Groundwater Recharge to Address Seawater Intrusion and Supply in an Urban Coastal Aquifer: *Orange County Water District, Orange County, California*

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ABSTRACT The Orange County Water District (OCWD) was created in 1933 by the California Legislature and tasked with managing water resources in Orange County. As a part of its strategy to fight seawater intrusion and guarantee a reliable groundwater supply in the basin, OCWD built a recycled wastewater facility that treats wastewater received from the Orange County Sanitation District and recharges the water into the basin through injection wells and infiltration ponds. OCWD's first recycled wastewater facility, Water Factory 21, began operating in 1975 and was replaced in 2008 by the Groundwater Replenishment System (GWRS). Recharged water not serving as a barrier for seawater instruction is pumped by local water districts and municipalities (referred to as "producers"), who pay a pumping fee to OCWD. Water provided by GWRS is both more reliable and less expensive for the producers than water acquired from other sources, including imported surface water. In responding to the recognized threat of seawater intrusion, OCWD owes its success to creatively enabling recharge through the development of novel source water. OCWD's broad purview and authority to manage groundwater, combined with its effective implementation and long-term stewardship of the recharge program as it has evolved over many years, have enabled innovation in MAR using treated wastewater. **KEYWORDS** groundwater, managed aquifer recharge, institutions, governance, recycled water

INTRODUCTION

The Orange County Water District (OCWD) has a long history of conducting managed aquifer recharge (MAR). MAR was initially implemented with excess surface water as a response to falling groundwater levels and the encroachment of seawater into the aquifer. Beginning in the 1970s, Orange County's MAR program was expanded to include an innovative effort to introduce recycled water as a source for recharge. Today, a large advanced treatment plant recycles municipal wastewater for recharge through both percolation and injection. The OCWD MAR project helps OCWD achieve its goals of preventing critical overdraft conditions, controlling seawater intrusion, and maintaining groundwater resources as the most economical and reliable water supply source for overlying communities.

The OCWD MAR project is an example of path breaking efforts to develop new technologies to respond to seawater intrusion while augmenting supplies through potable reuse. Because of the direct connection to potable use of treated wastewater, successfully addressing water quality concerns has been a key ingredient and achievement of OCWD's MAR efforts. One of the key broader impacts has been pioneering a treatment method for producing potable-quality water from wastewater, including developing methods and approaches to address emerging contaminants. The advances have laid groundwork for other efforts to recharge groundwater with highly treated wastewater [1–3] and helped to nationally and internationally normalize the notion of indirect potable water reuse through MAR. The case also highlights the

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importance of strong technical, institutional, and public engagement capacity, particularly in light of a history of continuous innovation.

CASE EXAMINATION

Methods

This case study forms part of the journal's special collection entitled "Institutional Dimensions of Groundwater Recharge." The collection examines empirical examples of MAR from across the United States to provide insights on the institutional structures and motivations of MAR implementation. An in-depth description of the special collection and its objectives, along with a discussion of the wider context of groundwater management concerns that MAR aims to address, is included in Miller et al [4]. Each of the case studies in the collection examines a different physical and institutional design for MAR. Case studies were developed through an analysis of documents and expert interviews. Documents reviewed include reports from governmental agencies implementing the MAR projects, permits and reports from regulatory agencies, state laws and regulations, academic literature and technical reports, and news articles. Interviews were conducted with key individuals involved in the development of each project including government officials, regulators, and project implementers.

Local Background

Orange County is a predominantly urban area located in southern California. In addition to an average of 14 in. of rainfall each year, the county receives surface water from the Santa Ana River. Orange County also relies upon water imported from Northern California via the State Water Project, and from the Colorado River, both supplied by the Metropolitan Water District of Southern California (MWD). Local groundwater also provides water supplies to Orange County. A large groundwater basin underlies the northern half of the county, which is also where the majority of the population and economic activity is located.

Groundwater overdraft was first observed as early as 1930 and worsened thereafter with increased development [5]. In response to requests from local leaders, the California Legislature created the Orange County Water District (OCWD) as a special act district in 1933 to manage surface and groundwater and to represent the interests of the county relative to the upstream areas of the Santa Ana River watershed.[1] OCWD immediately began experimenting with MAR by conducting in-stream recharge using Santa Ana River water, eventually making this a key part of its recharge efforts [7].

