RESEARCH ARTICLE

Recycled water could recharge aquifers in the Central Valley

Recycling more wastewater can help recharge aquifers in suitable areas of the Central Valley.

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Abstract

Drawing out too much groundwater, or overdrafting, is a serious problem in California. As a result, groundwater sustainability agencies are considering using recycled municipal wastewater to recharge aquifers. In our study, we employ suitability mapping and the models C2VSimFG and Ichnos to identify appropriate areas for managing aquifer recharge with recycled water in California's Central Valley. The factors that influence suitability include soil properties, proximity to recycled water sources, and the residence time, or amount of time that recharged water spends underground. There are many suitable areas in the Central Valley that are immediately adjacent to water recycling facilities. However, adequate supply is an issue in most locations. Roughly half of the groundwater sustainability agencies in critically overdrafted basins of the Central Valley have enough potentially suitable locations to meet their recharge goals, but not all of them have access to enough recycled water. The methods demonstrated here can serve as tools for agencies considering using recycled water for aquifer recharge.

California's Central Valley is a productive agricultural region with a history of unregulated groundwater pumping, which has resulted in overdrafting of groundwater (Springhorn et al. 2021). The Sustainable Groundwater Management Act (SGMA) of 2014 seeks to address overdraft by directing the Department of Water Resources to assign priority levels — critically overdrafted, medium, and high priority — to basins, and requires those with the greatest overdrafts to create and implement groundwater sustainability plans (GSPs). Out of the Central Valley's 45 subbasins, 11 are considered critically overdrafted (DWR 2020a), meaning that "continuation of present water management practices would probably result in significant adverse overdraft-related environmental, social, or economic impacts" (Springhorn et al. 2021). Within these 11 critically overdrafted subbasins, 36 groundwater sustainability agencies (GSAs) submitted GSPs (fig. 1) (Springhorn et al. 2021). These plans outline how GSAs will meet groundwater sustainability goals.

A field of sunflowers near Sacramento. Locating suitable land and available water are potential challenges for recycled water managed aquifer recharge in the Central Valley, with lack of available water likely to be the greater obstacle. *Photo*: tfoxfoto, iStock.com.

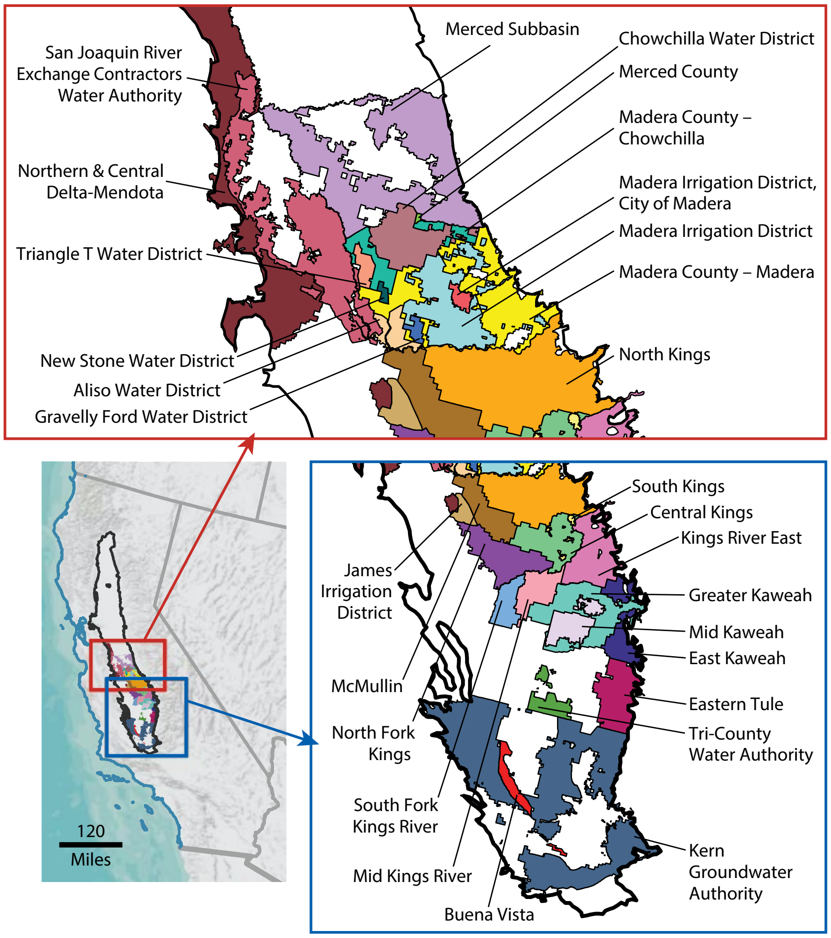

FIG. 1. Map of GSAs in critically overdrafted basins in the Central Valley requiring land for recharge (Benjamin Gooding, DWR, personal communication; DWR n.d.; DWR 2020b). *Sources:* Esri, USGS, NOAA.

One potential approach to groundwater sustainability is through managed aquifer recharge (MAR). MAR is the deliberate infiltration of water into aquifers for storage; storing water in aquifers tends to have less evaporative loss and fewer adverse effects on rivers than storing water in surface reservoirs. MAR can mitigate aquifer depletion, enhance dry-season streamflows, and improve the quality of recycled water used for infiltration (Bekele et al. 2011; Kourakos et al. 2019). Analysis of the GSPs submitted for basins in critical overdraft revealed that 29 of 36 GSAs have plans for using surface water to meet recharge objectives, resulting in about 200 MAR projects (Ulibarri et al. 2021). Recharge with high magnitude streamflows has shown promise for flood and overdraft mitigation, but the uncertain timing, amount, and location of these flows pose logistical challenges (Alam et al. 2020; Dahlke and Kocis 2018). Lack of nearby source water is a major factor preventing MAR projects from reaching recharge goals (Perrone and Rohde 2016). In fact, unallocated surface water is insufficient to fulfill the requirements of the 200 or so proposed MAR projects during a typical water year, suggesting that proposed MAR projects may need to reconsider their water source (Alam et al. 2020; Ulibarri et al. 2021).

One alternative water source for MAR is recycled water. Title 22 of the California Code of Regulations allows disinfected tertiary recycled municipal wastewater to be used for MAR, subject to water quality and residence time requirements. Disinfected tertiary is the highest quality of non-potable recycled water recognized in the regulatory code and is suitable for virtually any use except direct consumption (CCR 2018). Under the California Water Code, the owner of a wastewater treatment facility has exclusive rights to the treated water, though they must receive approval for new uses from the State Water Resources Control Board if a change might result in reduced flow to a watercourse (California Water Code 2002). Because treatment facilities are often owned by public utilities, it may be easier for a municipality to obtain treated wastewater than to obtain water from other sources (SWRCB 2021b). Conventional wastewater treatment plants may be replaced by facilities producing recycled water at the end of their lifespan or may be upgraded to produce recycled water for improved effluent quality (Cooley and Phurisamban 2016; Crook 2004). MAR projects using recycled water, called Groundwater Replenishment Reuse Projects in Title 22, have been implemented in the Orange County Water District and Montebello Forebay in Los Angeles County (McDermott et al. 2008; Mills and Watson 1994).

