MANAGEMENT CONSIDERATIONS FOR PROTECTING GROUNDWATER QUALITY UNDER AGRICULTURAL MANAGED AQUIFER RECHARGE

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EXECUTIVE SUMMARY

Unsustainable groundwater use in California - due in large part to historical over-pumping of aquifer systems, growing reliance on groundwater to meet irrigation and urban water demands, and increasing frequency of drought - affects all water users and threatens agricultural viability into the future, but has disproportionately impacted disadvantaged communities and jeopardizes their access to safe, clean and affordable water. To secure the availability of groundwater for all uses, the state enacted the Sustainable Groundwater Management Act (SGMA) in 2014. Groundwater Sustainability Agencies (GSAs) were charged with developing Groundwater Sustainability Plans (GSPs) to avoid undesirable effects of ongoing groundwater depletion. To meet these goals, many GSPs include managed aquifer recharge (MAR) as one of several key tools to improve groundwater sustainability.

Agricultural Managed Aquifer Recharge (AgMAR) is the act of intentionally flooding fallow, dormant, or active cropland when excess surface water is available. AgMAR has the potential to be a cost-effective and high impact form of MAR due to the large acreage of cropland throughout California. As more farmers adopt AgMAR, there is greater urgency to understand the potential water quality risks and benefits associated with recharge. While pesticides and geogenic contaminants such as arsenic pose additional water quality concerns in MAR projects, this paper focuses specifically on water quality considerations for nitrate and salts related to AgMAR activities.

Nitrate contamination of groundwater is expected to worsen into the future. However, a combination of improved nutrient management and carefully implemented AgMAR projects could improve groundwater quality faster than under business as usual. Improvements in nitrogen management practices should be prioritized to reduce current and future nitrogen (N) loading to groundwater. Furthermore, relatively clean (nitrate free) recharge water (e.g. high magnitude flood flows) should be used during AgMAR events in order to dilute incoming and existing nitrate in groundwater. AgMAR programs should prioritize sites that can recharge in longer-duration single-flooding events, such as sandier sites, to capitalize on the dilution effect and reduce biologically mediated mineralization of organic N (the conversion of organic N to nitrate).

AgMAR alone will not lead to substantive improvement in groundwater quality with respect to nitrate without concomitant improvements in current agronomic nitrogen management and sufficient water for dilution. The development of transparent and easy-to-use tools that estimate the amount of residual nitrate at the end of a growing season, the amount of water needed to dilute nitrate under AgMAR, and time of travel to groundwater will help in the successful implementation of recharge projects to avoid negative water quality externalities. Current nitrogen loading maps and locations of drinking water supply wells can be used by GSAs to get a sense of regional nitrogen loading to groundwater and help in planning and prioritizing efforts on sites to target for AgMAR.

Salt is another contaminant that poses a growing threat to drinking water quality and farm productivity and is particularly pernicious as its effects are slow to detect, long term, and expensive to remediate. Groundwater salinization is exacerbated and accelerated as groundwater basins become disconnected from surface water outlets, because salts cannot be exported from a system where the only outflow of water is through evapotranspiration. Reconnecting groundwater basins to surface water via AgMAR and other types of managed aquifer recharge could eventually help alleviate groundwater salinization, although it may take decades to centuries to achieve depending on the extent of overdraft in a basin. Steps to actively manage and mitigate salt accumulation, such as the CV-SALTS program, are paramount and therefore AgMAR should be planned synergistically with CV-SALTS efforts. AgMAR recharge water should be low in salts to help in the dilution effect and avoid sites with perched water tables that allow for accelerated evaporation and concentration of salts.

Additionally, the planning process should be coordinated with potentially affected communities who historically have been left out of water management decisions. GSAs should include these communities in the planning of AgMAR projects, communicate the potential risks, and develop monitoring and contingency plans in case of contamination and loss of access to clean drinking water.

Future research should focus on how AgMAR affects the entirety of the nitrogen cycle, including how flooding affects nitrogen mineralization and denitrification. Research on the implementation of soil health management practices to improve water quality will provide additional avenues for how current agricultural management can reduce nitrogen loading to California's water resources.

INTRODUCTION

Overview

In semi-arid regions such as California, ecosystem vitality, community health outcomes, and agricultural productivity hinge on access to safe, clean, and sufficient water. Groundwater is a finite and shared resource that plays a particularly vital role in California by supporting streamflow and essential habitat for groundwater dependent ecosystems, drinking water for communities across the state, and the state's agricultural economy valued at $50 billion USD (Hanak et al. 2019). However, over-pumping and increased frequency of drought threaten California's ability to provide a reliable supply of clean water for groundwater dependent ecosystems, communities, and the agricultural sector (Hanak and Mount, 2015).