Although these efforts partly alleviated groundwater overdraft, it became clear that seawater intrusion was affecting the quality of groundwater in the basin. To address this problem, OCWD partnered with the Los Angeles County Flood Control District in 1965 to construct an injection well barrier along the Pacific coast at the Alamitos Gap [6]. The objective of the barrier was to create a groundwater pressure ridge that would block further seawater intrusion into the aquifer. In 1975, OCWD added a second seawater intrusion barrier at the Talbert Gap, which used recycled wastewater from the newly constructed Water Factory 21 [6]. As recharge continued and monitoring showed injected water also flowed inland and provided the additional benefit of recharge to the basin, OCWD increasingly linked its recharge efforts to local water supply.

Regulatory Setting

OCWD's statutory standing as a special act district gives it unusual authority over groundwater users. For example, OCWD has the authority to manage groundwater through a combination of basin recharge projects and assessments (fees) on groundwater pumping [8]. Groundwater quality standards and regulation in Orange County are the responsibility of a state agency, the Santa Ana Regional Water Quality Control Board (Regional Board). The California State Water Resources Control Board's Division of Drinking Water and the Regional Board provide permits and authorization for GWRS.

Water recharged and recovered by OCWD must comply with federal and state water quality regulations. The state Porter-Cologne Water Quality Control Act requires the development of basin plans that specify beneficial uses of rivers and groundwater basins and establish water quality standards for these waters. The Regional Board implements the Santa Ana River Basin Plan, which covers the

1. During the 20th century, there were three lawsuits by the downstream area of the Santa Ana River watershed (i.e., Orange County) against the upstream area (mostly in Riverside and San Bernardino counties) over reduced inflow to Orange County as a consequence of increased water use upstream. After the first litigation, OCWD was created and it took the lead as plaintiff on behalf of the lower watershed area in the subsequent two lawsuits [6].

OCWD service area [9]. The basin plan specifies water quality standards for surface water and groundwater.

Expansion of Recharge—The GWRS

OCWD implements a suite of MAR projects that make use of Santa Ana River water, imported water, and recycled water. Recharge occurs through the Groundwater Replenishment System (GWRS), an indirect potable reuse system. There are two interrelated components to GWRS—treating wastewater to a high standard to generate source water for recharge and recharging that water. Recycled water is infiltrated into the Orange County groundwater basin and later extracted by wells and incorporated into the potable water distribution system.

GWRS is an expansion of and replacement for OCWD's prior recharge infrastructures. Previously, OCWD recharged water from a water treatment plant (Water Factory 21) into a seawater injection barrier (the Talbert Seawater Intrusion Barrier) [6, p. 52]. The Talbert Barrier is formed by forcing a blend of imported water and highly treated wastewater into network of wells located about 4 miles inland from the coast.[2] The Talbert Barrier is designed primarily to reduce inland migration of seawater in the shallow Talbert aquifer [10]. Water Factory 21 came online in 1975 and was the first facility in California to treat wastewater using reverse osmosis. Water Factory 21 produced 15 million gallons of water per day (MGD) and operated for 29 years [11, 12].

In the early 2000s, OCWD began development of the GWRS, a new facility to replace Water Factory 21. GWRS would increase the amount of treated wastewater, providing OCWD with additional guaranteed water supply via MAR. GWRS also implemented advanced treatment processes to purify the water to higher standards.[3]

The Orange County Sanitation District (OCSD) supplies the GWRS with effluent from its treatment plants that it would otherwise discharge via the Santa Ana River to the ocean. The GWRS includes an expanded recharge system to allow greater recharge of effluent into the groundwater basin. The additional recharge has two benefits. First, this additional supply was desirable due to the increasing costs and uncertainty of imported water, which OCWD had historically relied upon for its MAR activities. Second, due to growth, wastewater flows in OCSD were approaching its discharge capacity, necessitating construction of a second ocean outfall for the area's treated sewage. The GWRS's higher capacity would save OCSD hundreds of millions of dollars by avoiding the need for the second outfall. GWRS was completed in 2008 [11].