Despite the widespread interest in MAR siting and the potential of recycled water for recharge, few studies have examined the suitability of locations in California for recycled water MAR. Those that do focus largely on economic and logistical optimization (Bradshaw and Luthy 2017; Fournier et al. 2016; Merayyan and Safi 2014). Nevertheless, planning recycled water MAR requires consideration of unique criteria, such as natural attenuation of potential contaminants and proximity to a treatment plant for water supply (Ahmadi et al. 2017; Pedrero et al. 2011). In this paper, we identify areas in the Central Valley suitable for recycled water MAR and locations where future projects could be developed if existing wastewater infrastructure is upgraded to produce recycled water. Additionally, we evaluate the current recycled water produced at existing treatment facilities and compare it to predicted needs by each GSA as outlined in their plans.

Determining suitability

Suitability mapping was used to identify land within the Central Valley which might be ideal for recycled water MAR. Criteria were compiled in the form of ArcGIS raster maps of the valley, with each 328-foot-by-328-foot (100-meter-by-100-meter) pixel evaluated for each criterion. Each criterion was evaluated in one of two forms: (1) numerical or (2) binary. Numerical suitability scores were used for soil suitability and source proximity; binary suitability scores were used for land cover and proximity to drinking water sources. The binary score maps were multiplied by the averaged numerical score map to exclude unsuitable areas, resulting in a map giving an overall suitability score.

Land within the Central Valley was numerically scored — from 1 to 100, where 1 is unsuitable, and 100 is ideal — using two criteria: (1) relative suitability for MAR based on soil and (2) proximity to a potential recycled water source. The soil suitability and source proximity scores were combined with equal weighting.

Soil suitability was determined using the modified Soil Agricultural Groundwater Banking Index (SAGBI), which scores suitability of land for MAR on agricultural land (ag-MAR) in terms of deep percolation, root zone residence time, topography, soil salinity, and soil surface conditions (O'Geen et al. 2015) (fig. 2). The modified version assumes deep tillage in restrictive soil horizons, increasing infiltration potential.

Proximity to a potential source of recharge water was scored linearly from 1 (farthest, least suitable) to 100 (nearest, most suitable) (fig. 3). Beyond three miles (4.8 km), transporting the water is usually infeasible, so all farther locations received the least suitable score of 1 (online appendix section 6.4). Facilities were identified from the State Water Resources Control Board's 2019 Volumetric Annual Report of Wastewater and Recycled Water (SWRCB 2021a). The proximity score was calculated under three scenarios, considering (1) only facilities producing disinfected tertiary water, (2) any facility with recycled water, and (3) any treatment facility, including those only producing wastewater.

Suitable areas

Some areas cannot be used for recycled water MAR due to existing land cover or proximity to drinking water supplies; therefore, a binary assessment of suitability (i.e., suitable, unsuitable) was performed for (1) land cover and (2) proximity to drinking water sources.

Land cover was determined using the Land IQ 2018 crop map; the National Land Cover Database (NLCD) 2016 map of the Coterminous United States was used to fill gaps (Land IQ and DWR 2021; USGS 2021). Areas identified as undifferentiated urban (Land IQ) or as open water, wetlands, forest, or developed (except for "Developed, Open Space"; NLCD) were deemed unsuitable for MAR operations and excluded from further consideration (fig. 4).

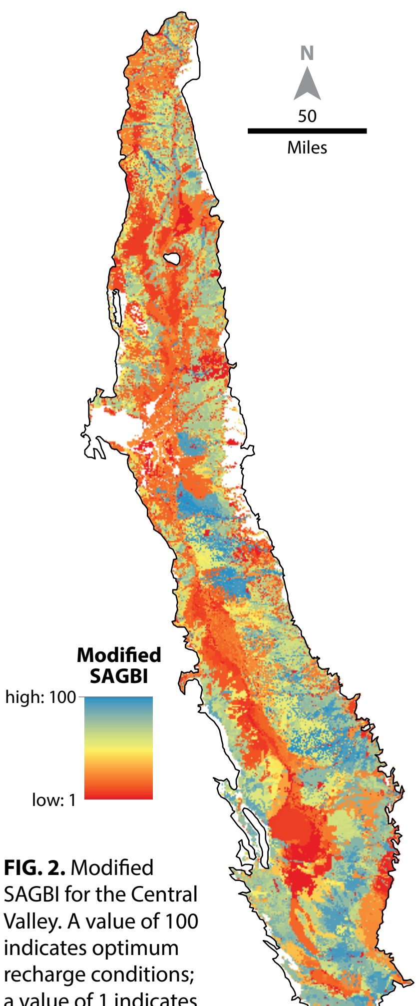

FIG. 2. Modified SAGBI for the Central Valley. A value of 100 indicates optimum recharge conditions; a value of 1 indicates recharge is unfeasible.

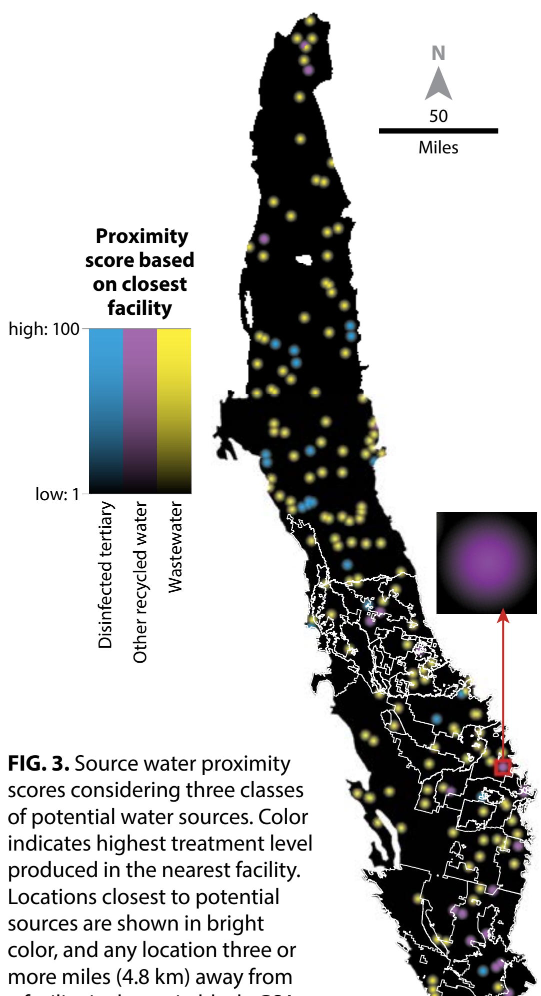

FIG. 3. Source water proximity scores considering three classes of potential water sources. Color indicates highest treatment level produced in the nearest facility. Locations closest to potential sources are shown in bright color, and any location three or more miles (4.8 km) away from a facility is shown in black. GSA boundaries outlined in white.

