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Assessing the Feasibility of Managed Aquifer Recharge in California

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Key Points:

- 233 Managed Aquifer Recharge projects are proposed in California, almost doubling the number of MAR projects in the United States.
- We identify multiple feasibility concerns, including inconsistent legal requirements and water, funding, and land availability.
- MAR's ability to help reverse decades of over-extraction in California can only be realized if implemented effectively.

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Abstract

With aquifers around the world stressed by over-extraction, water managers are increasingly turning to Managed Aquifer Recharge (MAR), directly replenishing groundwater resources through injection wells, recharge basins, or other approaches. While there has been progress in understanding the geological and infrastructure-related considerations to make MAR more effective, critical evaluations of its institutional design and implementation are limited. This paper assesses MAR projects, using a case study of projects proposed by groundwater sustainability agencies (GSAs) in California to comply with the state's Sustainable Groundwater Management Act of 2014; these projects will almost double the number of MAR projects in the United States. We draw on content analysis of Groundwater Sustainability Plans that propose these projects. We first assess the types of recharge projects proposed and the stated aims of the projects, to assess when and why agencies are turning to MAR as a solution. We find that recharge basins are by far the most common approach, and that GSAs hope these basins will improve water table levels, reduce subsidence, and improve water quality. We then analyze potential barriers to project implementation and assess the projects' ability to achieve the stated goals. Primary concerns identified include a potential lack of available water, a potentially challenging legal framework, and minimal consideration of funding and cumulative land needs. To conclude, we discuss broader considerations for ensuring that MAR is an effective water management tool.

1 Introduction

Groundwater resources around the world are becoming stressed from continued extraction. Advances in pumping technology, growth of irrigated agriculture, and increased population have rapidly increased groundwater use over the past 60 years (Dillon et al., 2018; OECD, 2015). At the same time, many rivers are fully appropriated, and surface water is becoming increasingly variable under climate change (Scanlon et al., 2016).

Water managers have responded with increased use of managed aquifer recharge (MAR), the "intentional storing and treatment of water in aquifers" (see also Dillon, 2005; National Research Council et al., 2008; Scanlon et al., 2016, p. 2). Equation 1 (Scanlon et al., 2016) relates total groundwater storage (GWS) to natural and anthropogenic sources of aquifer inflow and outflow. Inflow is the sum of natural recharge (R_{NAT}) and human recharge, including irrigation (R_{IRR}) and MAR (R_{MAR}); outflow is the sum of natural discharge (Q_{NAT}), including baseflow to streams and riparian evapotranspiration, and anthropogenic pumping (Q_{PU}).

$$\Delta GWS = Inputs\ -\ Outputs = (R_{NAT} + R_{IRR} +\ R_{MAR}) - \left(Q_{NAT} + Q_{PU}\right) \qquad (1)$$

To stabilize or increase groundwater levels, water managers can reduce outputs, increase inputs, or both. MAR (R_{MAR}) aims to directly influence recharge by moving water into the aquifer; it is generally contrasted with non-managed recharge that occurs as a side effect of irrigation, reservoir storage, and other practices (R_{IRR}) (Dillon et al., 2018; Scanlon et al., 2016). There are numerous physical aquifer recharge technologies, such as slowing down instream flows with check dams, letting water infiltrate through spreading basins, and injecting water through a well or borehole (Dillon et al., 2018; Dillon, 2005; Stefan & Ansems, 2017).

MAR is often part of a conjunctive use approach, the "optimal use of water sources over time when more than one water source is available at the same time" (Roberts, 2010, p. 1). Conjunctive use generally refers to temporally shifting between surface and groundwater when

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one is more abundant, often using surface water as a primary supply but with groundwater as a buffer for drops in surface water availability (Blomquist et al., 2010; Kundzewicz & Döll, 2009; Scanlon et al., 2016). Highlighting the interconnection between MAR and conjunctive use, in some jurisdictions--including California--legal definitions of MAR include decreasing pumping (Q_{PU}) by replacing groundwater use with surface water; this is termed in lieu recharge (Cal. Water Code §10721).

MAR is primarily used for its water supply benefits (Perrone & Rohde, 2016; Sheng & Zhao, 2015), as it helps utilize available subsurface storage and decrease reliance on surface reservoirs. The global storage volume of groundwater is estimated to be two orders of magnitude larger than available storage in reservoirs and lakes (Dillon et al., 2018). Aquifers have minimal evaporation losses relative to surface reservoirs (Dillon, 2005), and MAR projects are often substantially less expensive by volume than surface reservoirs (Dillon et al., 2010a; Dillon et al., 2009; Scanlon et al., 2016). Additionally, a variety of water sources can be used, including surface water, stormwater, and recycled wastewater (Beganskas & Fisher, 2017; Gonzalez et al., 2015; Page et al., 2018; Sheng, 2005). Taken together, these benefits enhance flexibility for water managers (Perrone & Rohde, 2016; Sheng & Zhao, 2015).

MAR is used worldwide, with over 1,100 projects in 50 countries presently listed in a comprehensive database (IGRAC, n.d.; Stefan & Ansems, 2017). Reported global MAR capacity increased from 1 km^3 annually in 1965 to 6.3 km^3 in 2005 to 9.9 km^3 in 2015, with India and the United States making up the majority of this increase (31% and 26% of global use, respectively, in 2015) (Dillon et al., 2018). Better understanding of the geological and infrastructural considerations behind MAR (Behroozmand et al., 2019; San-Sebastián-Sauto et al., 2018; Sheng & Zhao, 2015) has made MAR more technologically feasible and scalable. Despite these advances, the success of implementing MAR projects varies substantially, with a study of 204 US projects finding that 26% were inactive or discontinued (Bloetscher et al., 2014). In many jurisdictions, legal frameworks, lack of attention to economics, and a lack of experience with the technology remain a barrier to MAR implementation (Bray, 2020; Cruz-Ayala & Megdal, 2020; Megdal & Dillon, 2015; Yuan et al., 2016).

In the US state of California, the Sustainable Groundwater Management Act (SGMA) of 2014 resulted in numerous new MAR project proposals (Jezdimirovic et al., 2020). We identify 233 proposed MAR projects, a significant increase over an estimated 84 historic MAR projects in California and 288 across the entire US (IGRAC, n.d.). California has substantial aquifer capacity (Scanlon et al., 2016) and a number of suitable recharge sites (Alam et al., 2020), but MAR's ability to help reverse decades of over-extraction can only be realized if implemented effectively.

In this paper, we assess the barriers and feasibility of planned MAR projects in California using content analysis of submitted proposals. At the most basic, feasibility is simply an assessment of practicality, measuring how likely a given project is to come to fruition (Kenton, 2020). Here we conceive feasibility as having multiple dimensions. At the scale of the individual MAR project, baseline feasibility entails having the legal authority and permits, land, and funding to be built and the water to operate. Beyond simple operation, the projects need the right hydrogeological, climatological, and socioeconomic features to meet their goals and avoid unintended side-effects. After reporting the characteristics of proposed projects, we analyze legal, funding, water availability, and coordination barriers to project implementation. We then

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assess the projects' ability to achieve their stated goals. To conclude, we discuss broader considerations for ensuring that MAR is an effective water management tool.

2 Materials and Methods

2.1 Case background

The US state of California has an extensive water infrastructure system, built to withstand the state's naturally variable annual precipitation, seasonal mismatch between wet winters and summer agricultural demand, and geographic mismatch between where water is abundant and where people live (Hanak, 2011). Groundwater contributes approximately 30% of the state's water supply in average years, with substantial variation both temporally and regionally. During drought, groundwater can supply 60% of water uses (Lund et al., 2018); some regions of California are completely reliant on groundwater for their drinking water and/or irrigation. In groundwater-reliant areas, unconstrained pumping over the last 60 years has led to declining aquifer levels, paired with land subsidence, saltwater intrusion, and groundwater contamination (Famiglietti et al., 2011; Hanak et al., 2019; Perrone & Rohde, 2016). At the same time, declining snowpacks in the Sierra Nevada range (Cayan et al., 2006; Sun et al., 2019) are leading water managers to look for additional places to store surface water. Because there is substantial capacity for aquifer storage in California, MAR is generally considered to be a promising avenue both geologically and economically (Scanlon et al., 2016). Indeed, several regions, including Orange County, Kern County, and the Santa Clara Valley, have had active MAR projects for several decades (Luxem, 2017).

In 2014, at the height of California's last prolonged drought, the California Legislature passed the Sustainable Groundwater Management Act (SGMA), which created the first statewide system to manage groundwater. It seeks to achieve the "management and use of groundwater in a manner that can be maintained during the planning and implementation horizon without causing undesirable results" (Cal. Water Code §10721). The SGMA categorized California's 515 basins by level of priority, based on population, current and projected groundwater use, and groundwater-related impacts like saltwater intrusion or land subsidence (Cal. Water Code §10933). The SGMA mandated that actors in medium- and high-priority basins, which represent 98% of groundwater pumping, create Groundwater Sustainability Agencies (GSAs), which were tasked with developing and implementing Groundwater Sustainability Plans (GSPs) to achieve sustainability within 20 years and prevent the following six undesirable results from occurring: "(1) Chronic lowering of groundwater levels indicating a significant and unreasonable depletion of supply if continued over the planning and implementation horizon; (2) Significant and unreasonable reduction of groundwater storage; (3) Significant and unreasonable seawater intrusion; (4) Significant and unreasonable degraded water quality, including the migration of contaminant plumes that impair water supplies; (5) Significant and unreasonable land subsidence that substantially interferes with surface land uses; (6) Depletions of interconnected surface water that have significant and unreasonable adverse impacts on beneficial uses of the surface water" (Cal. Water Code §10721(w)).

The SGMA requires GSPs to include sustainable management criteria, which define the basin's sustainability goal (23 Cal. Code Regs. §354.24), describe the six undesirable results and how they pertain to the basin, describe the minimum thresholds and measurable objectives for identified sustainability indicators (23 Cal. Code Regs. §354.26 to 354.30), and propose project

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and management actions that will maintain the minimum thresholds, meet measurable objectives, and therefore achieve the sustainability goal (23 Cal. Code Regs. §354.44). GSAs in basins identified as critically overdrafted were required to have created and adopted a GSP by January 31, 2020 (Cal. Water Code §10720.7(a)(1)). Remaining medium and high priority basins have until 2022 to submit their GSPs (Water Education Foundation, 2015).