Technological advancements enabled GWRS to produce water of higher quality and comparable cost to treated imported water. The wastewater undergoes primary and secondary treatment before delivery to GWRS [12]. Once in the GWRS, the effluent is tertiary treated by microfiltration and reverse osmosis. The resulting purified water is then exposed to ultraviolet light and hydrogen peroxide (advanced oxidization) for further disinfection. Finally, water is blended with calcium hydroxide and cationic polymers to improve settling of any remaining undissolved particles, and pH is verified to avoid corrosion or scaling of pipes. At this point, water is ready for use in MAR [12].

The purified water then follows two paths to recharge: injection to the seawater barrier and recharge to the central part of the basin.[4] Approximately 35 MGD is sent to injection wells along the Talbert Barrier. The total amount of water sent to the Talbert Barrier varies from year to year, with 20,747 AF of GWRS water injected in 2017–2018 [15].[5] The remaining 65 MGD of water produced from GWRS is sent for recharge basins in north and central Orange County [16]. The Demonstration Mid Basin Injection Project site is testing the feasibility of injection directly into the deeper Principal aquifer in central Orange County.[6] Four infiltration basins farther inland (the Kraemer, Miller, Miraloma, and La Palma Basin) receive a mixture of recycled water from GWRS and other water sources to recharge the alluvial Orange County Groundwater Basin.

GWRS initially produced 70 million gallons of treated water per day and was designed to support two expansions

2. For details on the Talbert Barrier, see, for example, https://www.ocwd.com/media/1857/large-scale-aquifer-replenishment-and-seawater-intrusion-control-using-recycled-water-in-southern-california.pdf; https://www.ocwd.com/news-events/newsletter/2018/july-2018/ocwd-to-expand-groundwater-modeling/; https://www.ocwd.com/media/1857/large-scale-aquifer-replenishment-and-seawater-intrusion-control-using-recycled-water-in-southern-california.pdf.

3. Australian Water Recycling Centre of Excellence. Global Potable Reuse Case Study 1: Orange County GWRS (2014).

4. A small amount of GWRS water is also delivered directly to two nonpotable customers, a power plant and transportation center.

5. In 2015–2016, 47,524 acre feet was sent to the seawater barrier. [14] In comparison, only 24,848 acre feet was sent to the seawater barrier in 2017–2018. [15]

6. Orange County Water District. Groundwater Replenishment System 2018 Annual Report (2018).

during its lifetime. The initial expansion took place in 2015 and increased production of treated water to 100 MGD [17]. The second expansion, planned for completion in 2023, will increase production of treated water to 130 MGD [18].

Water Quality and Emerging Contaminants

OCWD's efforts on emerging contaminants such as pharmaceuticals, personal care products, and endocrine disruptors [19, 20] is of particular relevance for this case study of MAR. In 2013, the State Water Resources Control Board adopted its first policy with monitoring standards for recycled water projects [17]. This resolution was informed in part by OCWD's previous experience in 2000 when the agency discovered a potent carcinogen, N-nitrosodimethylamine (NDMA), had entered its groundwater as a by-product of its treatment train [18]. OCWD responded quickly and transparently, as discussed below. OCWD has taken a similarly proactive approach with respect to other emerging contaminants of concern. As the state of California was considering regulations for per- and polyfluoroalkyl substances (PFAS), OCWD began to monitor its wells and inform the public about its proactive approach [21, 22]. When the state issued regulations for PFAS, OCWD was prepared and temporarily removed 40 drinking water wells from production [23]. It plans to install advanced treatment technologies to address PFAS from these sources, enabling its recharge activities to continue. Complementing OCWD's proactive actions in relation to emerging contaminants, OCWD has also undertaken efforts to ensure water quality through a source control program to reduce household discharges and separate industrial discharges from the GWRS [24–26]. Such source control helps reduce the pollutant burden on treatment plants, another component of enabling the end goal of high-quality source water for recharge.