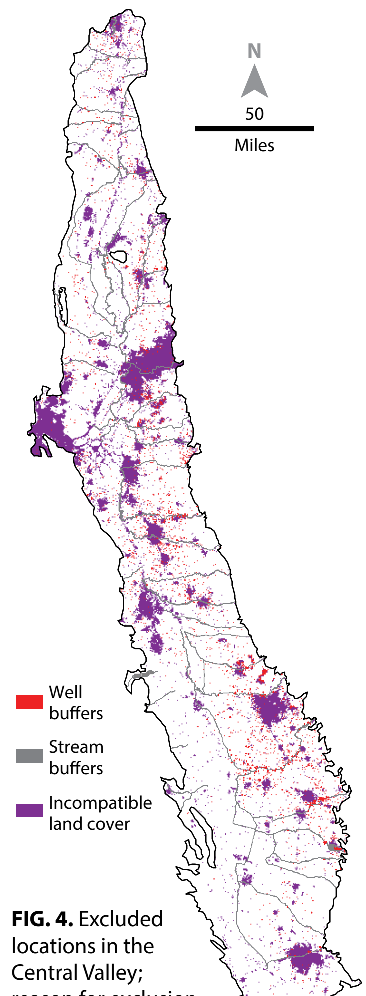

FIG. 4. Excluded locations in the Central Valley; reason for exclusion indicated by color.

We exclude some areas from consideration for MAR in order to protect drinking water sources. Recycled water MAR requires a minimum residence time between recharge and recovery for potable use (CCR 2018). Areas where surface recharge would reach a potable well or major river within a year were deemed unsuitable for recycled water MAR. Title 22 requires that recycled water undergo a 12-log virus reduction before being incorporated into a potable supply; i.e., finished water must contain one trillion times fewer active viruses than the original wastewater (CCR 2018). Six-log reductions can be credited to subsurface residence time, with 1-log reduction credited to each month spent underground (CCR 2018). Residence time demonstrated with a model as opposed to a tracer study receives only half credit; because we use a model, we considered residence times of at least one year (CCR 2018).

To determine residence times prior to arrival at wells and rivers, the groundwater system was modeled using the C2VSimFG, a finite element model that simulates surface and groundwater flows in the Central Valley (Hatch et al. 2020). Then, a particle tracker, Ichnos, was used to identify where surface recharge would arrive at any well or flow into a river within one year, by tracking backwards from the wells and rivers to the surface (Kourakos 2021) (appendix sections 4 and 5). For alternative methods, see appendix section 9.5. Any location in the Central Valley where surface recharge would reach a well or river within one year was excluded from further consideration (fig. 4). Additionally, Title 22 forbids impoundment of disinfected tertiary water, including in recharge basins, within 100 feet (30.5 meters) of a domestic well (CCR 2018). Accordingly, all wells classified as domestic were assigned a 100-foot buffer in which the land was deemed unsuitable (fig. 4).

To determine the location of domestic wells within the Central Valley, we used well completion reports (CNRA 2021). The data were quality controlled using methods by Jasechko and Perrone (2017). Records were retained for unique, active wells that produce water for human consumption (i.e., public, domestic, and transient non-community wells) with data for latitude, longitude, and completed depth (appendix section 3). Wells for other purposes were not considered for protection, because MAR uses disinfected tertiary water. Disinfected tertiary water may be used for most non-potable uses, including irrigation of food crops, without further treatment (CCR 2018). Of the 243,983 well completion records in the Central Valley, 50,031 were retained. Domestic wells received the required distance buffer, and then all classes of potable wells were evaluated using the groundwater models noted above.

Modelling groundwater transport requires knowing the screened interval of each well. Screen depths should be recorded in the Online System for Well Completion Reports (OSWCR) but are missing from approximately 45% of the retained well reports. Linear models of screen bottom depth (as a function of total well depth) and top of screen depth (as a function of bottom of screen depth) were developed for each subbasin to fill in the missing data (appendix section 3). The depths of the wells were then compared to the depths of the aquifer units used in the models. There were 3,906 wells that could not be modeled because they were either too shallow or too deep, resulting in a total of 46,125 wells included in the models. We also simulated a more conservative scenario in which the wells were modeled as fully screened to account for possible leaks in the casing (appendix section 9.3).

The majority of exclusions were due to land cover and were near major population centers, resulting in exclusion of several otherwise suitable areas. Particle tracking indicated that 1,086 wells (of 46,125) captured water within a year of its infiltration. Combining this with the 100-foot domestic well buffer resulted in the exclusion of 21 mi^2 (60 km^2) for well protection (fig. 4).

Following the exclusion of all unsuitable areas in the Central Valley, the final scores of the remaining land in the valley were divided into three equal intervals classified as “Good,” “Moderate,” or “Poor” recycled water MAR potential. (For alternative classification, see appendix section 9.4.) The total area of land with good suitability within the boundary of each of the 29 critically overdrafted GSAs with plans for MAR was compared with the area needed to meet its recharge goals, as determined from GSP project descriptions or estimated based on recharge type in cases where land needs are not defined (appendix section 7). The feasibility of meeting the stated goals was evaluated based on the availability of enough suitable land.

Water availability

The main focus of this analysis is the identification of suitable land; however, suitable land requires available water if a GSA is to consider MAR feasible. The quantity of potentially available recycled water was determined from the 2019 discharge volumes of each treatment facility in the Central Valley (SWRCB 2021a). Totals for each facility were calculated for disinfected tertiary water, all recycled water, and all effluent (including wastewater). This allows for consideration of the amount of disinfected tertiary water currently being produced, as well as the amount that could potentially be produced if existing facilities were upgraded to provide a higher treatment level. Water from the treatment facilities was divided among GSAs in proportion to the total amount of good suitability land surrounding the facility falling within their boundaries. Average annual water needs for surface recharge (excluding flood projects) were determined from estimates included in GSPs. These estimates were then compared with the amount of potential recycled water. For analyses considering water needs for different types of MAR, see appendix section 9.7.

Limitations of method

The suitability mapping process is subject to six limitations, underscoring the importance of local assessments as part of proposed MAR projects.

1. SAGBI is a powerful tool for evaluating the physical suitability of land for MAR, but it addresses only surface conditions. It does not address the ability of the underlying aquifer to store water in terms of thickness and specific yield of water-bearing units or depth to the existing water table (Fisher et al. 2017; Russo et al. 2015). While SAGBI incorporates soil salinity, it does not consider other potential contaminants that may be leached from agricultural soil, such as nitrate or pesticides, or geogenic contaminants like uranium, chromium, or arsenic (Lopez et al. 2021; McClain et al. 2019; Murphy et al. 2021; O'Geen et al. 2015). To the best of our knowledge, maps of soil contamination covering the entire Central Valley are not publicly available. (For a low-resolution analysis including estimates of groundwater arsenic and nitrate, see appendix section 9.1.) Because SAGBI was not developed for use with recycled water, it does not evaluate the potential of the soil to attenuate residual pathogens or chemicals. While MAR has been successful with a variety of source water qualities and environmental conditions, specific water quality improvements will depend on local soil properties (Bekele et al. 2011; Fox et al. 2001; Miller et al. 2006; Sharma et al. 2008).
2. Delineation of well protection buffers is limited by the resolution of reported locations and of C2VSimFG. Well completion reports submitted prior to 2015 report locations by township, range, and section, introducing an uncertainty of 0.7 miles (1.1 kilometers) to these wells' locations (appendix section 2.1).
3. C2VSimFG has an average element area of 407 acres, which is a fine resolution relative to the size of the Central Valley, but cannot capture local variations that could result in faster than expected arrival times (Gerenday 2022; Hatch et al. 2020). This is one reason for the reduced log-reduction credits assigned to modeled residence times by Title 22 and highlights the need for local testing (CCR 2018).
4. The 100-foot domestic well buffers are smaller than the 328-foot raster cells used for suitability calculations, making isolated wells effectively "invisible" (appendix section 6.2).
5. For the sake of simplicity, this analysis assumes that all water from the treatment facilities could be available for MAR; however, high quality recycled water generally already has a use from which it would need to be diverted for MAR. Consideration of the total water budget within a GSA and whether such diversion is feasible is beyond the scope of this study.
6. While linear distance to facilities is considered, it is not known whether the water can be practically transported over intervening topography.