As figure 1 shows, most critically-overdrafted basins are in the San Joaquin Valley (southern Central Valley), with the remainder in the Salinas Valley and Southern California; with the exception of Indian Wells Valley, the overdrafted basins are in agriculturally-intensive areas. In addition, the basins in the San Joaquin Valley are all hydrologically connected, but are treated as separate sub-basins under California law.

2.2 Data and analysis

Each basin has one or more GSAs; each GSA has written (or will write) a GSP. The GSPs include multiple proposed management actions, some of which include recharge projects. In this paper, we assess the recharge projects proposed in the 46 GSPs submitted through August 2020 (available at https://sgma.water.ca.gov/portal/gsp/all), which represents a census of critically-overdrafted basins. (Table S1 lists the location of the GSPs by basin.) Three of the GSPs were from GSAs in non-critically overdrafted basins that submitted their GSP early, but none of these plans mentioned recharge projects and therefore do not affect our analysis. Importantly, this study is not an assessment of all recharge projects in California, but only those used by GSAs in critically-overdrafted basins to comply with SGMA.

First, we identified all proposed recharge projects. From each GSP's list of proposed "Projects and Management Actions", we pulled all projects that specifically mentioned "recharge" in the name or text description (n=255). For each of these projects, we copied the full project description from the GSP. Upon review of project descriptions, 22 projects were excluded because they did not directly aim to achieve recharge (e.g., a surface water supply project that briefly mentions that the added supply might be used for recharge). A total of 233 MAR projects were identified. We include both physical and in lieu MAR as both are officially considered MAR under California law (Cal. Water Code §10721); however, recognizing the very different mechanisms that the two approaches comprise, we present results for physical versus in lieu recharge, where pertinent, throughout the text.

Second, we conducted content analysis of each project, which required detailed reading and iterative assessments of all descriptions to collect and catalog information on the project characteristics, stated aims, and implementation status and feasibility. Some variables were copied directly from the text description, including completion date, capital costs, and land area estimate. For others, we used a modified grounded theory approach (Corbin & Strauss, 2008), in which we first copied the raw text as used in the GSP (e.g., for water source, "Surplus surface water is expected to be available from the Kaweah River and from the CVP [Central Valley Project] contract") and then iteratively developed categories to summarize the range of possible responses (e.g., "local surface water" and "CVP"). All variables are described in Table 1. The level of detail varied substantially across GSPs, and not all GSPs contained information for all variables.

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Table 1. Variables derived from Groundwater Sustainability Plan (GSP) project descriptions

Variable	**Description**
Groundwater Basin	Official basin name as recognized by CA Dept. of Water Resources Bulletin 118
GSA	Groundwater Sustainability Agency submitting the GSP
Project Name	Name of the Managed Aquifer Recharge (MAR) project
Project Type	MAR approach (recharge basin, direct injection, aquifer storage and recovery, dry well, creekbed recharge, flood-MAR, on farm spreading, unspecified banking, in lieu)
Goals	Stated aims or benefits of the MAR project
Water Source	Existing or planned source of water to be used for recharge
Status of Implementation	Extent to which the project is underway
Completion Date	First year of operation
Capital Costs	Cost to build project
Capacity	Estimated potential recharge capacity at full operation, acre-feet per year
Funding Source	Known or potential sources of funding for construction and operation
Land Area	Acreage needed for MAR project
Legal Authority	GSA’s stated authority to do MAR project
Permitting	Permits required to construct or operate project

3 Overview of proposed MAR projects

The GSPs described a total of 233 individual recharge projects. They used a range of approaches. One hundred and ninety four (83%) were physical, 19 (8%) were in lieu, 12 (5%) included both physical and in lieu, and 8 (3%) lacked sufficient detail to categorize. Among the physical recharge projects, spreading methods were most common, particularly recharge basins (n=127) and on-farm recharge (n=16). Other types of technology included in-channel modifications (in-creek recharge, n=9), direct injection or dry wells (n=7), flood-MAR (a general term for MAR using floodwaters, often on agricultural land (State of California, 2020)), n=4), and both basins and flood-MAR (n=4). Eight projects referred to “water banks”, which use unspecified technology to store water for individual users to extract at a later date; the remaining 17 projects included a variety of single-use approaches (e.g., tile drains) or lacked sufficient detail to determine.

The number of proposed recharge projects varied substantially across the basins that were required to submit GSPs (Table S1). The Kings basin had the most, with 82 individual recharge projects, followed by 53 in Kern and 28 in Kaweah. No other basin proposed more than 13. Figure 1 displays the distribution of proposed recharge projects by GSA.

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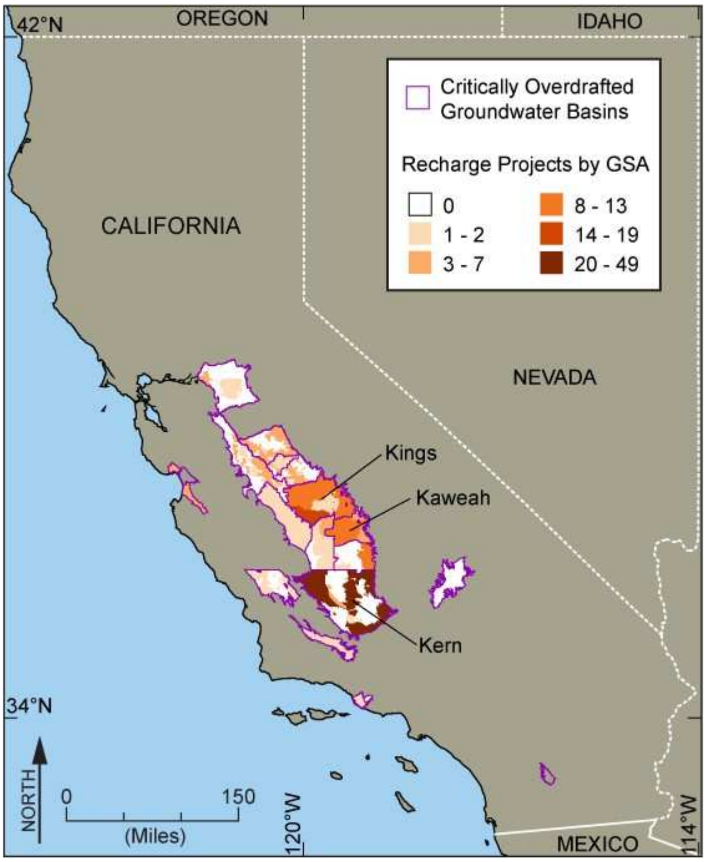

Figure 1. Map showing the number of recharge projects proposed by Groundwater Sustainability Agency (GSA). Purple outline denotes boundaries of critically overdrafted groundwater basins; many basins have multiple GSAs. GSAs are shaded by the number of proposed recharge projects, with those that did not propose recharge projects in white. The basins with the largest number of proposed projects are named.

Figure 2 shows the cumulative number of proposed recharge projects and their targeted completion years. Two-thirds of the projects are scheduled for the first 10 years following the passage of SGMA, with a gradual decline after 2025. The year 2020 has the single largest number of projects, with 25 scheduled to come online. (Timelines were not included for 83 projects.)

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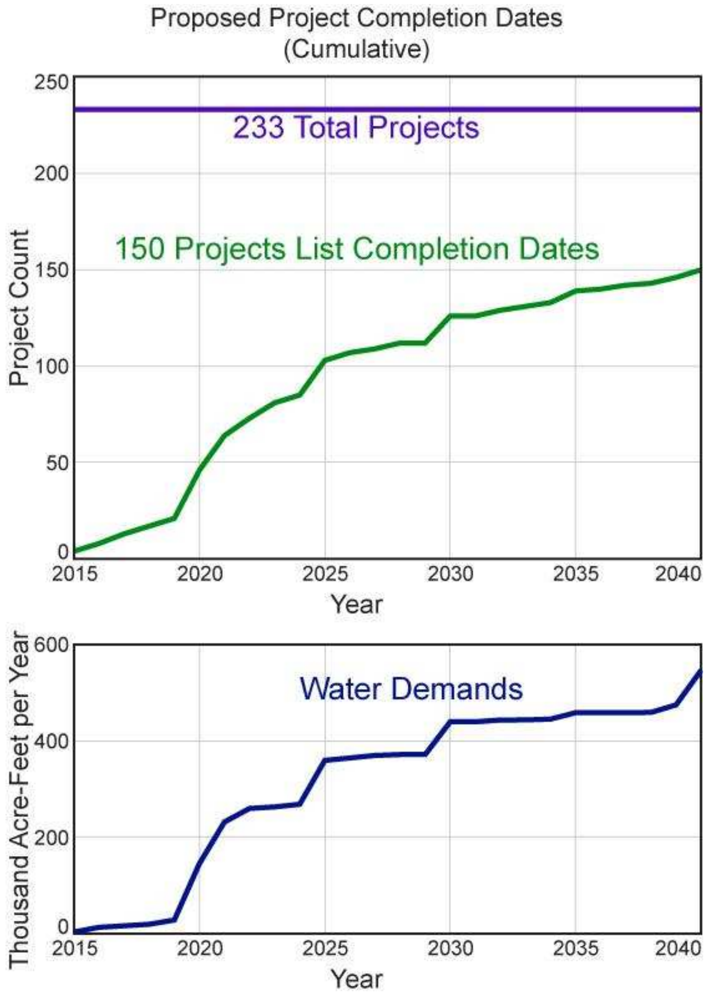

Figure 2. Top: cumulative count of Managed Aquifer Recharge (MAR) projects by completion date, 2015-2040. The count does not include 83 projects for which timelines were not described, nor existing California recharge projects unless they were included in a Groundwater Sustainability Plan (GSP). Bottom: cumulative water estimated MAR capacity in TAF by year; year and/or estimated capacity are not stated for 97 projects.