Accounting and Monitoring

With OCWD's authority to manage water has come the necessity and responsibility to monitor and track groundwater use. Given the connection to drinking water and the importance of water quality described above, OCWD closely monitors groundwater quality [14, 27]. OCWD and other local governments overlying the groundwater basin are required to monitor and periodically report on the amount and quality of water recharged in each groundwater management zone, according to protocols established by the Regional Board [28]. The permits issued by the SWRCB that allow OCWD to operate the GWRS system are conditional on GWRS system performance. OCWD is required to regularly test the quality of the GWRS product water. If any of the samples do not pass quality standards, there will be an immediate and full shutdown of the GWRS plant [29].

OCWD's implementation of aggressive monitoring and modeling protocols beyond those strictly required by the state has allowed it to stay ahead of regulatory changes. OCWD employs 30 chemists and lab technicians and 12 water quality monitoring personnel for quality assurance and testing of both final GWRS product water and the nearly 200 large-capacity drinking water wells within OCWD's boundaries. An advanced water quality assurance laboratory is located on the OCWD campus and performs over 400,000 analyses of 20,000 water samples each year [14].

In addition, OCWD collects information on basin conditions (supplies, storage, demand, and water quality), the amounts of imported water purchased and recharged to the basin, and the amounts of water injected in the seawater intrusion barrier facilities. These data are reported annually through a combination of published reports available at the District's website [30].

Recovery

Recharged groundwater is eventually pumped by local production wells throughout the basin, where it is disinfected before being introduced into potable water delivery systems [16]. The largest groundwater users in the basin are overlying cities and water service companies. In 2017–2018, total groundwater production in the basin amounted to 236,916 AF [15].

OCWD itself does not extract groundwater or directly supply water to customers; its responsibility is managing the groundwater basin as a shared resource. OCWD sets limits for groundwater pumping and charges a pumping fee for groundwater production in the basin. These fees are based on a basin pumping percentage (BPP) set by OCWD. Each year, OCWD determines the BPP for groundwater producers in the basin. The BPP is the percentage of total water use that producers are allowed to meet with basin groundwater. For example, in 2019, the BPP was set at 77%, which meant that groundwater producers could supply 77% of their water needs with groundwater pumping. Producers pay a pumping fee (called a Replenishment Assessment) of $487 per AF extracted, up to the BPP limit. If producers pump over their BPP limit, they incur an additional pumping fee (called a basin equity assessment), which is charged at $542/AF for every AF over the BPP limit that is extracted [31].

Institutional Arrangements

OCWD has one primary responsibility—the management of the groundwater basin. OCWD is a special act district, not a general-purpose local government such as a city or county, and as such does not need to juggle water resource management responsibilities with other essential services such as public safety, public health services, street maintenance, and so on. OCWD has statutory rights to all the groundwater storage space in the basin [8]. OCWD manages this storage within certain limits to ensure there are supplies available during droughts and to minimize undesirable effects such as seawater intrusion and subsidence. Storage is managed on behalf of all groundwater producers, which include city water departments, local water districts, and private water service companies that supply water to residents, businesses, and public spaces within OCWD's boundaries.

OCWD is governed by a 10-member Board of Directors. OCWD's boundaries contain 10 subdistricts, with one Board Member representing each district.[7] The Board of Directors appoints members to the GWRS Steering Committee, which includes three members of the OCWD Board and three members of the OCSD Board.[8] Several other subcommittees handle other aspects of the project, including interagency relations with the Municipal Water District of Orange County (MWDOC).[9] The Director of Water Production oversees day-to-day operations of GWRS.

In addition to its internal governance structure, OCWD relies on engagement with stakeholders and on an Independent Advisory Panel (IAP) to govern the basin. Groundwater producers constitute OCWD's most directly engaged stakeholder group. A producer committee meets regularly with OCWD staff to discuss basin conditions and recharge operations and to provide input on proposed pumping fees. The IAP provides ongoing scientific peer review by analyzing the data of the plant operations and checking water quality data. The National Water Research Institute, a nonprofit research organization, appoints scientists who serve on the IAP,[10] publishing scientific and technical reports on the results of their tests. These reports are written to enable the health and regulatory communities to understand and assess the operations and performance of the GWRS [29]. These actions contribute to the overall legitimacy of OCWD's operations, as described in the next section.