Eastern valley most suitable

Suitability of land for recycled water MAR is dependent on recycled water proximity, as the poor proximity score of any land not within three miles of a treatment facility overrides the other factors and results in a low overall suitability score (fig. 5). The majority of land is

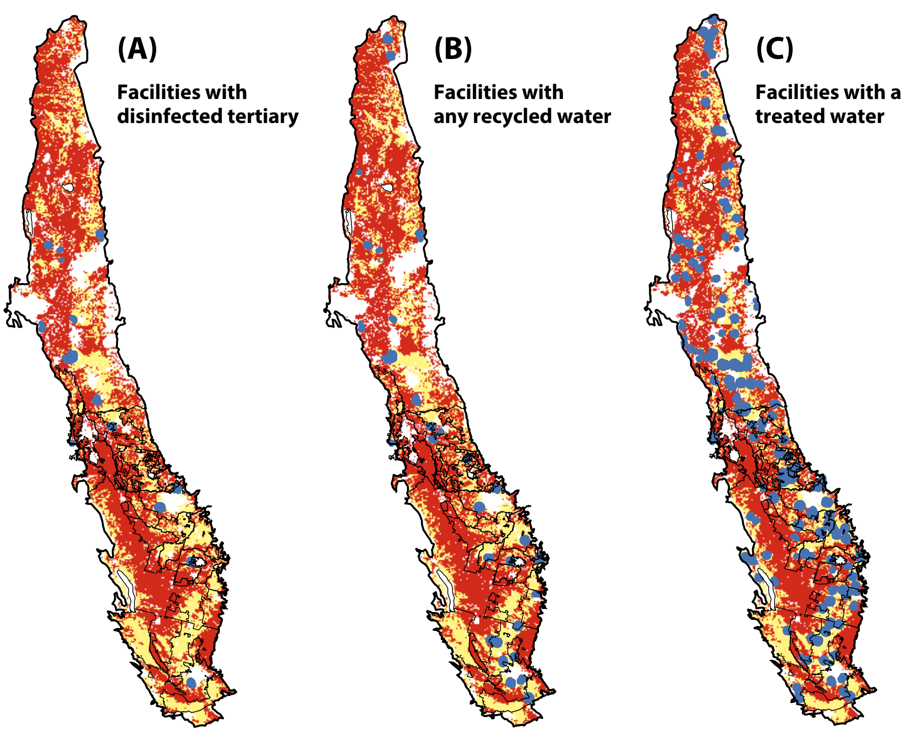

FIG. 5. Suitability of potentially available land considering (A) only facilities producing disinfected tertiary, (B) any facility with recycled water, (C) any treatment facilities, including those with only wastewater. Good areas (blue) are visually enlarged; for a map with all areas to scale or for regional maps, see appendix section 8.1.

rated as poorly or moderately suitable (table 1). Land of good suitability is more likely to be found on the eastern side of the valley, where soils tend to be better for infiltration and there is a higher density of recycled water sources. Areas in the southwest tend to be unsuitable due to a relative scarcity of treatment facilities and limited deep percolation capacity. The majority of land rated as suitable (87% to 91%) is agricultural, with deciduous fruit and nut crops making up one of the largest portions (appendix section 8.3).

If treatment plants currently producing disinfected tertiary water are the only water source, two of 29 GSAs have enough suitable land, assuming average land needs (figs. 6 and 7). If all facilities producing any kind of recycled water are considered, six GSAs have enough suitable land. If facilities only producing wastewater are also considered, an additional eight GSAs would have suitable land to meet their needs. Several others may have enough land under these water conditions if minimum, instead of average, land needs are assumed in cases where recharge areas are unspecified in GSPs (see fig. 6 upper error bars and appendix section 7).

We also assess whether recycled water could be used as a potential source to meet the water needs of MAR projects proposed within each GSP (fig. 8). The North Kings area could have access to enough total recycled water to supply its recharge goals if water treatments were upgraded. Similarly, if all treated water, including

TABLE 1. Area (mi^2; 1 mi^2 = 2.6 km^2) available to each GSA by suitability

	Facilities with disinfected tertiary			Facilities with any recycled water			Facilities with any treated water		
	Good	Moderate	Poor	Good	Moderate	Poor	Good	Moderate	Poor
Aliso Water District	0	7.6	33	0	7.6	33	0.035	7.9	33
Buena Vista	0	0.24	79	0	0.24	79	0.089	4.9	74
Central Kings	0	160	66	0	160	66	24	150	50
Chowchilla Water District	0	48	78	0	49	77	2.8	53	70
East Kaweah	0	100	68	2.2	100	64	11	97	61
Eastern Tule	0	80	140	0.25	80	140	5.0	84	130
Gravelly Ford Water District	0	3.5	9.6	0	3.5	9.6	0.0	3.5	9.6
Greater Kaweah	2.2	88	230	4.5	91	220	4.9	100	210
James Irrigation District	0	0.9	42	0	0.9	42	0	6.7	37
Kern Groundwater Authority	0	890	580	21	880	570	34	870	570
Kings River East	0	170	100	5.9	160	98	20	150	94
Madera County - Chowchilla	0	14	52	0	16	50	0.097	17	49
Madera County - Madera	0.11	49	190	1.4	58	180	5.0	67	170
Madera Irrigation District	0	110	94	0.94	110	89	15	120	68
Madera Irrigation District, City of Madera	0	1.9	2.2	0	1.9	2.2	1.8	2.2	0.14
McMullin	0	73	110	0	73	110	4.5	77	100
Merced County	0	1.7	0.12	0	1.7	0.12	0	1.7	0.12
Merced Subbasin	0.78	140	320	3.3	150	310	11	160	290
Mid Kaweah	0.86	18	98	0.86	18	98	1.3	26	90
Mid Kings River	0	77	57	2.7	80	52	7.8	76	50
New Stone Water District	0	0.31	6.2	0	0.31	6.2	0	0.31	6.2
North Fork Kings	0	36	220	0	36	220	0.98	45	210
North Kings	5.9	160	150	5.9	160	150	18	160	130
Northern and Central Delta-Mendota	0.37	96	310	0.37	96	310	2.9	110	300
San Joaquin River Exchange Contractors Water Authority	0	25	360	0	25	360	1.1	36	350
South Fork Kings	0	17	85	0	17	85	0.10	30	72
South Kings	0	2.4	1.0	0	2.4	1.0	1.5	1.6	0.34
Tri-County Water Authority	0	41	53	0	41	53	0.089	41	53
Triangle T Water District	0	0.86	22	0	0.86	22	0	0.86	22
Central Valley total	**25**	**5,500**	**11,000**	**87**	**5,500**	**11,000**	**400**	**5,900**	**10,000**

Highlighting indicates type of facilities necessary to meet land needs:
= current facilities with disinfected tertiary, = facilities with any recycled water, = facilities with any treated water (including wastewater), = needs not met.