Rural communities in California disproportionately share the largest burden of this challenge, compared to their urban counterparts (Balazs et al. 2011). Within rural communities, disparities exist between those who have the financial, technical, and managerial resources to address the challenges of accessing clean water and those disadvantaged communities who do not. To secure water resources for sustained use and in direct response to the 2012-2016 drought, the Sustainable Groundwater Management Act (SGMA) was passed in 2014. Under SGMA, Groundwater Sustainability Agencies (GSAs) are charged with developing Groundwater Sustainability Plans (GSPs) that outline how to meet sustainability goals to avoid the six undesirable effects of lowering groundwater levels, groundwater storage reduction, seawater intrusion, land subsidence, surface water depletion, and water quality degradation. Local control over basin management granted to GSAs via SGMA provides a unique opportunity to bring together diverse coalitions of farmers, water managers, environmental justice and conservation groups, and community members to address the management of this shared resource.

In order to meet these goals, many GSPs include managed aquifer recharge (MAR) as a key strategy to combat overdraft. MAR is an approach where water is intentionally harvested and infiltrated into the subsurface to replenish depleted unconfined aquifers (Dahlke et al. 2018a). Traditional MAR approaches include injection wells and dedicated recharge basins, of which there are many successful examples in California (Dahlke et al. 2018a). However, these approaches can be expensive and limited in impact due to the sheer scale of groundwater overdraft. More recent efforts are targeted at recharging water on working landscapes such as refuges, floodplains, flood bypasses, and agricultural lands. Agricultural lands in particular provide a promising landscape for MAR due to the extensive acreage and the existing irrigation infrastructure to apply large amounts of water on cropland in California, a strategy known as agricultural managed aquifer recharge (AgMAR). This paper focuses on the potential water quality effects, both positive and negative, of using current and former agricultural lands for groundwater recharge efforts.

Although promising, AgMAR has the potential to negatively impact water quality by mobilizing nutrients and other salts from legacy and continued fertilizer application. In this paper, a review of the current knowledge of water quality risks due to leaching of nitrate and other salts under AgMAR is presented to inform the accelerated pursuit of on-farm recharge programs. Although new research on these issues is continuing to evolve, the considerations presented here include management practices that are supported by current research findings. Soil and agricultural management practices with higher uncertainty in their ability to improve water quality under AgMAR are highlighted in the emerging and future research section. Risk evaluation, monitoring and contingency plans are briefly discussed in order to give some guidance in avoiding, tracking and mitigating any negative water quality outcomes as a result of AgMAR. Resources for risk evaluation, monitoring and contingency plans are provided; however, a thorough discussion is beyond the scope of this paper.

