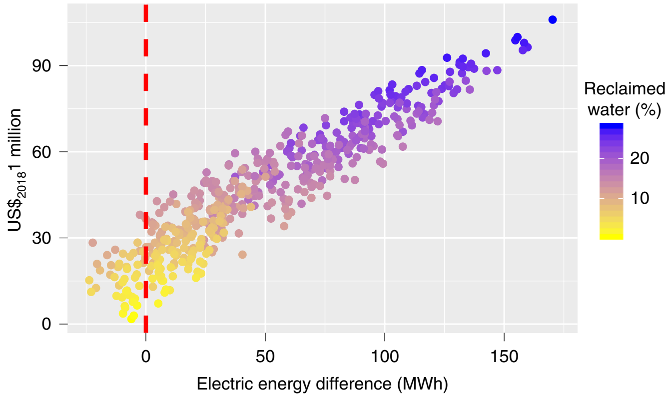

Fig. 6 | Difference in electric energy consumption versus additional financial costs identified by reclaimed water percentage. Each dot represents one DPR configuration. The dashed line divides configurations with net energy saving from those with net energy increase. Mid-case energy intensity for AT is assumed.

configuration of DPR to identify specific configurations that balance tradeoffs associated with multiple goals.

The conventional approach to augment water supply is to build more surface water or groundwater treatment capacities. The City of Houston is currently undertaking a $1.4 billion Northeast Water Purification Plant Expansion project to amplify surface water supply by 320 MGD ($1.21\times10^6\,m^3\,d^{-1}$). Using the same financial model as in this study, the amortized capital cost for the project is approximately $104 million per year, equivalent to a unit capital cost of about $0.24 m^{-3}. Completion of this expansion will help the city to meet water demands as well as to prevent groundwater overdraft. Our study helps evaluate distributed DPR as a candidate for the portfolio of solutions that can alleviate stress on freshwater resources and enhance urban water sustainability and resilience at a unit capital cost of $0.28 m^{-3} and O&M cost of $0.47 m^{-3}. Although the O&M cost of distributed DPR is still more than that of conventional (centralized) drinking-water treatment ($0.16 m^{-3}), it is much closer to that of the treatment processes to be implemented at the expansion project. With the benefit of a substantially reduced pumping cost for distribution (Supplementary Fig. 14), the overall cost could become highly competitive. It is also competitive with seawater desalination ($0.14 m^{-3}—$0.64/m^3) (ref. [28]) or brackish-water desalination ($0.14 m^{-3}—$0.31 m^{-3}) (ref. [33]).

Reducing freshwater withdrawal is of great importance for water security and environmental sustainability. The decision on whether and how to reuse requires a thorough understanding of the financial, environmental and societal impacts. Comprehensive, analytical and computational tools, such as the one developed in our study, are needed to support data-driven decision making as well as system design and operation. The modelling framework and associated databases developed in this study can be applied to any real-world water systems, filling an important gap for quantitative characterization of distributed water infrastructure systems. We were able to explore novel water and wastewater infrastructure designs envisioned in earlier studies[2,20] and be adaptive to customizable performance metrics and different network scales. In addition, our model has the capacity and flexibility to incorporate other alternative water supply sources such as desalinization of brackish water and seawater and rain- and storm-water harvesting. This modelling framework is powerful because it enables water resource planners and decision makers to quantify costs and benefits from distributed water supply and identify reuse strategies for meeting different objectives on system efficiency, resiliency and sustainability.

Other barriers for implementing DPR include public acceptance and legislative support. DPR is likely to be more cost effective in the future due to technology advancement[30]. Although federal potable reuse regulations have not been developed in the United States, a majority of states have established their own regulations or guidelines for water reuse[13]. Undoubtedly, distributed DPR could play an important role in utilities' future water supply portfolio.

Methods

Decentralized versus distributed. In the water systems literature, the terms 'decentralized' and 'distributed' are sometimes used interchangeably. In this study, we use the term 'distributed' as defined for electric power systems[34,35]: In a decentralized system, each control entity directly communicates and exchanges information with other entities; in a distributed system, a central coordinator coordinates independent control entities. In the context of water systems, each entity, for example, a WWTP, operates on its own but responds to a central coordinator, such as the water distribution network operator. In this paper, we define a distributed urban water system as a system that collects, treats and reuses wastewater at multiple WWTPs and supplements a centralized water supply system with potable water.