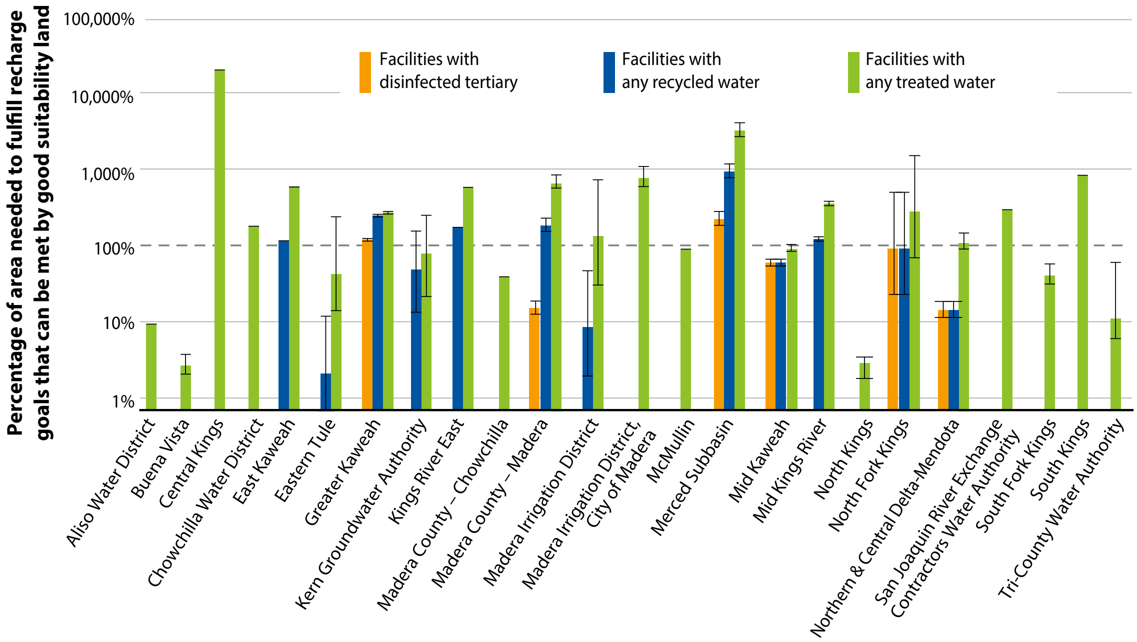

FIG. 6. Land with proximity to facility assessment. Percentage of area needed by each GSA to fulfill recharge goals that can be met by good suitability land, considering proximity to different types of treatment facilities (e.g., facilities with disinfected tertiary, facilities with any recycled water, and facilities with any treated water). Some plans did not explicitly state land needs; for these plans, we estimated a mean, minimum, and maximum amount of land based on proposed MAR projects. For these GSAs, bars represent the mean land; minimum and maximum estimated land requirements are shown with error bars. GSAs without suitable area not shown. Dashed line indicates that 100% of area needed to fulfill recharge goals can be met by good suitability land within proximity to treatment facilities.

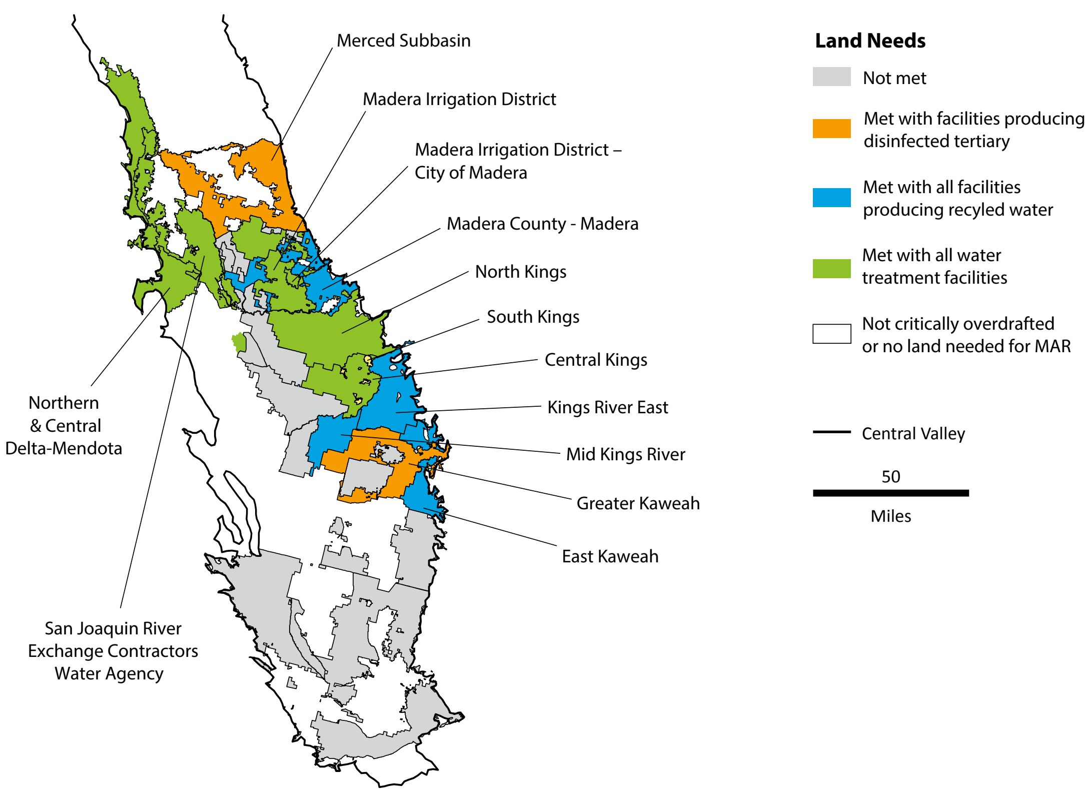

FIG. 7. GSAs by most conservative scenario in which land needs can be met (if any). GSAs needs met by: disinfected tertiary facilities only shown in orange; all facilities with any recycled water shown in blue; and all treatment facilities, including those with only wastewater, shown in green. GSAs without enough suitable land given their current facilities shown in gray.