Figure 3 shows the most commonly cited goals GSPs stated in building the recharge projects. Prevalent goals are *Raise water table or reduce overdraft* (n=142), *Increase storage* (n=112), *Improve water quality* (n=98), and *Mitigate subsidence* (n=85). These goals map clearly onto SGMA's objective of avoiding lowered groundwater levels, reduced storage, seawater intrusion, degraded water quality, land subsidence, and surface water depletion (Cal. Water Code §10721). The remaining categories cover a variety of water supply, environmental, and social goals that may be related, though less directly, to SGMA goals; while there are a handful of projects in almost every other category, they are not widespread. Additionally, 157 projects mention two or more goals, with four stated goals being most prominent (n=62).

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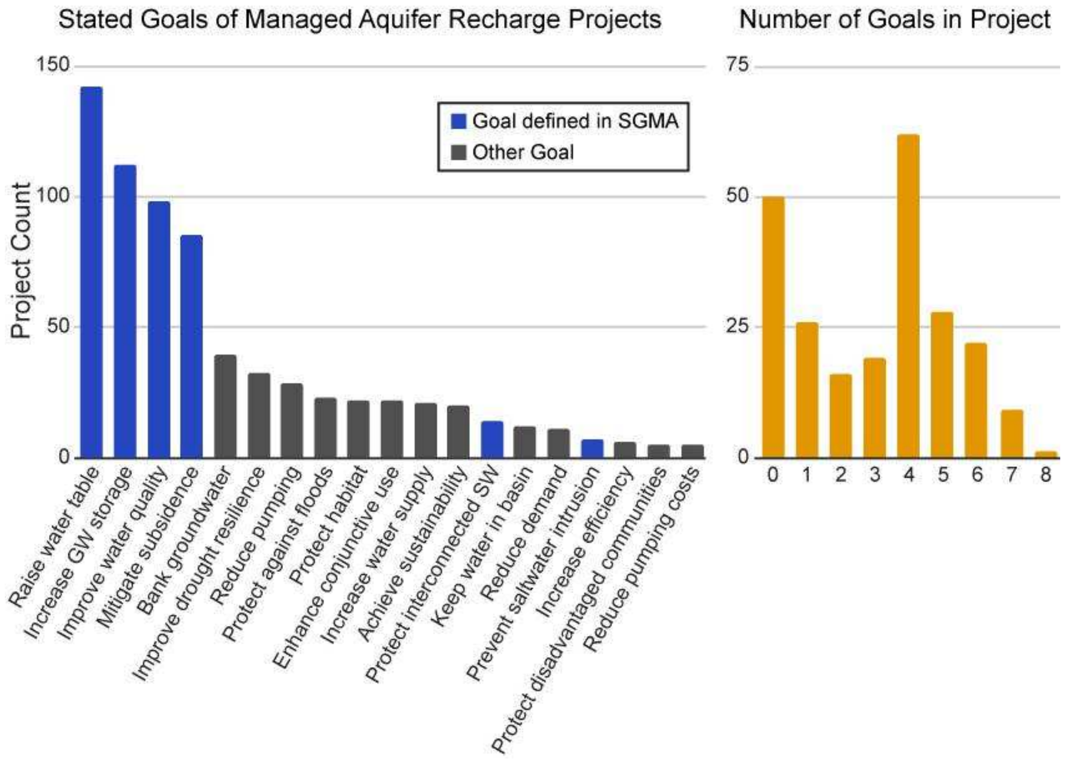

Figure 3. Left: count of projects by stated goal. Right: number of goals mentioned by project; many projects aim to provide multiple benefits. Fifty projects did not list goals. Regarding the counterintuitive “reduce pumping”, multiple Groundwater Sustainability Plans (GSPs) mentioned that by converting agricultural lands to recharge basins, they would reduce their overall water demand and thereby reduce groundwater extraction. GW = groundwater; SW = seawater; SGMA = Sustainabile Groundwater Management Act

4 Feasibility of proposed MAR projects

We next assess project feasibility. To be built, projects need land, permits and adequate legal authority, and funding; once built, they will need water to operate; once operational, they will need the right hydrogeological, climatological, and socioeconomic features to meet their goals and avoid unintended side-effects. Of the 233 recharge projects in the GSPs, 32 were in operation, 16 were underway (either under construction or with permits in hand), and 4 were in pilot studies. The remaining projects were either planned for the future (n=76), conceptual (n=32), extremely speculative (n=14), or lacked information on implementation status (n=58). Given that 78% of proposed MAR projects are planned or speculative, it is important to consider how likely it is that they actually happen. The following sections pair considerations from the literature with an assessment of the GSPs to determine each step’s feasibility.

4.1 Legal feasibility

Having a comprehensive and supportive legal framework provides the necessary foundation for effective implementation. From a legal perspective, a jurisdiction may decide to retrofit existing water laws to deal with MAR projects by relatively small legal adjustments, or it may create a special-purpose legal regime to deal with MAR (Nelson & Casey, 2013). The legal

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complexity of MAR projects varies based on the source of the water to be stored, whether they intend short-term storage followed by extraction (as distinct from longer or even indefinite residence times to help raise groundwater levels), whether water is to be injected or percolated, and whether the water is to be stored and recovered by the same entity, or offered for sale and use by third parties. Even in simple cases, to ensure that MAR can be effective, a legal framework needs to perform several key functions to account for well-recognized problems and challenges (Bray, 2020; Nelson & Casey, 2013; Thompson, 2011; Ward & Dillon, 2011), summarized in Table 2.

Table 2. Issues to be addressed by an effective legal framework for Managed Aquifer Recharge (MAR).

Stage of project	**Key legal issues**
Funding	• Clear legal authority to raise funds for MAR projects, which should account for varying costs of retrieving and treating water, and distribution of benefits
Source of water	• Clear rights to water intended for storage (e.g. water right, water service contract, or other right). • Right to use source water for storage at the relevant places of use without risking forfeiture for non-use
Recharge	• Access to land for injection wells or infiltration basins, and recovery wells, if required, e.g. through land ownership, lease or flood easement • Clear rights to use aquifers to store the water (i.e., rights to storage space) and not be vulnerable to a claim for trespass by storing it • Clarity regarding interaction with other aquifer storage activities (e.g. carbon capture and storage)
Extraction	• Clear rights to withdraw the stored water (where the project is intended for recovery), rules for transfer of these rights, and rules adjusting the quantity available for recovery, taking into account migration of the stored water • Accounting systems for storage and recovery, taking into account implications for ‘native’ (i.e., not intentionally replenished) groundwater • Clear protections against ‘poaching’ of the stored water by neighbors (e.g., widespread and transparent metering)
Unintended consequences	• Controls in relation to foreseeable environmental disruption to the surface and protected groundwater-dependent ecosystems, including environmental impact assessment • Measures to try to prevent potential adverse effects, and clear liability for adverse effects that do occur, including: o direct and indirect effects on water quality; o impacts on subsurface infrastructure due to groundwater mounding during recharge, or unintended groundwater discharge; and o potential rapid lowering of neighboring well levels or subsidence during extraction.

California has taken a bare bones approach to its legal framework for MAR compared to more comprehensive systems established under special-purpose legislation in other western US states such as Arizona (Megdal et al., 2014; Ronstadt, 2012). Recent legal reforms in California, including those under SGMA, help to clarify some issues, but confusing inconsistencies and key

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uncertainties remain. Water quality for MAR is regulated pursuant to federal and state requirements, but only for aquifer injection, not infiltration or spreading basins (Nelson et al., 2015). This means that very few of the projects proposed under SGMA are subject to water quality regulations. Water quality-related permit requirements allow injection of potable water to proceed under a generally applicable rule, rather than requiring individual discharge requirements (SWRCB Water Quality Order 2012-0010), but this does not apply to non-potable water. Stringent regulations apply to recharge of recycled municipal wastewater for drinking water purposes (Yuan et al., 2016, Cal. Code Regs. §§60320.100-60320.230).

A second uncertainty relates to whether recharged water is legally protected as a "beneficial use". This term is not exhaustively defined, but includes using water for domestic, irrigation, power, mining and aquaculture purposes (Cal. Code Regs tit. 23 §659). Under California's Water Code, storing water underground is a beneficial use of the water, provided the recovered water is used for a beneficial purpose (Cal. Water Code §1242). However, after a series of failed bills (Cal. AB 441, 2019; Cal. AB 1427, 2017; Cal. AB 647, 2015), storing groundwater is not clearly a beneficial use of the water in itself. This makes MAR for long-term storage to recover water levels, for example, vulnerable to forfeiture. Only 16 projects clearly specify the intended beneficial use of the stored water, so it is unclear the extent to which short-term storage will meet GSAs' needs. California also lacks a legal framework for more complex MAR projects that involve water banking, giving individual local agencies the freedom and burden of developing local contractual agreements (Nelson et al., 2015). State efforts to develop appropriate contractual templates could address this challenge.

We also assessed how individual GSPs considered their legal authority and relevant approvals to undertake their proposed MAR projects. While some GSPs discuss legal issues in relation to groundwater replenishment activities, this tends to merely recite their source of statutory authority to engage in replenishment or, in a few cases, rights to source water. Relatively few GSPs discuss, in a more nuanced way, the legal issues that could arise in relation to MAR and propose methods for dealing with them. Looking across GSPs reveals a significant range of issues that may arise: the need to purchase land for infiltration basins; obtain rights-of-way; make agreements with landowners for flood easements, potentially involving new incentive structures; make agreements to use the facilities of other agencies; or annex land into the district's territory. While a detailed treatment of these issues could not be expected in GSPs, and the scope of relevant issues will be specific to each individual project, this range of issues indicates sources of legal complexity that could affect feasibility, timing, or cost.