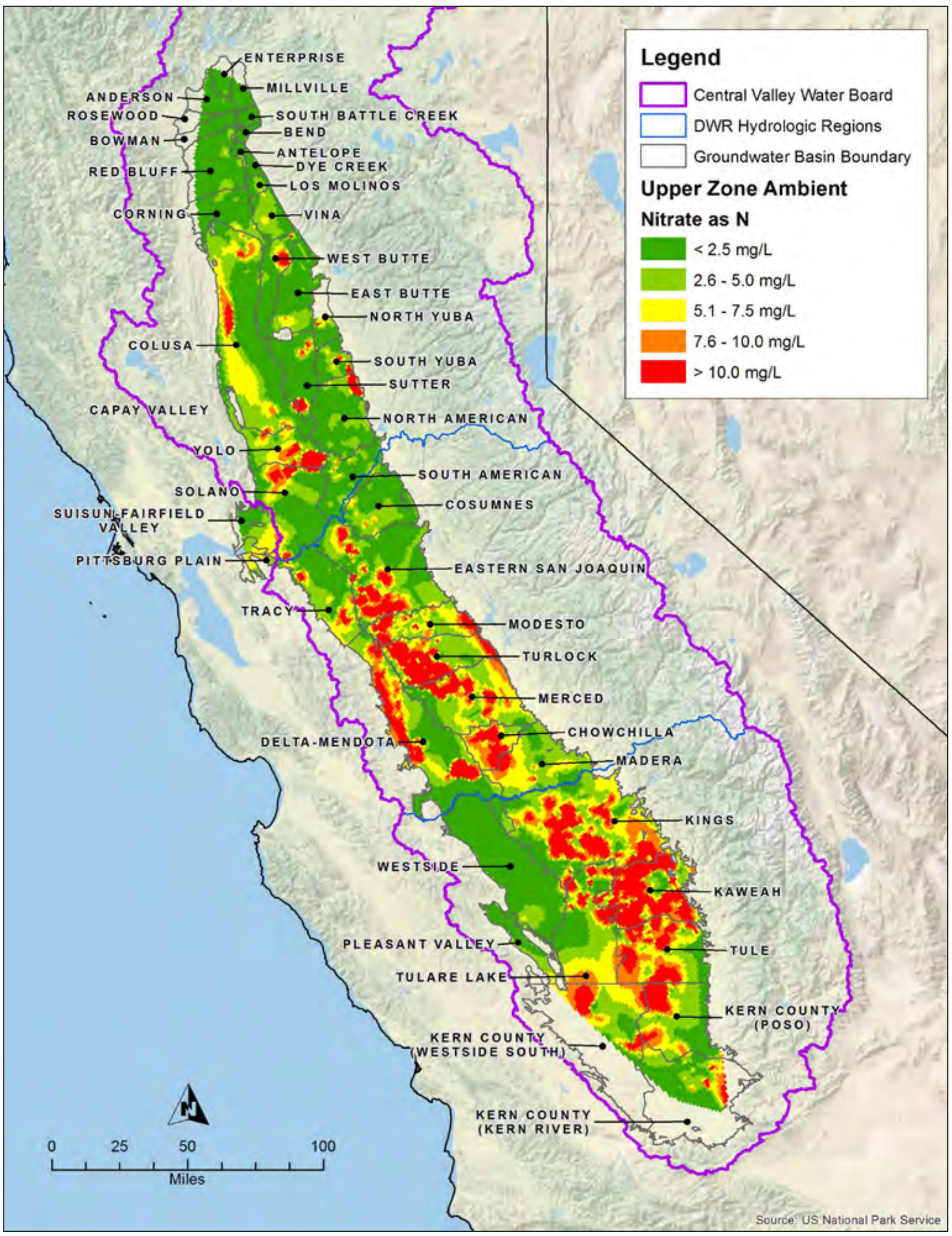
Water Quality Impacts to Communities

Eighty-five percent of people in California depend on groundwater as part of their water supply (Macleod and Méndez-Barrientos, 2019). During the most recent drought of 2012-2016, declining groundwater dropped beyond the reach of 3,500 shallow domestic wells, most of which were located in disadvantaged communities (defined as a median household income <80% of the state median) (Macleod and Méndez-Barrientos 2019, Pauloo et al. 2020). Even with the most aggressive intervening measures, such as reduced pumping and/or increased groundwater recharge, ~1,500-2,500 domestic wells are predicted to be affected by declining groundwater by 2040, with an additional estimated cost of $3 - 5 million USD to deepen impacted wells by 6 meters (Pauloo et al. 2020). However, if water quality in deeper parts of the aquifer does not meet drinking water standards, additional costs will be incurred from securing alternatives for safe drinking water or to deepen wells further. The cost of constructing a new domestic well is estimated to be between $3,250 and $87,000 (Jasechko and Perrone 2020).

Nitrate: There are many areas in the Central Valley where poor water quality impacts human health. One contaminant of particular concern is nitrate, which has been linked to multiple deleterious health outcomes, including low infant blood oxygen levels, hypertension, cancers, and miscarriage (Ward et al. 2018). Sources of nitrate to groundwater include: (1) nitrate from septic systems and industrial discharge; (2) legacy nitrate built up in the unsaturated zone between the surface and groundwater from historical nitrogen fertilizer use; (3) nitrate leaving the root zone due to currently applied nitrogen use and water use inefficiencies; and (4) nitrate from dairy operations.

A sampling of 200 private wells in the Central Valley found that 40-50% exceeded the EPA Drinking Water Quality Standard for the maximum nitrate (NO_3^-) concentration of 10 mg nitrate per liter (NO_3^- N/L) with higher average concentrations in communities of color (Lockhart et al. 2013, Safe Water Alliance et al. 2014). A study by Balazs et al. (2011) found that small public water systems (<200 connections) serving predominantly low-income communities of color had higher levels of nitrate compared to their white counterparts. In communities of color, 0.5-7% of systems exceeded the Maximum Contaminant Level (MCL) whereas 0% of systems exceeded the MCL in predominantly white communities. This inequity was not found for larger water systems (>200 connections). In addition to domestic well contamination, an estimated 400+ public supply wells throughout California are contaminated by nitrate, affecting 600,000 people predominantly in the San Joaquin Valley (Belitz et al. 2015). This means that disadvantaged communities in the Central Valley, who already pay disproportionately more for clean drinking water (10-12% compared to the UN's benchmark for affordable rates of 2-5% of household income), are at risk of losing access to safe and affordable groundwater (Safe Water Alliance et al. 2014).