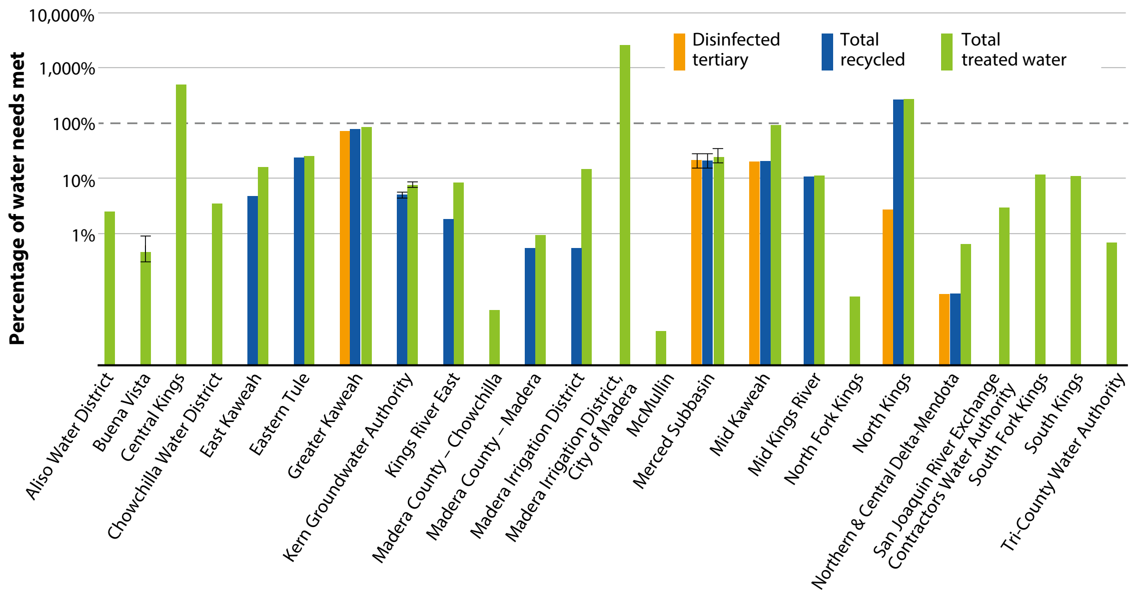

FIG. 8. Water needs assessment based on recharge goals set in GSPs and types of water produced in facilities near or within each GSA. Percentage of water needed by each GSA to fulfill recharge goals that can be met by different types of available water, assuming treatment processes can be upgraded where needed. Some plans did not explicitly state water needs; for these plans, we estimated a mean, minimum, and maximum amount of water based on proposed MAR projects. For these GSAs, the bars represent the mean; minimum and maximum estimated water requirements are presented with error bars. GSAs without available water are not shown. Dashed line indicates 100% water needs are met by available water.

wastewater, is considered, North and Central Kings, as well as Madera Irrigation District – City of Madera, could access enough recycled water to meet their goals. These three GSAs also have enough potentially suitable land when all facilities are considered. Sensitivity analyses considering water needs for different types of projects yield the same result in terms of which GSAs have sufficient recycled water but do show a difference in terms of how close some GSAs are to meeting their goals (appendix section 9.7).

Increasing recycling capacity

Local recycled water availability is the most limiting factor in siting recycled water MAR projects. This is evident from the fact that recharge for recycled water MAR projects tends to be conducted at the treatment facility, and many MAR operators cite limited water availability as their greatest challenge (Al-Otaibi and Al-Senafy 2004; Bennani et al. 1992; Lopes and dos Santos 2012; Perrone and Rohde 2016; Pi and Wang 2006). In order for a project to be successful, suitable land and water must be available in the same location. Constructing or retrofitting facilities to produce disinfected tertiary water can result in more potential for recharge. Costs of upgrading wastewater treatment plants to produce recycled water suitable for MAR may range from $140,000 to $620,000 per acre-foot over 30 years (Cupps and Morris 2005). If patterns of groundwater extraction remain the same, increased water recycling capacity will likely be needed to balance overdraft in the Central Valley. Depending on the degree of future recycling and groundwater depletion, such efforts may be able to offset 41% to 94% of groundwater depletion statewide by 2030 (Badiuzzaman et al. 2017). Over the period of 2005–2018, the average decline in groundwater storage in the Central Valley was between 8,600 and 20,900 thousand acre-feet per year (Springhorn et al. 2021). Total effluent produced by treatment facilities in the Central Valley in 2019 was only enough to offset 3% to 7% of this deficit (SWRCB 2021a). The majority of facilities currently producing disinfected tertiary water in the Central Valley are not located in critically overdrafted basins (fig. 3); however, they may provide a future opportunity for lower priority basins as they continue to develop their water management strategies.

Transporting water

It is possible to recharge farther from the source if transporting water is more feasible than obtaining suitable land nearby or if a regional facility distributes water to many decentralized sites. For instance, the Chino Basin Recycled Water Groundwater Recharge Program distributes recycled water to 11 infiltration sites distributed throughout Chino Basin (Campbell and Fan 2021). When completed, the Metropolitan Water District of Southern California's Regional Recycled Water Program will deliver recycled water for recharge through 60 miles (96.6 kilometers) of pipe to four regional groundwater basins (MWD 2016).

Major factors influencing the maximum acceptable distance include local land values and the cost and energy use of transporting water (Bradshaw and

Luthy 2017). Costs of land acquisition for recharge basins and conveyance rights-of-way estimated in GSPs range from $15,000 to $42,000 per acre, resulting in normalized costs of $5 to $42 per acre-foot of recharge over a 30-year period (Aliso Water District GSA 2020; Central Kings GSA 2019; McMullin Area GSA 2019; South Kings GSA 2019). Factors including the availability of existing conveyance networks and topography along the transport route affect costs (Fournier et al. 2016; Trussell et al. 2012). The cost of constructing new conveyance systems has been estimated at $2.3 to $34 million per mile or $25 to $1,100 per acre-foot, while the operation and maintenance costs range from $25 to $29 per acre-foot per mile (Bradshaw and Luthy 2017; Cooley and Phurisamban 2016; McMullin Area GSA 2019). Water savings due to recycled water MAR may be negated by water consumption for power generation if excessive uphill pumping is required to move recycled water (Fournier et al. 2016). Recycled water MAR projects more than one to two miles (1.6 to 4.8 kilometers) from their source tend to make use of gravity flow or are integrated with a wastewater system (Hutchinson 2013; Johnson 2009; Kanarek and Michail 1996; Page et al. 2010).

Local siting decisions

Although this study demonstrates the power of suitability mapping and groundwater modeling for evaluating large land areas for potential recycled water MAR, selecting locations is best done at the local level. GSAs are more likely to know the status and exact locations of wells and availability of land and water. If a GSA does not have a source of recycled water within its boundaries, it will have to negotiate with other entities. This is not surprising, as water recycling projects often require partnerships with multiple agencies, but it could be a challenge if another GSA already has plans for the water (Sokolow et al. 2019). Additionally, while mapping is a useful tool for selecting candidate sites, any recycled water MAR project will require local soil studies, pilot testing, and tracer experiments before operating at scale, as well as a series of permits to ensure minimal social and environmental impacts (Ulibarri et al. 2021).