Many projects also will need to obtain permits and undergo environmental review for construction or operation. GSPs detail 13 different types of site-specific permits from local, state or federal agencies needed for many MAR projects. Examples include water transfer agreements, county building permits, streambed alteration agreements from the California Department of Fish & Wildlife, approval under the federal Endangered Species Act, and water quality certifications from the relevant California Regional Water Quality Control Board. Ninety five proposed projects specified they will require some combination of these permits and 28 projects explicitly specified that permits will not be needed; 110 lacked information on permits, though the lack of mention does not mean permits will not be required. While some GSAs have obtained these permits or started the process, many more were speculative about potential permits. Eighty six projects also recognized that they are subject to the California Environmental Quality Act (CEQA), California's environmental impact assessment requirement. One hundred thirty six

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projects lacked information on CEQA, though again we note that a lack of mention of CEQA in the GSP is not equivalent to a project not requiring CEQA; only 11 projects that specified CEQA will not apply. Some GSAs have already commenced submitting environmental review documents for their MAR projects, but many have not. As permitting and CEQA can add substantial financial costs and extend the timeline of projects (Ulibarri et al., 2017; Ulibarri & Tao, 2019), these requirements may challenge the feasibility of some MAR projects. Recognizing the significance of permitting challenges, in late 2019 the state prioritized convening a group of agencies involved with environmental permitting in a three-year project to develop recommendations for addressing these challenges in the flood-MAR context (California Department of Water Resources, 2019).

4.2 Funding availability

Another feasibility consideration is funding. The median estimated capital cost for these projects is $2.15 million, with a mean of $12 million; total estimated capital cost of the 142 projects with cost estimates is $1.675 billion. (Table S2 provides capital costs by project type.) Besides these capital costs, ongoing operational activities and maintenance are required to deal with well clogging and unanticipated water quality issues that require treatment, which can be key reasons for abandoning projects (Bloetscher et al., 2014). Actual ongoing costs depend on site conditions and can vary widely (Dillon & Arshad, 2016). Despite these costs, very few projects had known sources of funding. Twenty three proposers said they would finance the project internally, 13 had grant funding (federal or state), 8 planned to use landowner assessments or fees, 4 said it was the responsibility of individual landowners where recharge would take place, and 2 did not require any funding. Of the remaining projects, 52 were speculative, listing several unconfirmed sources of funding, and 130 projects had no information on existing or potential sources of funding.

4.3 Water supply availability

MAR projects also need water. At full buildout, the GSPs estimate that all recharge projects will provide a cumulative total 961,027 acre-feet/year if operated at full capacity. This estimate does not include 31 projects that did not list an estimated recharge volume. Providing this full benefit will require that adequate water supplies are available for recharge.

Figure 4 displays the water sources mentioned as definite or likely supplies for recharge, as well as the volumes needed for full operation. The most common water sources are local surface water (135 projects accounting for approximately 373 thousand acre-feet, TAF) and water from the Central Valley Project (a vast network of dams and canals operated by the US Bureau of Reclamation) (83 projects accounting for approximately 258 TAF). A few (21) plan to import surface water from non-local rivers. Very few projects use non-surface water: 14 use recycled water or stormwater, 1 uses groundwater from the same aquifer, 1 uses carrot wash water, and 1 uses reclaimed oilfield water. Tables S3 and S4 provide proposed supplies and needed volumes by basin.

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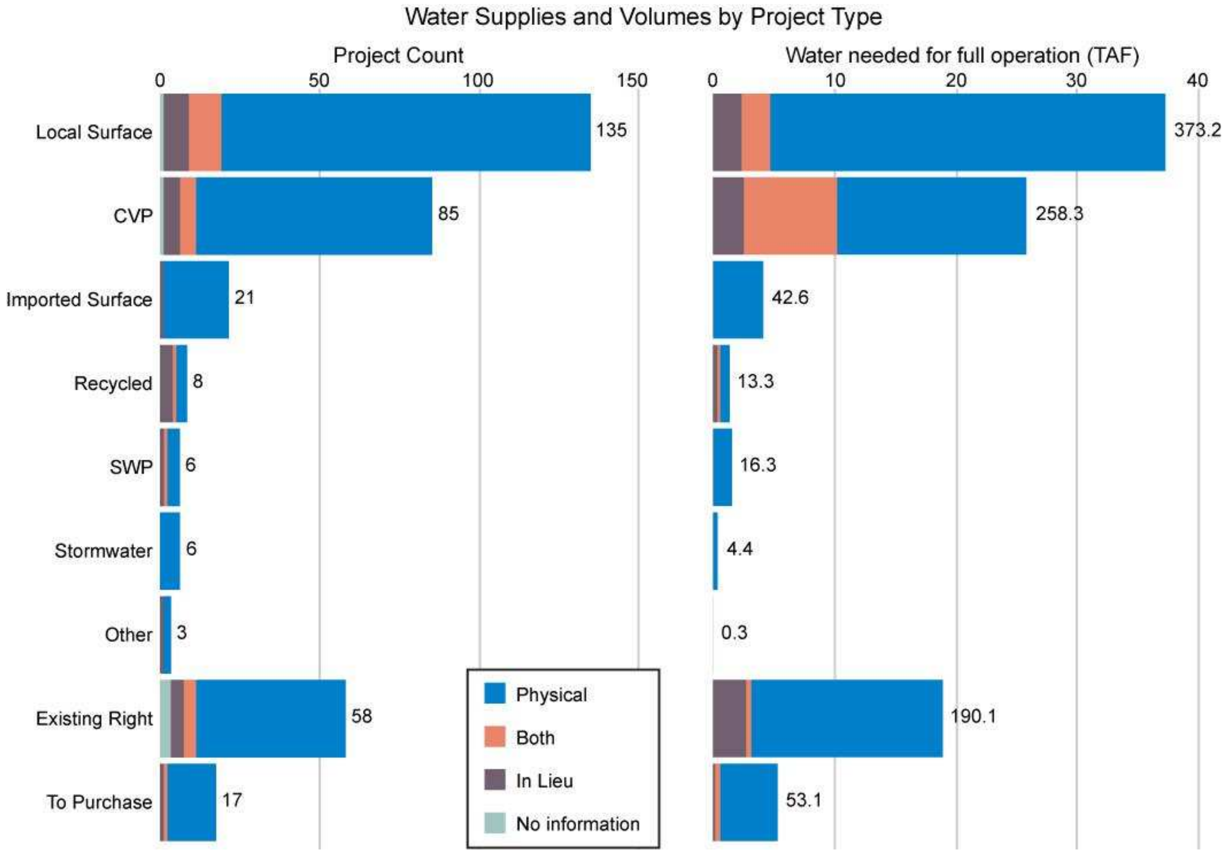

Figure 4. Possible water supplies for Managed Aquafir Recharge (MAR) projects and status of proposed supply. Left: count of projects; Right: volume needed for full capacity operation. For projects with multiple possible water sources (e.g., Local Surface and CVP), volumes are divided equally across each source category. CVP = Central Valley Project; SWP = State Water Project. Sixty-four projects lack information on water supply; an additional 13 are missing estimated recharge capacity.

A key consideration is whether the GSAs will be able to access these water sources for recharge. While most projects include proposed supplies, relatively few GSPs are explicit about the status of this water supply. Only 58 projects explicitly mention that they will use an existing water right or supply (mostly CVP and Kings River), and 17 say they would need to purchase new water or acquire new water rights. While these numbers are likely both underestimates given a lack of detail in water supply descriptions, they do highlight that many GSAs are planning to acquire or develop new water supplies to support recharge. For these GSAs, purchasing water adds to the overall costs of MAR and will depend on whether sufficient water is available for purchase at an affordable price.

For projects turning to local surface water, a challenge is that many rivers are already fully allocated, often with more than 100% of the average annual runoff claimed in existing water rights (Grantham & Viers, 2014, p. 7). For instance, the Kings River (listed as a source for 59 projects), has water rights allocations representing 520% of its mean annual runoff, and the San Joaquin River (listed as a source for 20 projects), has water rights allocations representing 1,585% of its runoff (Grantham & Viers, 2014). Both rivers are also considered fully

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appropriated by the State Water Resources Control Board (California State Water Resources Control Board, 2019), a status that some GSAs are challenging in court (Maven, 2018). It is important to note that allocated volumes overestimate actual water withdrawals, as some return flows do return to the river (Owen, 2014; Thompson et al., 2018). The CVP is similarly fully allocated, regularly delivering volumes smaller than the contracted rights held by users (Dowall & Whittington, 2003, p. 52).

A number of GSPs specifically mention flood flows as a potential supply. Eight projects mention CVP Section 215 uncontrolled flows, 41 mention local surface water flood flows, and many others estimate that the MAR projects will only operate in wet water years. For both local surface water and CVP supplies, some water may be available in high flow years. Historically, high flows have occurred in approximately 4.7 of 10 years in the San Joaquin and Tulare watersheds (Kocis & Dahlke, 2017), where the majority of the proposed MAR projects are located. Existing studies estimate that if flood flows (defined as flows over the 80th or 90th percentile) were allocated to MAR, the San Joaquin and Tulare watersheds could provide between 220 and 970 TAF/yr for recharge (Alam et al., 2020; California Department of Water Resources, 2018; Kocis & Dahlke, 2017). However, with numerous GSPs competing for the same water source, it is likely that excess supplies will not be available for all projects. For instance, 2 projects mention Orestimba Creek as a potential water source. According to Alam et al.'s (2020) assessment of water availability for aquifer recharge, Orestimba Creek can provide between 4.9 and 5.8 TAF annually for recharge. To operate at full capacity, the two proposed projects require 22.5 TAF, far more than is physically (let alone legally) available. The 20 projects mentioning San Joaquin River water require 76.5 TAF to operate at full capacity, yet Alam et al. (2020) estimate that no San Joaquin River water is available for recharge. For similar comparisons for other Central Valley watersheds, see Table S5. Moreover, California law requires a permit to appropriate floodwater as it does in relation to non-flood flows, meaning this water is subject to the same challenges as any surface water right, although flood flows benefit from a more streamlined permitting process (see Text S1 for more discussion).

Finally, the projects need conveyance facilities to get available water to the MAR site. Seventy-six proposed projects specifically mention the need to construct canals, turnouts, pipelines, and other conveyance infrastructure.

5 Additional considerations

5.1 Ability to achieve stated goals

Once a MAR project is constructed, an additional consideration is whether it achieves the goals for which it was intended (Figure 3). While a complete assessment to answer this question would require monitoring the MAR projects over time, here we evaluate whether the MAR project descriptions have reasonable justification of MAR as a tool to achieve these goals or show awareness of relevant issues.