Legitimacy and Public Support

OCWD illustrates the importance of a public relations strategy for implementation of recharge projects at the intersection of recycled water and drinking water supply. Proposals to use highly treated wastewater for public water supply have been derailed by public opposition in other areas [33]. OCWD's strategy to avoid similar opposition has included a range of activities to develop legitimacy with the public over time, which resulted in a lack of concerted opposition to the GWRS. These efforts

7. Each December following an election for the OCWD Board, the newly elected Directors and current Directors all meet together to hold position elections. They elect a President, First Vice President, and Second Vice President. The President and both Vice Presidents must be members of the Board of Directors. The Board also appoints a Treasurer, Auditor, General Counsel, and District Secretary, and Assistant District Secretary. These individuals may be, but are not required to be, appointed from existing OCWD Staff. [8] The Board also appoints county-specific roles as needed and can employ attorneys and engineers and other specialized positions as needed. [8] The Board is in charge of specific hiring and firing of employees, work requests, and communicating instruction to the appointed individuals [32].

8. Transparency is required for OCWD actions and decisions under the Orange County Water District Act and a variety of other California statues that collectively require public hearings and records availability for a range of its actions. Due to its status as a Special District, OCWD operates under the Orange County Water District Act and is subject to the Brown Act of 1953. The OCWD Act requires all public notices be published in the local newspaper. The Brown Act protects the public's right to attend and participate in local legislative body meetings. Public hearings are required for a variety of Board actions, including approval of Engineer's Reports on groundwater conditions, water supply, basin utilization, investigation and report on water supplies; the levy, modification, exclusion, or exemption of groundwater pumping fees; petition for inclusion of land in the OCWD boundaries; and approval of any annual reports. OCWD also complies with the California Public Records Act. The Public Records Act states that all government records with regard to conduct of public business must be about government agencies in California, both local and state. This means that any person can receive a copy of the OCWD public records with a written request.

9. Those committees include Administration and Finance, Communications and Legislative Liaison, OCWD/MWDOC Joint Planning, Property Management, and the Water Issues Committee. Ad hoc committees are also appointed by the President for limited timer periods and serve as an advisory capacity only. [32]

10. Scientists on the IAP include chemists, microbiologists, hydrogeologists, environmental engineers, and water treatment technicians. Note that the NWRI.

included, but went far beyond, public campaigns designed to foster consumer acceptance, which have in some cases failed to support viable potable reuse projects [34].

OCWD engaged in a portfolio of activities that developed legitimacy [34]. For example, OCWD not only engaged in targeted outreach and education campaigns but also developed emergency intervention and quality monitoring plans, framed potable reuse as recycling and groundwater protection, and had OCWD management personally involved in engagement with the community.

One of the crucial outcomes of OCWD's outreach efforts was to build trust and confidence through operations consistent with local social norms [35]. A concrete illustration of the importance of trust came during the discovery of NDMA in OCWD's treatment train in 2000, described above. The utility not only responded promptly by shutting down wells with the contaminant and adding ultraviolet light with hydrogen peroxide to its treatment process to destroy NDMA, it maintained the public's trust by doing so in a transparent way, while taking the opportunity to prove its technical competence, further boosting the legitimacy of OCWD and its reuse operations [36].

These efforts resulted in both positive local media coverage and a favorable public image. The successful operation of Water Factory 21 for many years further helped gain public support for its replacement with GWRS. The success of GWRS, in turn, has played a role in increasing public acceptance of water reuse in other communities in California and beyond.

Costs and Financing

The GWRS system depends on funding from several different sources, including grants, usage fees, and government support. Construction of the plant was a joint partnership between OCWD and OCSD, with the two organizations sharing the cost of building the plant. Construction began in 2002 and cost $481 million [11]. The project was supported by $92.5 million of grant funding from various state and federal agencies [37].[11] In the early years of GWRS plant operation, MWD provided $7 million a year for 12 years to subsidize operating costs. MWD, which supplies water to a large number of Southern California urban entities but faces significant supply reliability challenges, supported the project because it reduced demand on MWD's imported water supply.