Competing uses of water

Finally, the value of groundwater recharge must be weighed against that of other uses for water and land. For instance, 700,000 acre-feet (860 million meters^3) of recycled water was used for irrigation in California in 2019, comprising 50% of total reported reuse (SWRCB 2021a). In addition, surface outflows from treatment plants can support riparian ecosystems (Rohde et al. 2021). Currently, the majority of suitable land in the Central Valley is in use for agriculture. Growing seasons, as well as limits on how long perennial crops can

An aqueduct and water tower in the San Joaquin Valley. Upgrading water treatment facilities to produce a higher class of recycled water increases the number of locations in the Central Valley where recycled water MAR is possible. *Photo*: JohnnyH5, iStock.com.

tolerate flooding, place restrictions on the total time infiltration can occur on active farmland (Ganot and Dahlke 2021). Recharging recycled water on agricultural land is still largely unexplored (Grinshpan et al. 2021). Given the scarcity of available recharge water, it is unlikely that there will be an excess at times when MAR is impossible. Furthermore, the relative predictability of recycled water supplies can facilitate planning of water allocations (Perrone and Rohde 2016; SWRCB 2021a). Nevertheless, focusing recharge efforts on agricultural areas may require land fallowing. This can assist in bringing water budgets into balance and benefit habitats, but it will be expensive and require compensating farmers (Bourque et al. 2019). (For required MAR area broken down by whether plans include on-farm recharge, see appendix section 9.6.) Given that fruit and nut crops are among the state's most valuable, the cost of acquiring land may be high (CDFA 2021).

More recycled water necessary

Although recycled water MAR is feasible in many locations in the Central Valley, more recycled water sources are necessary to implement these recharge solutions across the valley. Currently, six GSAs have enough suitable land to meet their recharge needs with recycled water MAR, but none of them have enough suitable water. Upgrading treatment plants could increase the capacity that recycled water MAR could contribute to GSAs. Highly populated areas are more likely to have access to recycled water but tend to have less suitable land and a greater density of wells. Suitability mapping and particle tracking are useful tools for GSAs considering recycled water MAR. However, these areas will need infiltration studies and tracer tests to ground truth results and receive project approval. Recycled water MAR can help GSAs that have sufficient suitable land and access to water achieve their recharge goals, enabling them to comply with the Sustainable Groundwater Management Act and maintain a sustainable water supply. CA

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References

Ahmadi MM, Mahdavirad H, Bakhtiari B. 2017. Multi-criteria analysis of site selection for groundwater recharge with treated municipal wastewater. Water Sci Technol 76(4):909–19. https://doi.org/10.2166/wst.2017.273

Alam S, Gebremichael M, Li R, et al. 2020. Can managed aquifer recharge mitigate the groundwater overdraft in California's Central Valley? Water Resour Res 56:e2020WR027244. https://doi.org/10.1029/2020WR027244

Al-Otaibi M, Al-Senafy M. 2004. Recharging aquifers through surface ponds: Hydraulic behaviour. Emir J Eng Res 9:21–7.

Aliso Water District GSA. 2020. Aliso Water District Groundwater Sustainability Agency Groundwater Sustainability Plan.

Badiuzzaman P, McLaughlin E, McCauley D. 2017. Substituting freshwater: Can ocean desalination and water recycling capacities substitute for groundwater depletion in California? J Environ Manage 203:123–35. https://doi.org/10.1016/j.jenvman.2017.06.051

Bekele E, Toze S, Patterson B, et al. 2011. Managed aquifer recharge of treated wastewater: Water quality changes resulting from infiltration through the vadose zone. Water Res 45:5764–72. https://doi.org/10.1016/j.watres.2011.08.058

Bennani AC, Lary J, Nrhira A, et al. 1992. Wastewater treatment of Greater Agadir (Morocco): An original solution for protecting the Bay of Agadir by using the dune sands. Water Sci Technol 25:239–45. https://doi.org/10.2166/wst.1992.0355

Bourque K, Schiller A, Loyola Angosto C, et al. 2019. Balancing agricultural production, groundwater management, and biodiversity goals: A multi-benefit optimization model of agriculture in Kern County, California. Sci Total Environ 670:865–75. https://doi.org/10.1016/j.scitotenv.2019.03.197

Bradshaw JL, Luthy RG. 2017. Modeling and optimization of recycled water systems to augment urban groundwater recharge through underutilized stormwater spreading basins. Environ Sci Technol 51:11809–19. https://doi.org/10.1021/acs.est.7b02671

California Water Code. 2002. Div. 2, Part 2, Chapt. 1, Art. 1.5 Treated Waste Water. https://leginfo.legislature.ca.gov/faces/codes_displayText.xhtml?lawCode=WAT&division=2.&title=&part=2.&chapter=1.&article=1.5

Campbell A, Fan B. 2021. *Chino Basin Recycled Water Groundwater Recharge Program 2020 Annual Report*. Chino, Calif.: Inland Empire Utilities Agency. 184 p.

[CCR] California Code of Regulations. 2018. Title 22, Div. 4, Chapt. 3 Water Recycling Criteria. https://govt.westlaw.com/calregs/Browse/Home/California/CaliforniaCodeofRegulations?guid=IE8ADB4F0D4B911DE8879F88E8B0DAAAE&originationContext=documenttoc&transitionType=Default&contextData=(sc.Default)

[CDFA] California Department of Food and Agriculture. 2021. County Agricultural Commissioners' Reports Crop Year 2018–2019. 82 p.

Central Kings GSA. 2019. Central Kings Groundwater Sustainability Agency Groundwater Sustainability Plan.

[CNRA] California Natural Resources Agency. 2021. Well Completion Reports.

Cooley H, Phurisamban R. 2016. The Cost of Alternative Water Supply and Efficiency Options in California. Oakland, California: Pacific Institute. 30 p.

Crook J. 2004. Innovative applications in Water Reuse: Ten Case Shimtudies. WateReuse Association. 49 p.

Cupps K, Morris E. 2005. Case Studies in reclaimed water use. Washington Department of Ecology. 44 p.

Dahlke H, Kocis T. 2018. Streamflow availability ratings identify surface water sources for groundwater recharge in the Central Valley. Calif Agr 72:162–9. https://doi.org/10.3733/ca.2018a0032

[DWR] California Department of Water Resources. n.d. GSA notice submitted.

DWR. 2020a. B118 SGMA 2019 Basin Prioritization.

DWR. 2020b. C2VSimFG boundary.

Fisher AT, Lozano S, Beganskas S, et al. 2017. *Regional Managed Aquifer Recharge and Runoff Analyses in Santa Cruz and northern Monterey Counties, California*. California State Coastal Conservancy. 119 p.

Fournier ED, Keller AA, Geyer R, et al. 2016. Investigating the energy-water usage efficiency of the reuse of treated municipal wastewater for artificial groundwater recharge. Environ Sci Technol 50:2044–53. https://doi.org/10.1021/acs.est.5b04465

Fox P, Narayanaswamy K, Genz A, et al. 2001. Water quality transformations during soil aquifer treatment at the Mesa Northwest Water Reclamation Plant, USA. Water Sci Technol 43:343–50. https://doi.org/10.2166/wst.2001.0658

Ganot Y, Dahlke HE. 2021. A model for estimating Ag-MAR flooding duration based on crop tolerance, root depth, and soil texture data. Agric Water Manag 255:107031. https://doi.org/10.1016/j.agwat.2021.107031

Gerenday SP. 2022. Soil and infrastructure suitability for managed aquifer recharge with recycled water. www.grac.org/media/files/files/76ffbde3/sarah-paschal-gerenday.pdf

Grinshpan M, Furman A, Dahlke HE, et al. 2021. From managed aquifer recharge to soil aquifer treatment on agricultural soils: Concepts and challenges. Agr Water Manage 255:106991. https://doi.org/10.1016/j.agwat.2021.106991

Hatch T, Guobiao H, Guillien A, et al. 2020. C2VSimFG. Fine Grid California Central Valley Groundwater-Surface Water Simulation Model. DWR. 275 p.