Raising the water table and storing groundwater were the two most commonly-stated goals of MAR projects, referenced by 142 and 112 projects, respectively. These goals result from the same physical action (increasing water volume in aquifers) but have different intent. However, none of the project descriptions specify targets for storage and/or level increase to be achieved by MAR.

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The third most common goal, cited in 98 projects, was improving groundwater quality. However, most project descriptions were not specific in how they intend to improve groundwater quality and many included the caveat that this is a secondary benefit. In 28 projects, lower quality groundwater is expected to be improved by diluting it with surface water, either relying on high quality water from the Sierra Nevadas or simply stating that surface water is expected to have lower concentrations of total dissolved solids. Seventeen projects described a need to monitor groundwater quality, and placed higher uncertainty on the potential for water quality improvement. Ten project descriptions indicated that water quality impacts are complex, discussing locally relevant details such as existing nitrate concentrations, management approaches to mitigate fertilizer leaching, previous pilot studies and modeling, or geologic structures of local aquifers and percolation effects.

The fourth most common goal, cited in 85 proposals, was mitigating land subsidence. Most project descriptions that mentioned land subsidence defined it as a measurable outcome, while ten discussed it as an incidental outcome. Ten projects specified that they intend to reduce the rate of land subsidence, with rates or thresholds to be defined at a future time. Only a few project descriptions discussed additional details regarding the ability of MAR to mitigate land subsidence, such as measurement of land subsidence methods or the relationship between subsidence, recharge, and pumping.

While only 32 projects specifically named drought resilience as an objective, drought has been a long-standing motivation for conjunctive management in California (California Department of Water Resources, 2016) and the timing of SGMA was significantly influenced by drought conditions (Leahy, 2015), signaling droughts’ motivating role in creating MAR projects. Moreover, a subset of the other stated goals (Bank Groundwater, Conjunctive use, Increase water supply, and Reduce demand) also have the potential to smooth out variations in water supply variability over time and balance the water budget. The design of any given project and particularly the way it is managed during drought conditions will determine the extent to which MAR actually serves as a conjunctive management tool for addressing interannual variations in water supply. However, none of the GSPs provided sufficient detail to determine whether the proposed MAR projects have been designed to operate in a way that accounts for these issues.

In sum, the GSPs lack sufficient detail to determine whether the proposed MAR projects are likely to support the goals they state.

5.2 Cumulative impacts of land conversion

A final consideration is the impact of building a large number of new recharge projects in a relatively short period of time. Without considering their cumulative impact on a regional scale, GSAs and the communities they serve could face unintended side effects (Nelson, 2018). In particular, the proposed recharge projects need land, and using land for recharge will impact both ecosystem services (e.g., by removing trees and other vegetation, or by increasing riparian bankflows) and the present economic value of that land (e.g., by potentially removing land from agricultural production). Eighty-eight of the 215 physical recharge project descriptions included the estimated land required for recharge (e.g., size of recharge basins or acres that will be watered for on-farm recharge). Table 3 provides summary statistics for these projects. In total, these projects estimate that they will use 68,000 acres.

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Table 3. Estimated land areas required for Managed Aquifer Recharge (MAR) projects

Project Type	**Count w/ area estimate (Total count)**	**Mean area (acres)**	**Estimated total area (acres)**
ASR/injection/dry well	0 (8)		
Banking	1 (8)	100	800
Basin	103 (139)	159	22128
Basin & Flood-MAR	1 (4)	600	2400
Flood-MAR	2 (4)	14330	28677
Creekbed	7 (9)	8	74
On Farm	6 (17)	3105	18721
Other physical	5 (18)	520	2708
No information	2 (8)	490	1030

We used these estimates to extrapolate average acreage by recharge project type for projects lacking an estimate. (See Text S2 for approach and Table S6 for results by aquifer.) Summing across all projects yields a mean area of 101,000 acres (+/- 39,000 acres). This estimate suggests that some aquifers will be using a sizable amount of their total land area for MAR. For instance, the Kings aquifer, for which the most recharge projects were proposed overall, could see 3.6% (+/-0.4%) of its overlying land used for MAR and 2.3% specifically for recharge basins. The Chowchilla aquifer is estimated to use 8.3% of its land area for MAR; about 7% will be for Flood-MAR with the rest for basins. While Flood-MAR and on-farm recharge do not fundamentally change land use, converting 1.5% of land area to basins is removing that land from other potential uses.

As for the type of land that will be used, 42 projects were using agricultural lands, including 6 on an abandoned or fallowed farm; of these, 30 were basins or injection wells requiring land conversion. Eleven were in a creek or slough, 6 were on private land (unspecified type), 4 in a former quarry or mine, 4 in an existing stormwater basin, 1 in a public park, and 1 in an industrial area. The remaining 148 lacked information on land type. The cumulative extent of the area of land required raises another feasibility issue, since selecting a site for MAR raises complex issues of surface and subsurface characteristics, and some available land areas may simply be unsuitable (Rahman et al., 2012). Moreover, the large number of projects proposed for agricultural land raises a potential socio-political challenge because many farming communities are hesitant to give up farmland, a concern raised whenever fallowing is suggested as a water conservation strategy (Walters, 2019).

6 Discussion and conclusions

6.1 Feasibility concerns

This paper assessed the proposed use of MAR as a tool to combat groundwater overdraft in California. GSPs proposed a total of 233 individual MAR projects, which almost doubles the existing 288 projects in the United States (IGRAC, n.d.). Implementing these successfully could substantially shift the long-term sustainability of groundwater in California. However, our assessment raises a number of potential feasibility concerns that could limit the ability of MAR projects to be built and operated, including water availability, potentially challenging legal requirements, lack of attention to legal arrangements and funding, and access to land. In

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particular, many projects need to obtain water rights in already over-allocated basins, and projects' reliance on local surface water raises doubts about project operation at scale. Consistent with comments from other studies (Dillon et al., 2018; Ghasemizade et al., 2019), we emphasize that MAR projects must adequately address these barriers to achieve implementation.

Additionally, our assessment did not consider all dimensions of feasibility. For instance, while we assessed funding availability, the broader financial feasibility of these projects is a major consideration that would benefit from further study. Adding the high projected capital costs to potential operating costs may suggest that low utilization rates of MAR projects are not economically efficient, even if the full MAR capacity can be utilized in rare flood years.

6.2 Planning for and meeting stated goals

Our assessment highlighted that the GSAs have a variety of objectives for the MAR projects, indicating their potential to provide multiple benefits if they are able to be constructed and adequate water is available for operation. Unfortunately, the project descriptions did not provide sufficient detail to assess whether the GSAs have sufficiently considered the complex set of requirements necessary to achieve these goals. While SGMA's guidelines did not require this detail, using MAR to achieve the goals will require that the projects be designed to account for complex hydrological and geological settings. To aid in understanding this complexity, we discuss some key considerations for each of the top stated goals (increasing aquifer storage, improving water quality, reducing land subsidence, and improving drought resilience).

Numerous projects globally and in California's Santa Clara Valley have established that it is feasible to increase stored groundwater and raise the water table through MAR (Dillon et al., 2012; Ingebritsen & Jones, 1999; Luxem, 2017). However, achieving these benefits depends on water availability, suitable subsurface characteristics (Rahman et al., 2012), and ongoing maintenance of the infrastructure to prevent clogging of the infiltration basins (Martin, 2013), which is a leading cause of abandonment (Bloetscher et al., 2014). It will also depend on whether MAR is used in conjunction with other groundwater management approaches, including reduced pumping (which we discuss later).

Anticipating the influence of MAR on water quality is often not as straightforward as the dilution effect that many of the GSPs rely on, as specific regional aspects of each MAR project can provide numerous mechanisms to improve or degrade water quality. MAR can improve water quality by using recharge water chemistry to drive natural reactions during infiltration and storage that improve water quality (Bekele et al., 2011; Dillon et al., 2003, 2010a; Doza et al., 2020) or by preventing or minimizing reactions linked to groundwater extraction that degrade water quality (Smith et al., 2018). However, geochemical and biological responses are specific to aquifer characteristics (e.g., geologic composition, hydrologic composition, microbe population, structure, temperature) and added water temperature and chemical composition (e.g., contaminants, pH) (Page et al., 2018). Quality concerns can vary seasonally (Ahearn et al., 2004) and by source. For example, urban stormwater runoff can contain ensembles of contaminants that complicate its direct use in recharge (Song et al., 2019), whereas the high purity of treated wastewater can mobilize natural contaminates (Fakhreddine et al., 2015). The chemistry of available water sources for MAR can introduce and support microorganisms, adding infection concerns (Dillon et al., 2010b) and influencing the mobility of heavy metals (Siegel, 2002). Geochemical concerns specific to California include mobilizing dangerous contaminants, such as

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hexavalent chromium (Cr^{6+}) through reactions with agricultural nitrogen or chemicals intentionally added for treating soil and water (Hausladen et al., 2018), nitrates from agriculture (Anning et al., 2012), arsenic (Anning et al., 2012), and uranium (Jurgens et al., 2010). Water quality challenges encountered in existing California MAR projects, such as arsenic mobilization in Orange County, suggest that pretreating water can address unintended consequences (Fakhreddine et al., 2015), but this increases costs and complicates implementation. It will also be important to monitor MAR projects to identify water quality hazards if they arise, especially during initial project installation and/or when switching to new water sources. California's Groundwater Ambient Monitoring and Assessment program (GAMA) (California State Water Resources Control Board, 2020) provides a clear framework to quantify changes in groundwater quality introduced by MAR with comprehensive benchmarks and routine monitoring. There are also risk-based guidelines for MAR (in use in Australia) that address these issues for different water sources, types of recharge, groundwater condition and intended end use; these enable appropriate monitoring, evaluation and risk management measures to be implemented (NRMMC et al., 2009).