Currently, OCWD has the full financial responsibility for ongoing operation costs and maintenance expenses. Operation costs of GWRS amount to roughly $40 M per year, including the costs of electricity and staffing for operations & maintainence [29, 38]. To cover these costs, OCWD relies on revenues from several different sources, with basin assessment fees comprising the main source of OCWD revenues. In 2017–2018, the Replenishment Assessment provided $134.4 M, and the Basin Equity Assessment provided $1.8 M [38]. Additional revenues came from ad valorem property taxes ($24.2 M). Other revenues included $1.5 M from investments, $1.5 M from water sales, $0.6 M in annexation fees, and $1.2 M rents and leases, and other sources [38]. OCWD has also received significant grant funding for studies related to GWRS, which enables it to continue to innovate on treatment and potable reuse strategies.[12]

Project Benefits

OCWD and OCSD have clear motivations to take on their roles as the primary participants in the GWRS and MAR in Orange County. The overarching motivation to avoid sea water intrusion and its attendant water resource impacts ties directly to the principal benefits to OCWD, avoided costs and increased water reliability. Avoiding the cost of a second ocean outfall is significant for OCSD, and OCWD receives the flow from OCSD at no cost. In light of the additional treatment costs for this water in the GWRS (microfiltration, reverse osmosis, and ultraviolet disinfection), it is unclear whether OCWD would have been willing or able to build and operate the GWRS if needing to pay for its source water. With the GWRS, OCWD insulates its recharge program somewhat from the uncertainties associated with imported water through MWD and the variability of Santa Ana River flows.

11. Funding sources included $37 M from the State Water Board (approved by California voters under Prop 13), $30 M from California Department of Water Resources, $20 M from the US Bureau of Reclamation (USBR), $5 M from the State Water Resources Control Board, and $500,000 from the EPA. [37]

12. For example, during the 2017–2018 Annual Budget, the Santa Ana Watershed Project Authority funded the Middle Santa Ana River Pathogen Total Maximum Daily Load Study, the California Energy Commission funded a study on Improving Membrane Treatment Energy Efficiency through monitoring and removal of colloidal particle foulants, and Water Environment & Reuse Foundation (WE&RF) funded the evaluation of Post-Treatment Challenges for Potable Reuse Applications, the utility validation of NDMA Analysis Alternative Methods, and the Characterization of Microbiome of State of the Art Water Reuse System to Enhance Treatment Performance (funding for this last study was supplemented by the USBR) [38].

FIGURE 1. The Groundwater Replenishment System. Source: 2017 GWRS Annual Report. Map of the Groundwater Replenishment System, including locations of the infiltration basins. Orange County Water District. *Groundwater Replenishment System 2017 Annual Report*. Available at https://www.ocwd.com/media/6822/2017-gwrs-annual-report.pdf.

Groundwater producers and end users of water also benefit because Orange County's efforts on MAR have helped sustain the local groundwater supply. Pumping groundwater, even with the OCWD Replenishment Assessment, remains a more reliable alternative to local rainfall and imported water. The current population and economy of the northern half of Orange County might not have been possible in the first place, or sustainable in the long run, without an effective MAR program to preserve and protect the groundwater basin.

For groundwater producers in the area, the estimated cost of using groundwater is roughly $754/AF, inclusive of pumping costs and OCWD's replenishment assessment fee. This is in sharp contrast to the estimated cost of treated imported water, which is estimated at $1,144/AF [15]. MWD also benefits from the existence of GWRS because a more reliable groundwater supply means that MWD will face less demand on its imported water supply.

Finally, the supply diversity resulting from the development of multiple water sources combined with effective storage may impart useful flexibility. OCWD is now in a position to shift among three potential sources of recharge water for the basin—local surface water, imported surface water, and treated wastewater, according to changes in their relative availability and costs.

CONCLUSION

Orange County's efforts to use MAR to address seawater intrusion, and subsequently to help manage the entire groundwater basin, have been extremely successful, garnering international recognition [39]. Since the 1960s, the negative consequences of groundwater overuse have been offset through MAR and managing groundwater pumping. Groundwater levels in most of the basin have been maintained above sea level, the inward intrusion of seawater has been largely arrested, and overlying communities have been able to continue their reliance on groundwater supplies in ways that would not have been sustainable in the absence of MAR. The intimate and mutually beneficial linkage between groundwater recharge and water recycling has spurred an international model for indirect potable water reuse through MAR.