Hutchinson AS. 2013. *2011–12 Report on Groundwater Recharge in the Orange County Groundwater Basin*. Orange County Water District. 96 p.

Jasechko S, Perrone D. 2017. Hydraulic fracturing near domestic groundwater wells. P Natl Acad Sci 114:13138–43. https://doi.org/10.1073/pnas.1701682114

Johnson TA. 2009. Ground water recharge using recycled municipal waste water in Los Angeles County and the California Department of Public Health's draft regulations on aquifer retention time. Ground Water 47:496–9. https://doi.org/10.1111/j.1745-6584.2009.00587_3.x

Kanarek A, Michail M. 1996. Groundwater recharge with municipal effluent: Dan region reclamation project, Israel. Water Sci Technol 34:227–33. https://doi.org/10.1016/S0273-1223(96)00842-6

Kourakos G. 2021. Ichnos, GitHub. https://github.com/giorgk/ichnos

Kourakos G, Dahlke HE, Harter T. 2019. Increasing groundwater availability and seasonal base flow through agricultural managed aquifer recharge in an irrigated basin. Water Resour Res 55:7464–92. https://doi.org/10.1029/2018WR024019

Land IQ and DWR. 2021. i15 Crop Mapping 2018.

Lopes RL, dos Santos AS. 2012. Característica do Solo da Área de Infiltração de Efluentes Domésticos de uma ETE. In: VII CONNEPI Congresso Norte Nordeste de Pesquisa e Inovação. 6 p.

Lopez AM, Wells A, Fendorf S. 2021. Soil and aquifer properties combine as predictors of groundwater uranium concentrations within the Central Valley, California. Environ Sci Technol 55:352–61. https://doi.org/10.1021/acs.est.0c05591

McClain CN, Fendorf S, Johnson ST, et al. 2019. Lithologic and redox controls on hexavalent chromium in vadose zone sediments of California's Central Valley. Geochim Cosmochim Ac 265:478–94. https://doi.org/10.1016/j.gca.2019.07.044

McDermott JA, Avisar D, Johnson TA, et al. 2008. Groundwater travel times near spreading ponds: Inferences from geochemical and physical approaches. J Hydrol Eng 13:1021–8. https://doi.org/10.1061/(ASCE)1084-0699(2008)13:11(1021)

McMullin Area GSA. 2019. McMullin Area Groundwater Sustainability Agency Groundwater Sustainability Plan.

Merayyan S, Safi S. 2014. Feasibility of groundwater banking under various hydrologic conditions in California, USA. Comput Water Energy Environ Eng 03:79–92. https://doi.org/10.4236/cweee.2014.33009

Miller JH, Ela WP, Lansey KE, et al. 2006. Nitrogen transformations during soil–aquifer treatment of wastewater effluent—Oxygen effects in field studies. J Environ Eng 132:1298–1306. https://doi.org/10.1061/(ASCE)0733-9372(2006)132:10(1298)

Mills WR, Watson IC. 1994. Water factory 21 – the logical sequence. Desalination 98:265–72. https://doi.org/10.1016/0011-9164(94)00151-0

Murphy NP, Waterhouse H, Dahlke HE. 2021. Influence of agricultural managed aquifer recharge on nitrate transport: The role of soil texture and flooding frequency. Vadose Zone J 20. https://doi.org/10.1002/vzj2.20150

[MWD] The Metropolitan Water District of Southern California. 2016. *Potential Regional Recycled Water Program Feasibility Study*. 218 p.

O'Geen AT, Saal M, Dahlke H, et al. 2015. Soil suitability index identifies potential areas for groundwater banking on agricultural lands. Calif Agr 69:75–84. https://doi.org/10.3733/ca.v069n02p75

Page D, Dillon P, Vanderzalm J, et al. 2010. *Managed aquifer recharge case study risk assessments*. CSIRO. 156 p.

Pedrero F, Albuquerque A, Marecos do Monte H, et al. 2011. Application of GIS-based multi-criteria analysis for site selection of aquifer recharge with reclaimed water. Resour Conserv Recy 56:105–16. https://doi.org/10.1016/j.resconrec.2011.08.003

Perrone D, Rohde M. 2016. Benefits and economic costs of managed aquifer recharge in California. San Fran Estuary Watershed Sci 14. https://doi.org/10.15447/sfews.2016v14iss2art4

Pi Y, Wang J. 2006. A field study of advanced municipal wastewater treatment technology for artificial groundwater recharge. J Environ Sci-China 18:1056–60. https://doi.org/10.1016/S1001-0742(06)60038-7

Rohde MM, Stella JC, Roberts DA, et al. 2021. Groundwater dependence of riparian woodlands and the disrupting effect of anthropogenically altered streamflow. P Natl Acad Sci 118:e2026453118. https://doi.org/10.1073/pnas.2026453118

Russo TA, Fisher AT, Lockwood BS. 2015. Assessment of managed aquifer recharge site suitability using a GIS and modeling. Groundwater 53:389–400. https://doi.org/10.1111/gwat.12213

Sharma SK, Harun CM, Amy G. 2008. Framework for assessment of performance of soil aquifer treatment systems. Water Sci Technol 57:941–6. https://doi.org/10.2166/wst.2008.188

Sokolow S, Godwin H, Cole B. 2019. Perspectives on the future of recycled water in California: Results from interviews with water management professionals. J Environ Plann Man 62:1908–28. https://doi.org/10.1080/09640568.2018.1523051

South Kings GSA. 2019. South Kings Groundwater Sustainability Agency Groundwater Sustainability Plan.

Springhorn S, Wyckoff B, Hull R, et al. 2021. *California's Groundwater Update 2020 (draft).* DWR. 324 p.

[SGMA] Sustainable Groundwater Management Act. 2014. www.waterboards.ca.gov/water_issues/programs/sgma/docs/sgma/sgma_20190101.pdf

[SWRCB] California State Water Resources Control Board. 2021a. 2019 Volumetric annual report of wastewater and recycled water.

SWRCB. 2021b. Regulated facility report. California Integrated Water Quality System Project. www.waterboards.ca.gov/ciwqs/publicreports.html#facilitieshttps://www.waterboards.ca.gov/ciwqs/publicreports.html (accessed Nov. 8, 2021).

Trussell R, Anderson H, Archuleta E, et al. 2012. *Water Reuse: Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater*. Washington, D.C.: National Academies Press. 277 p.

Ulibarri N, Garcia NE, Nelson RL, et al. 2021. Assessing the feasibility of managed aquifer recharge in California. Water Resour Res 57(3):e2020WR029292. https://doi.org/10.1029/2020WR029292

[USGS] United States Geological Survey. 2021. NLCD 2016 Land Cover Conterminous United States.