Assumptions about AT processes. The model assumed the same AT processes as applied in a pilot DPR facility in El Paso, Texas[36]: ultrafiltration, reverse osmosis (RO), followed by ultraviolet light disinfection and granular activated carbon adsorption. The RO recovery rate was assumed to be 80% in this study, which is the same as that for the pilot DPR facility in El Paso, Texas[37]. Following the City of Houston's current water reuse permit[38], it was assumed that no more than 62.5% of the secondary treated wastewater was further treated by AT (given 80% RO recovery rate) and pumped directly into the existing drinking-water distribution system (that is, pipe-to-pipe DPR). The remaining secondary effluent is discharged to natural water bodies to maintain environmental services. Brine concentrate from wastewater treatment is discharged to surface water, assuming the concentrated solution is safe for disposal, which is often the case for municipal waste stream.

Houston's existing water infrastructure. The City of Houston is an interesting test bed for this study due to its massive water distribution network that spans over 600 square miles and serves 2.2 million citizens[39] as well as its geographic mismatch between surface water supply and growth in municipal water demand. Houston is the fourth most populous city in the United States, with roughly 2.3 million people[40]. The city operates three surface DWTPs—East Water Purification Plant, Southeast Water Purification Plant and Northeast Water Purification Plant—all located on the east side of the city. They provide 85–90% of the City's ~440 MGD (2 million $m^3\,d^{-1}$) water supply. It also has 49 groundwater wells that provide the rest of the water demand[39]. The largest portion of the population and the fastest population growth are on the west end of the city (Supplementary Fig. 1). Currently, a total of 39 conventional WWTPs treat an average of 239 MGD ($9.05\times10^5\,m^3\,d^{-1}$) of raw sewage for the city. The city plans to consolidate the 39 WWTPs into 12 at their existing sites, with 9 of the 12 consolidated WWTPs falling within the city's current water distribution network (Supplementary Fig. 3). After consolidation, these nine WWTPs will provide wastewater treatment service for the entire city. The consolidated WWTPs are geographically scattered across the city's water distribution network (Supplementary Fig. 1) and will treat on average 252 MDG ($9.54\times10^5\,m^3\,d^{-1}$) of raw sewage. The city does not currently reuse its municipal wastewater[41], although a water reuse permit was granted in 2011[38] and different water reuse options have been evaluated by the city[41].

EPANET and related R packages. EPANET[42] is an application for modelling drinking-water distribution systems. It is developed and maintained by the US Environmental Protection Agency. EPANET is used to analyse movement of drinking-water constituents and can be applied to design and investigate infrastructure operations within distribution systems. More information about modelling capabilities and applications can be found on the EPANET website[43]. The visual user interface of EPANET offers tools for network modification and validation, while user-specific codes need to be developed for reading and running multiple networks simultaneously.

Packages developed in R programming enable simulations of water network using EPANET in offline mode, thus making it possible to run the full factorial experiments outlined in this study. The R packages used in this study include epanetReader[44,45] and epanet2toolkit[46]. Both packages are publicly available through GitHub[47,48].

Data descriptions. The water distribution network for the City of Houston in EPANET-readable format is provided by Houston Public Works. Total water demand is prescribed at 460 MGD ($1.74\times10^6\,m^3\,d^{-1}$) and varies over hour of the day (Supplementary Fig. 2). In this network, there are 43 reservoirs, 60 tanks, 127 valves, 160 pumps, and 5,607 pipes (Supplementary Fig. 1). By default, head loss in pipes is computed with the Hazen-Williams method. The model is run for a total duration for 24 h at intervals of 1 h.

Houston Public Works also provided information on capacity and permit flow for the three surface-water purification plants as well as five WWTPs in the Southeast region. This information is incorporated into the formulation of energy intensity for different treatment plants (Supplementary Note 2).

Historical (2008–2017) electric energy consumption for operation of the groundwater wells and the three surface-water purification plants is retrieved from City of Houston electricity bills[31]. Cost per unit of electricity ($\$\,\mathrm{kWh}^{-1}$) is calculated from historical electricity bills and adjusted to be compatible with current dollar value (Supplementary Fig. 13).