The majority of land subsidence in California related to groundwater results from physical compaction of the aquifer pore space and dehydration of clays (Liu & Lin, 2005) following the removal of groundwater (Galloway et al., 1999). Most land subsidence is irreversible and permanent, with a minor amount of recovered land elevation resulting from rehydrated clays. MAR that maintains or increases the height of the water table above its historic minimum has substantial capacity to slow or stop land subsidence resulting from a decrease in the water table. The Santa Clara Valley serves as a regional example of successfully pairing MAR with groundwater extraction regulations to curb rapid land subsidence originating from groundwater extraction (Ingebritsen & Jones, 1999).

The underlying assumption of how MAR can function as a drought resilience strategy builds directly on the relationship outlined in Equation 1: When surface water supplies decrease during a drought, an individual or agency increases pumping (Q_{PU}), decreasing GWS; this is analogous to making a withdrawal from the bank. Then, when the drought is over, GWS is replenished either directly (increasing R_{MAR}) and/or by shifting from groundwater use back to surface water (decreasing Q_{PU}); this is analogous to making a bank deposit (Roberts, 2010; Scanlon et al., 2016). In practice, aquifers do not function as straightforwardly as a bank. First, as Scanlon et al. (2016, p. 2) explain, "The natural hydrologic system also functions as a groundwater bank, storing groundwater during wet periods through increased recharge and depleting groundwater during dry periods through continued natural discharge...Because GWS responds to these various inputs and outputs, it is often difficult to isolate the impacts of [conjunctive use] or MAR." Second, there is a lag time between changes in the precipitation regime (i.e., drought as defined by meteorological indicators (Heim, 2002)) and changes to the groundwater system (Thomas et al., 2017). When a drought is beginning, this lag is helpful, as the aquifer will not reach a state of groundwater drought for some time after meteorological conditions indicate a drought. But at the end of a drought, aquifers will not recover as quickly as meteorological conditions return to normal (Bloomfield & Marchant, 2013; Uddameri et al., 2019); lags of six months to a year were observed following recent droughts in California (Thomas et al., 2017; Wang et al., 2016).

As a result, MAR projects may need to operate in a way that accounts for this buffering and time lag, particularly in situations where the project operator wishes to accelerate

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groundwater replenishment rates (e.g. the case of an over-allocated aquifer). For instance, the amount of water to be recovered over some period might be some percentage of the amount intentionally recharged; this depreciation rate may be considered analogous to the way water stored in a dam is often subject to an adjustment to account for evaporative losses (Ward & Dillon, 2011). Additionally, using MAR for drought resilience may concentrate water withdrawals in time, which itself can have unforeseen impacts: "intense recovery operations over a short duration could cause a significant cone of depression with adverse short-term impacts on adjacent groundwater users (particularly in confined aquifers) or on groundwater dependent ecosystems (particularly in unconfined aquifers)" (Ward & Dillon, 2011, p. 15). Managing explicitly for drought, for instance through creating drought reserves (groundwater set aside with the intention of only being used in case of drought rather than to smooth out intra-annual shortages (Langridge & Daniels, 2017)) or adopting guidelines like the Australian National Water Commission recommendation to limit annual withdrawals to an amount equal to annual anthropogenic recharge (Ward & Dillon, 2011), may help achieve the necessary balance.

6.3 Managing cumulative effects

As MAR in California is planned to be implemented on a large scale over a relatively short timeframe, another feasibility consideration requires assessing the cumulative effects of this roll out. Concerns at the regional and state level could valuably inform the state's guidance and support, especially as the next rounds of GSPs are submitted. First, MAR could dramatically affect surface water resources, as water that is used for recharge is lost for other uses, both socioeconomic and environmental. In particular, the large reliance on surface water and flood flows likely means that riverine flows will be affected. As seasonal and interannual flood pulses are an important feature in supporting aquatic habitat (Feyrer & Healey, 2003; Tonkin et al., 2017), additional withdrawals have the potential to damage already degraded ecosystems (Lund et al., 2010). Some environmental benefits of flood flows will be protected by constraining the availability of streamlined permitting to winter diversions and imposing minimum flows under the federal Endangered Species Act for some ecosystems. Even so, some change to ecologically relevant flow metrics like magnitude, duration and timing (Whipple et al., 2017) will inherently occur with withdrawals of flood flows, even if those flows are later released through discharge from MAR sites to rivers. MAR-induced changes to peak flood flows have raised concerns with environmental advocates in other jurisdictions (Rawluk et al., 2013). These impacts may be exacerbated in drought years, as drought stresses ecosystems at the same time as human water supplies (Crausbay et al., 2017; Mount et al., 2017). Additionally, while our assessment has focused only on recharge projects, the GSPs also propose numerous surface water storage and trading projects (Jezdimirovic et al., 2020; "PPIC San Joaquin Valley GSP Supply and Demand Projects," n.d.); these may further strain the surface water sources intended to supply recharge. Groundwater trading, which is currently in development, could create both localized and regional impacts if used on a wide scale (Babbitt et al., 2017).

It is also important to consider broader environmental and public health impacts of MAR, as significant impacts could prevent projects from being built or operated as intended. De-vegetating large areas of land to build recharge basins may create dust and impact air quality, at least initially (Provost & Pritchard, 2020). Recharge basins can benefit waterfowl, shorebirds, and pollinators (Audubon California et al., 2020), provide littoral habitat, and potentially increase baseflow (Kourakos et al., 2019). Yet changing aquifer levels can negatively affect groundwater-dependent ecosystems (Dillon et al., 2009), particularly if water is withdrawn when

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aquifers are already in drought conditions (e.g., RECON Environmental, Inc. et al., 2012). At scale, each of these impacts has a sizable potential footprint on California's ecology.

The environmental impact assessment requirement that most MAR projects will have to undergo provides one opportunity to account for these cumulative impacts. CEQA requires consideration of cumulative impacts in three key ways: at the initial study stage (when determining whether an environmental impact report (EIR) is necessary); a substantive discussion of cumulative impacts in the EIR if the project's incremental effect is cumulatively considerable; and when determining whether the project will have a significant impact (Prahler et al., 2014). A cumulative impact analysis involves considering the impacts of "past, present, and reasonably foreseeable probable future projects" (Cal. Code of Regs. tit. 14 § 15355). A key issue will be whether MAR projects that could affect the same environments constitute "probable future projects" for these purposes, particularly since they have been detailed in GSPs to varying degrees. The way that EIRs deal with probable future projects in cumulative impact analysis has been the basis of past litigation (e.g., Gray v. County of Madera, 167 Cal. App. 4th 1099, 85 Cal. Rptr. 3d 50 (5th Dist. 2008)). Ultimately, what needs to be considered will vary based on the facts of a particular project. Though perhaps inconvenient, these CEQA provisions will provide important safeguards for already stressed sources of surface water for recharge.

6.4 MAR and demand-side management

Finally, the feasibility barriers we identify also call into question the overall effectiveness of SGMA, given the prominence of MAR as a proposed tool to achieve basin-wide sustainability. Our assessment suggests that MAR may not perform as promised, yet MAR is the largest (by water volume) proposed management tool in GSPs in the Central Valley (Jezdimirovic et al., 2020). The GSPs also rarely propose demand side approaches, like land fallowing or pumping restrictions (Jezdimirovic et al., 2020). The lack of alternative management strategies means that if MAR fails to perform, there are not other tools that will instead help a basin achieve sustainability. A portfolio of management tools, water supplies, and technologies adds system resilience by dispersing risk relative to relying on a single approach (Leroux & Martin, 2016). More generally, it is hard to imagine successful reversal of decades long overdraft without addressing the removal of water from the aquifers: "MAR … is not, however, a substitute for groundwater management based on decreasing abstraction and adapting withdrawal to resource availability" (Casanova et al., 2016, p. 414; Dillon et al., 2012). Studying the long-term trajectory of California's aquifers as the GSPs are implemented will provide valuable insights about the appropriate balance between recharge and demand side management.

Realizing the promise of MAR to address groundwater overdraft ultimately depends on specifics about how individual projects are designed and implemented as well as on how multiple projects interact at regional scales. It will be valuable to watch the response to SGMA further develop, as it presents an opportunity to observe MAR (and other groundwater management approaches) implemented widely. California, an exceptionally wealthy and industrialized region, is poised to contribute research findings and lessons learned in MAR construction and operation. This may identify important solutions to hydrological, legal, institutional, and operational challenges that translate to more effective and sustainable use of MAR as a water management approach.

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Acknowledgments, Samples, and Data