The success of OCWD's recharge efforts is owed, in part, to OCWD's specific mandate from the legislature and its institutional structure. The focus enabled by its status as a special act district enables it to excel in its

TABLE 1. Groundwater Replenishment System Case Study Overview.

OVERVIEW	
Location	Orange County, California
Groundwater Challenges	Seawater intrusion and groundwater overdraft
MAR Motivating Factors	Halting seawater intrusion; increasing reliability of groundwater supply
MAR Project Goal	Maximize use and storage of purified wastewater; halt further seawater Intrusion
Recharge method	Injection wells and infiltration basins
Water source	Recycled wastewater
Key actors	Orange County Water District (OCWD); Orange County Sanitation District (OCSD)
Nonregulatory challenges	Technical—maintaining percolation capacity of recharge basins and ensuring adequate water flows from OCSD Institutional—establishing and maintaining public acceptance for recharge with treated wastewater
Regulatory issues	OCWD must meet water quality requirements set by the state, but no significant regulatory challenges were reported in meeting these requirements.
Milestones	1975—Water Factory 21 begins operation 2002—Construction of the Groundwater Replenishment System (GWRS) begins 2004—Water Factory 21 ceases operation 2008—GWRS begins operation 2015—Completion of first GWRS expansion 2023—Projected completion date of second GWRS expansion
Current status	First two phases implemented, with a final expansion online in 2023; in the 2017–2018 water year, the project recharged 105,624 AF
Cost	\$850/AF (without grants factored into cost); \$525/AF (with grants and OCSD contributions factored into cost)

mandate. OCWD personnel pursue multiple programs, projects, and activities, but they are all oriented around the mission of ensuring a well-managed groundwater basin. OCWD also benefits from high levels of interagency cooperation and coordination with the entities connected to it via contracts, partnerships, and collaborations.

Years of research, technological development, and incremental expansion have also compounded to enable OCWD to tackle the challenging work of MAR with recycled water. OCWD's MAR program has been built in stages over 70 years. The program started with instream recharge of river flows, expanding to include use of adjacent off-stream recharge basins and injection wells over time. The development of recycled water as an alternative and reliable source for recharge, and the resultant foregrounding of water quality as a crucial concern, simultaneously leveraged OCWD's previously existing technical capacity and pushed the agency to expand it with the development of the GWRS. The notably forward-looking approach to emerging contaminants is laudable and necessary. It also exemplifies that the flipside of a reliable source water in recycled water projects is potential regulatory and public health risks and the need to manage them carefully.

The public acceptance and support for OCWD's recharge programs illustrates the importance of carefully developing the legitimacy of MAR projects that use recycled water for their source. The successful operation of Water Factory 21 for many years built trust with the public, facilitating OCWD's subsequent portfolio of engagement that ultimately avoided the public opposition that has surfaced for other recycled water projects.

Although OCWD's MAR efforts have largely been successful, it is not without its long-term challenges. A large portion of OCWD's source water for recharge comes from OCSD. When GWRS and its predecessor, Water Factory 21, were designed and built, it seemed inevitable that wastewater flows would remain stable or increase forever. Instead, the effectiveness of water conservation over the last two decades has lowered water consumption per capita and per household, and consequently wastewater flows have also declined [40, 41]. If OCSD water volumes continue to decrease, other sources of water for MAR may be needed. Given increasing pressure on surface water supplies, and the contentiousness, impacts, and expense of alternative sources like seawater desalination, expanding the MAR program may require new rounds of innovation by OCWD in the future (**Figure 1**).

AUTHOR CONTRIBUTIONS

KM and AH researched and wrote the original draft. MK, AM, WB, and AH contributed to research and writing. MK and AM reviewed and edited the paper and managed the project. MK. conceptualized and secured funding for the project.

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COMPETING INTERESTS

The authors have declared that no competing interests exist.

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