Scenario configurations. There are nine WWTPs listed in the city's consolidation plan: Almeda Sims, International Airport, Keegans Bayou, Northbelt, Northwest, Sims Bayou-South, 69th Street, Southeast and Upper Braes. To fully capture the impact of distributed DPR, we configured scenarios in which a certain number of consolidated WWTPs are equipped with advanced treatment systems that treat water to potable standards. The number of such WWTPs ranges from 0 (Baseline) to 9 (All open). Following combinatorial rules, there are 512 water reuse scenarios corresponding to 512 system configurations. The notation of scenarios is included in Supplementary Table 1.

The configurations range in their degree of distribution. For each configuration, the model quantified four performance metrics: water residence time (as a water quality indicator), electric energy consumption, capital and operating costs, and total freshwater withdrawal. Within the same degree of distribution, the location and treatment capacity of the individual WWTPs had an important impact on the performance metrics of the system. Configurations that exhibited the least/most effect on these criteria were identified to support investment decisions (Supplementary Fig. 4).

Model setup and output analysis. EPANET does not include WWTP as an available network component; hence, we approximated WWTPs with available hydraulic components in EPANET: reservoir, valve, pipe and pump. We treated WWTP reservoirs as water sources, where water flow out of WWTP reservoirs is controlled by valve setting and pumping power. Settings for each hydraulic component are based on operational data in conjunction with best engineering principles (Supplementary Note 1).

We conducted quality checks in EPANET to ensure model runs without warnings or errors. Then we ran a full factorial experiment with 512 model runs using R programming for a simulation period of 24 h. Output reports are generated by EPANET for each run, containing results for each node and link defined in the network. Post processes are conducted to analyse water age and water pressure at each node, electric energy consumption at each treatment facility and embedded financial cost for each of the 512 scenarios. We made exogenous assumptions about energy intensity for different treatment plants as well as unit cost for water infrastructure components (Supplementary Note 2). Electric energy at the system level and overall financial cost are estimated following the method described in Supplementary Note 3.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data that support the findings of this study are available from Houston Public Works, but restrictions apply to the availability of these data, which were used under license for the current study and so are not publicly available. Data are, however, available from the authors upon reasonable request and with permission of Houston Public Works.

Code availability

The software and custom-developed code for this study are available from the corresponding author upon request.

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Author contributions

All authors contributed intellectual input to this study. L.L., L.D.-O., L.S. and Q.L. designed the study, L.L. performed all analyses and worked with E.L. in configuring the model. L.D.-O., L.S., E.L., Y.X., P.J.J.A. and Q.L. worked on revising the manuscript. All authors contributed to the discussion of the results.

Competing interests

The authors declare no competing interests.

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

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Data collection	We used the public domain software EPANET2.0 to build the model.
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Study description	We develop a novel modeling framework to assess the environmental and economic implications of a hybrid water supply system that supplement a centralized surface water supply with distributed direct potable reuse (DPR) of municipal wastewater, as a strategy to address such challenges. The model is tested with real water and wastewater systems data from the City of Houston, Texas.
Research sample	The water distribution network for the City of Houston in EPANET-readable format is provided by Houston Public Works. In this network, there are 43 reservoirs, 60 tanks, 127 valves, 160 pumps, and 5607 pipes. Houston Public Works also provided information on capacity and permit flow for the three surface water purification plants as well as five WWTPs in the Southeast region. Historical (2008 – 2017) electric energy consumption for operation of the groundwater wells and the three surface water purification plants is retrieved from City of Houston Electricity Bills.
Sampling strategy	No sample size calculation were performed. There are 9 consolidated WWTPs in the network and we used available data for all of them.
Data collection	Houston Public Works provided the network data and WWTP capacity and flow data. Electricity consumption data and energy intensity data for advanced treatment was collected by the first author, Lu Liu.
Timing and spatial scale	Network data was obtained from Houston Public Works in 2018. All other data were collected throughout the duration of the project.
Data exclusions	No data were excluded.
Reproducibility	All scenario simulations are reproducible with the model.
Randomization	This is not relevant to this study as it is not an experimental research but a modeling study.
Blinding	This is not relevant to this study as it is not an experimental research but a modeling study.

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