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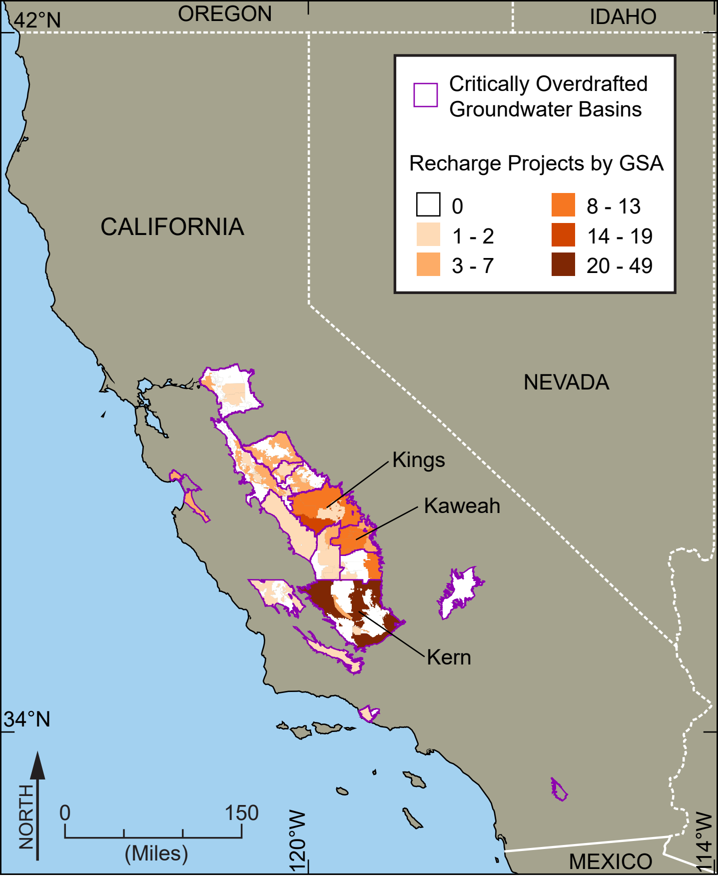
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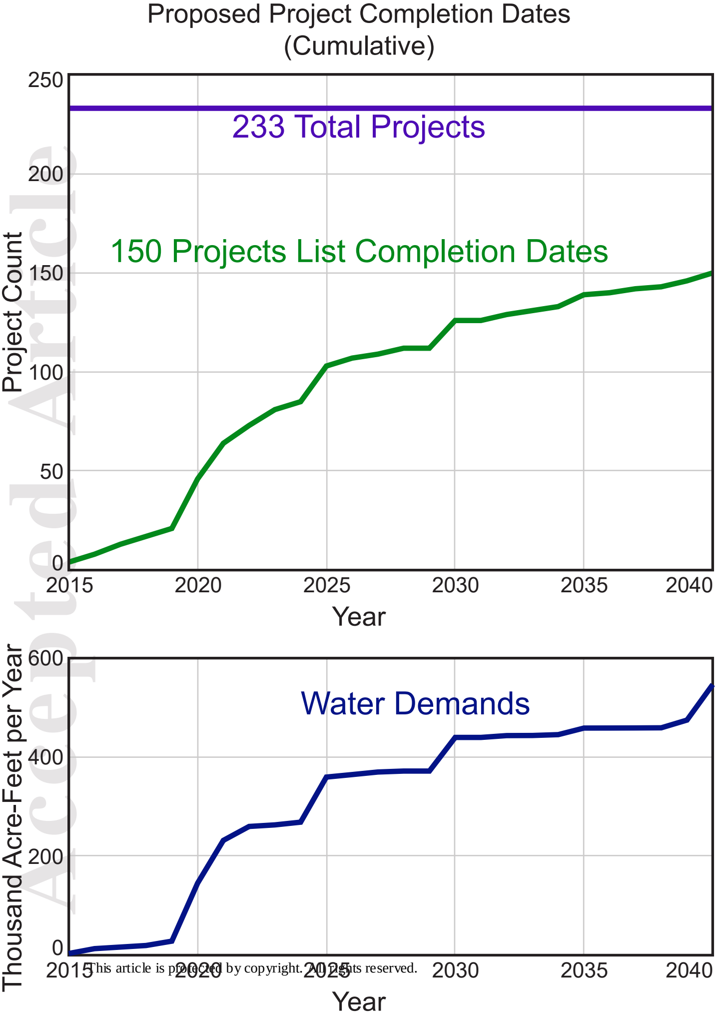

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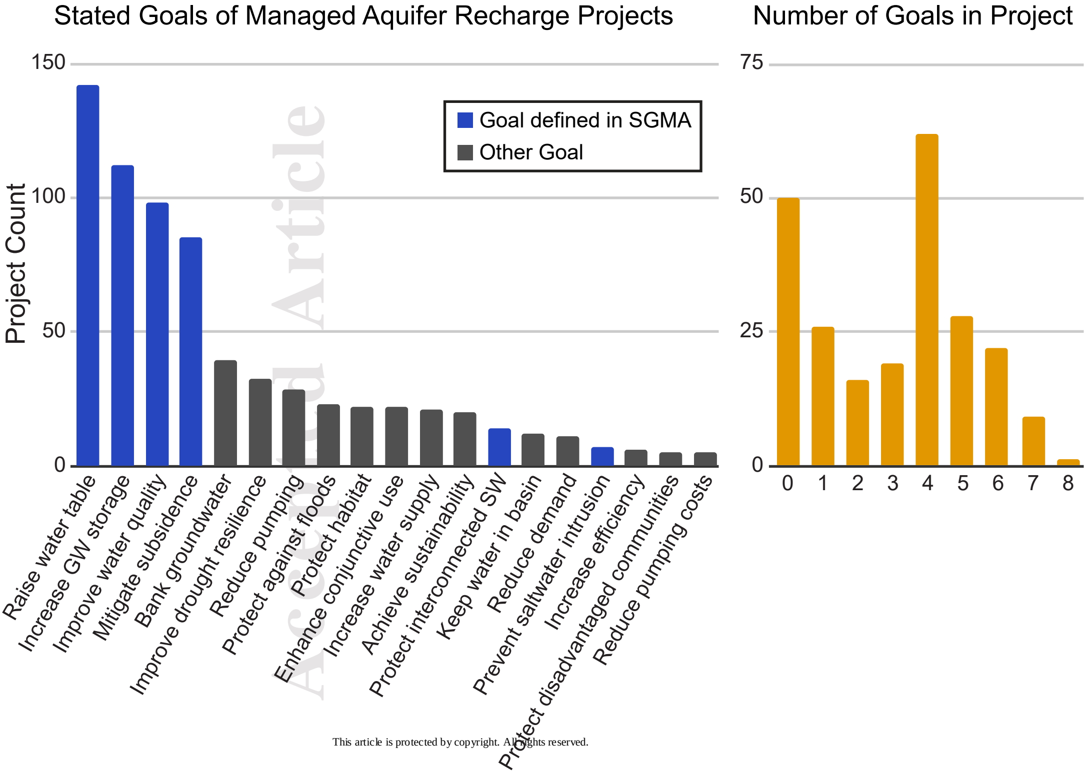

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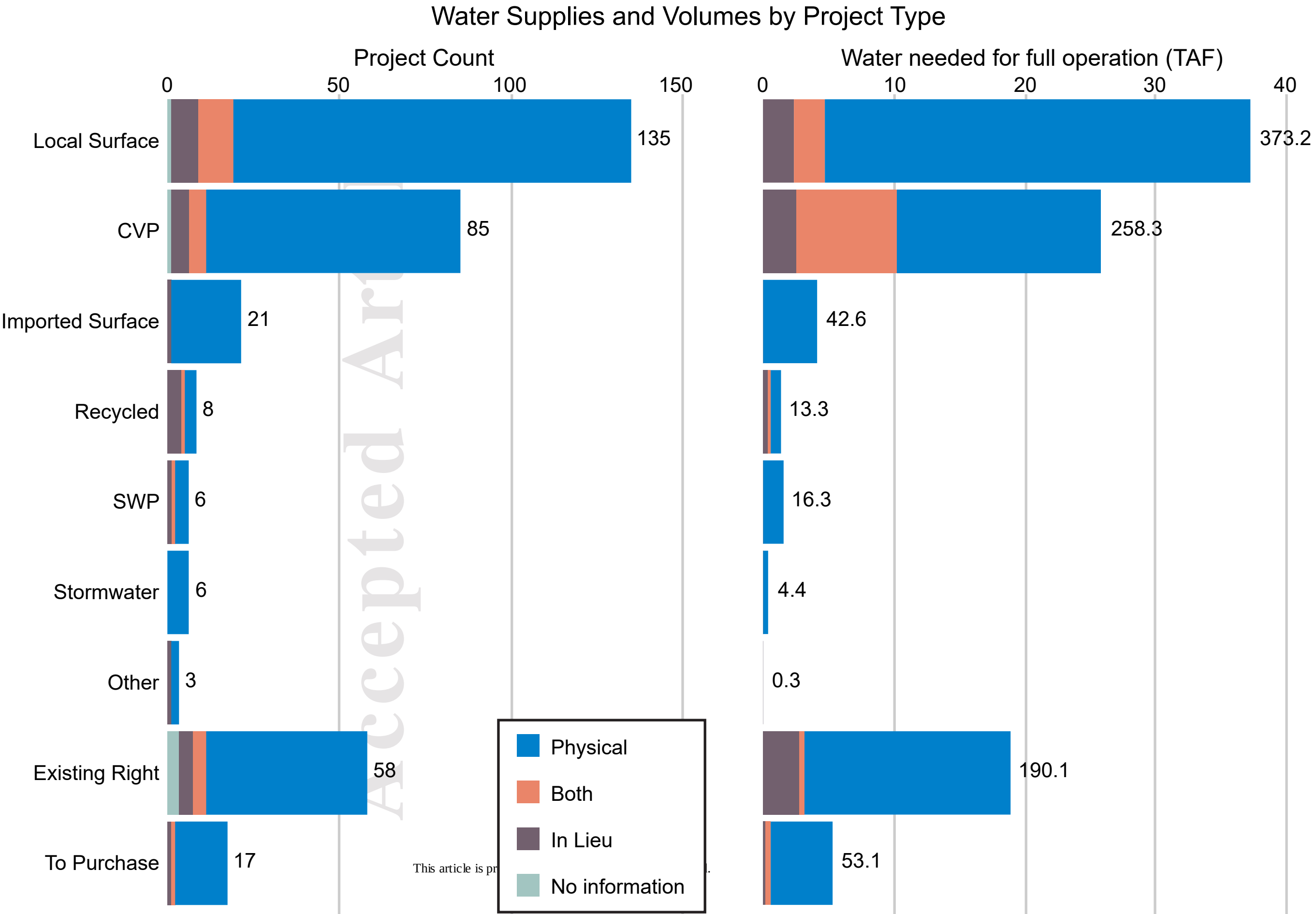

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Water Resources Research

Supporting Information for

Assessing the Feasibility of Managed Aquifer Recharge in California

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Text S1. Water rights requirements for flood flows

Diverting floodwater with the intention to increase groundwater recharge requires a water right, meaning that there must be unappropriated water for a new right to be permitted (California State Water Resources Control Board, n.d.). While water rights processes are not known for their simplicity or speed, new streamlined permitting processes have been designed to assist SGMA implementation to facilitate recharge of floodwater. Provided an environmental impact review has been undertaken, a local groundwater management agency may be granted an ‘umbrella water right’ designed to maximize the area where groundwater can be recharged using new diversions of high river flows (California State Water Resources Control Board, 2019). This process reduces complexity and provides flexibility for various accounting methodologies, administrative prioritization and a less costly filing fee (23 California Code of Regulations § 1062).

Text S2. Method for land area estimates

To estimate the total land area required for recharge, we first calculated the mean and standard error of each project type, using the estimates provided by a subset of the GSPs (Table 3). For projects for which no area estimates were provided in the GSP, we then used the calculated estimates to impute the mean area for that project type, +/- the standard error. These values form the basis of the total area estimate provided in the text.

As some projects included multiple recharge approaches, we disaggregated areas where available (e.g., listing separate acreages for basins versus on farm recharge). In all cases, if a range of possible areas was provided, we used the minimum estimate. For creekbed recharge, the GSPs estimated the miles of river, creek, or ditch along which recharge would take place. To convert this to an area, we estimated an average width of 10 ft (likely an underestimate); the river miles were multiplied by 10 ft and then converted to acres.

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Groundwater Sustainability Plan	Groundwater Basin	Basin Number	Proposed MAR projects
Salinas Valley Basin GSP	180/400 Foot Aquifer	3-004.01	5
Chowchilla GSP	Chowchilla	5-022.05	5
Cuyama Basin GSP	Cuyama Valley	3-013	1
Northern & Central Delta-Mendota GSP	Delta-Mendota	5-022.07	6
Farmers WD GSP	Delta-Mendota	5-022.07	0
Aliso WD GSP	Delta-Mendota	5-022.07	2
Grasslands WD GSP	Delta-Mendota	5-022.07	1
San Joaquin River Exchange Contractors WA GSP	Delta-Mendota	5-022.07	4
County of Fresno GSP	Delta-Mendota	5-022.07	0
Eastern San Joaquin GSP	Eastern San Joaquin	5-022.01	3
Indian Wells Valley GSP	Indian Wells Valley	6-054	0
East Kaweah GSP	Kaweah	5-022.11	7
Greater Kaweah GSP	Kaweah	5-022.11	11
Mid-Kaweah GSP	Kaweah	5-022.11	10
Henry Miller Water District GSP	Kern	5-022.14	1
Kern County Subbasin Olcese GSP	Kern	5-022.14	0
Buena Vista GSP	Kern	5-022.14	3
Kern River GSP	Kern	5-022.14	0
Kern Groundwater Authority GSP	Kern	5-022.14	49
Olcese WD GSP	Kern	5-022.14	0
Central Kings GSP	Kings	5-022.08	1
North Fork Kings GSP	Kings	5-022.08	18
South Kings GSP	Kings	5-022.08	19
McMullin GSP	Kings	5-022.08	10
Kings River East GSP	Kings	5-022.08	12
North Kings GSP	Kings	5-022.08	9
James ID GSP	Kings	5-022.08	13
Madera Subbasin Joint GSP	Madera	5-022.06	11
Gravelly Ford Water District GSP	Madera	5-022.06	1
New Stone Water District GSP	Madera	5-022.06	1
Root Creek Water District GSP	Madera	5-022.06	0
Merced Subbasin GSP	Merced	5-022.04	3
Oxnard Subbasin GSP	Oxnard	4-004.02	2
Paso Robles Subbasin GSP	Paso Robles Area	3-004.06	2
Pleasant Valley GSP	Pleasant Valley	4-006	0
Santa Cruz Mid-County Groundwater Agency GSP	Santa Cruz Mid-County	3-001	3

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Tulare Lake GSP	Tulare Lake	5-022.12	7
Pixley ID GSP	Tule	5-022.13	0
Eastern Tule GSP	Tule	5-022.13	10
Delano-Earlimart ID GSP	Tule	5-022.13	0
Alpaugh GSP	Tule	5-022.13	0
Lower Tule River ID GSP	Tule	5-022.13	0
Tri-County WA GSP	Tule	5-022.13	1
Westlands WD GSP	Westside	5-022.09	2

Table S1. Location of GSPs by groundwater basin, with count of proposed Managed Aquifer Recharge (MAR) projects. ID = Irrigation District; WA = Water Authority; WD = Water District.

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Project type	Count w/ cost estimate	Median	Mean
ASR/Injection	4	18.0	17.9
Banking	3	0.5	2.3
Basin	90	2.2	9.2
Basin & Flood	2	76.0	76.0
Creekbed	8	0.2	0.6
Dry Well	2	1.3	1.3
Flood-MAR	1	29.8	29.8
Other Physical	8	5.0	13.8
On Farm	1	0.1	0.1
In lieu	12	2.0	17.8

Table S2. Mean and median estimated capital costs (in million US$) by Managed Aquifer Recharge (MAR) project type. ASR = Aquifer Storage and Recovery.

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Basin	**Local Surface**	**CVP**	**Imported Surface**	**Recycled**	**SWP**	**Stormwater**	**Other**
180/400 Foot Aquifer	2	0	0	2	0	0	1
Chowchilla	4	2	1	0	0	0	0
Cuyama Valley	0	0	0	0	0	0	0
Delta-Mendota	11	1	4	0	0	1	0
Eastern San Joaquin	1	2	0	0	0	0	0
Indian Wells	0	0	0	0	0	0	0
Kaweah	19	21	0	1	0	1	0
Kern	5	3	4	0	6	2	2
Kings	76	45	6	0	0	1	0
Madera	12	9	6	0	0	0	0
Merced	1	0	0	0	0	0	0
Oxnard	1	0	0	1	0	0	0
Paso Robles Area	0	0	0	2	0	0	0
Pleasant Valley	0	0	0	0	0	0	0
Santa Cruz Mid-County	0	0	0	2	0	1	0
Tulare Lake	0	0	0	0	0	0	0
Tule	1	0	0	0	0	0	0
Westside	2	2	0	0	0	0	0

Table S3. Count of proposed water sources by groundwater basin. Many projects include multiple possible water sources. CVP= Central Valley Project; SWP = State Water Project. Data not included for 64 projects with no water supply information.

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Basin	Local Surface	CVP	Imported Surface	Recycled	SWP	Stormwater	Other
180/400 Foot Aquifer	1.6	0.0	0.0	3.5	0.0	0.0	0.0
Chowchilla	35.5	6.5	3.6	0.0	0.0	0.0	0.0
Cuyama Valley	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Delta-Mendota	31.5	3.8	13.8	0.0	0.0	0.9	0.0
Eastern San Joaquin	10.0	24.0	0.0	0.0	0.0	0.0	0.0
Indian Wells	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kaweah	24.9	33.3	0.0	1.8	0.0	0.8	0.0
Kern	6.5	19.8	11.3	0.0	16.3	1.4	0.3
Kings	201.3	145.4	2.8	0.0	0.0	1.3	0.0
Madera	54.1	19.4	11.2	0.0	0.0	0.0	0.0
Merced	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxnard	0.0	0.0	0.0	4.8	0.0	0.0	0.0
Paso Robles Area	0.0	0.0	0.0	3.2	0.0	0.0	0.0
Pleasant Valley	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Santa Cruz Mid-County	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tulare Lake	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tule	1.5	0.0	0.0	0.0	0.0	0.0	0.0
Westside	6.2	6.2	0.0	0.0	0.0	0.0	0.0

Table S4. Volume of proposed water sources in thousands of acre-feet (TAF) by groundwater basin. CVP= Central Valley Project; SWP = State Water Project. For projects with multiple possible water sources (e.g., Local Surface and CVP), volumes are divided equally across each source category. Either volume or water supply data are not available for 77 projects.

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Source River(s)	**Average water availability (min-max), TAF**	**Count of MAR projects with stated use of river(s)**	**GSP estimated water needs for operation at full capacity (TAF)**	**% of average available water (min-max)**
American River, Cosumnes River, Dry Creek, Mokelumne River and Calaveras River	130 - 492	2	29.00	5.9% - 22.4%
Orestimba Creek	5 - 6	2	22.50	396.5 - 462.6%
Stanislaus River	50 - 88	1	19.00	21.5% - 37.8%
Tuolumne River and Merced River	79 - 229	0	0.00	0.0%
Bear Creek, Deadman’s Creek, Chowchilla River and Fresno River	13 - 17	11	74.90	439.9% - 577.4%
Kings River	90 - 99	59	285.42	288.6% - 317.2%
San Joaquin River	0 - 0	20	76.47	
Kaweah River, Tule River, Deer Creek and White River	24 - 37	16	36.72	98.5% - 151.0%
Kern River	49 - 71	2	0.00	0.0%
Poso River	2 -3	1	0.00	0.0%

Table S5. Comparison of Groundwater Sustainability Plans (GSPs) estimated Managed Aquifer Recharge (MAR) water needs with average annual water available for recharge from rivers. Water availability data from Alam et al. (2020), table S2. Ranges reflect different scenarios based on maximum depth of water applied for recharge and whether streamflow above the 80th or 90th percentile is allocated to MAR. TAF = thousands of acre-feet.

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Basin	**Basin area (acres)**	**MAR area stated in GSP (acres)**	**Mean estimated area required (% of total basin area)**	**Standard error of estimated area required**
180/400 Foot Aquifer	112049	300	6510 (5.8%)	9354
Chowchilla	182781	1610	2210 (1.2%)	0
Cuyama Valley	295439	300	300 (0.1%)	0
Delta-Mendota	960566	1217	2145 (0.2%)	96
Eastern San Joaquin	972215	0	0 (0%)	0
Indian Wells	382000	0	0 (0%)	0
Kaweah	548198	3304	6895 (1.3%)	4821
Kern	2192353	5739	8917 (0.4%)	733
Kings	1225184	24978	28610 (2.3%)	4834
Madera	435913	750	2322 (0.5%)	287
Merced	645521	68	227 (0.0%)	47
Oxnard	70154	0	318 (0.5%)	94
Paso Robles Area	537689	0	0 (0%)	0
Pleasant Valley	19840	0	0 (0%)	0
Santa Cruz Mid-County	45003	0	3264 (7.2%)	4724
Tulare Lake	664483	1100	4683 (0.7%)	4818
Tule	591186	0	91 (0.0%)	30
Westside	774768	0	6210 (0.8%)	9354

Table S6. Estimated land required for proposed Managed Aquifer Recharge (MAR) projects by groundwater basin. Estimates do not include Flood-MAR or in lieu recharge, as neither permanently shifts land use. GSP= Groundwater Sustainability Plan

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