FIGURE 1: Ambient conditions for nitrate (mg/L as N) in the upper zone of groundwater basins/subbasins in the Central Valley. *Source: Figure 3-23 from Final SNMP for Central Valley Water Board Consideration: December 2016.* https://www.cvsalinity.org/docs/central-valley-snmp/final-snmp.html.

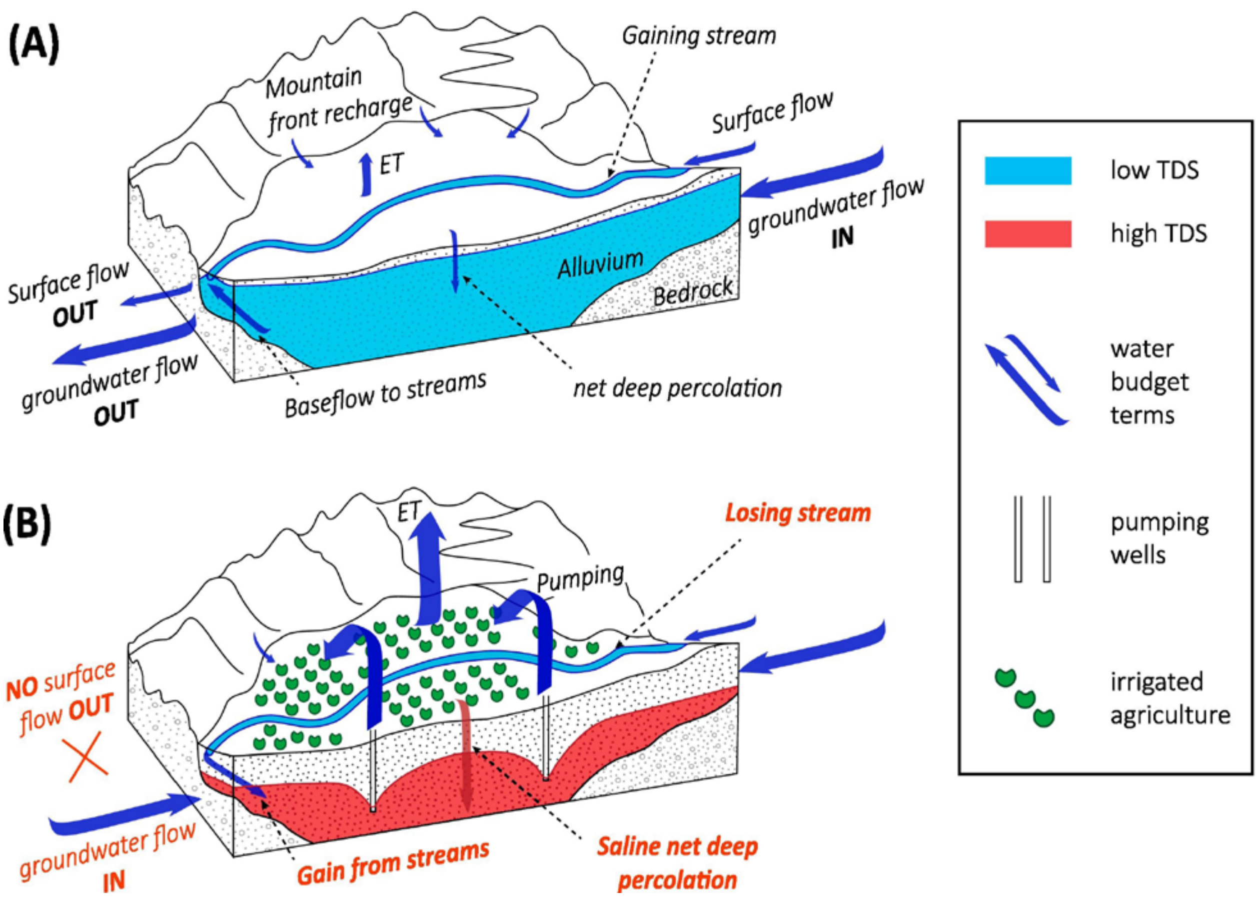


Salt: Salt is another contaminant that poses a growing threat to drinking water quality and farm productivity and profitability. Water quality standards for total dissolved solids (TDS) have been established for agricultural water quality (450 mg/L) and secondary maximum contaminant levels for taste, odor and discoloration (500 mg/L) (CSWRCB 2019a & b).

Risk of salt accumulation also has an impact on California's agricultural economy. 1.5 million agricultural acres have been identified as salt impaired, resulting in 250,000 acres already being taken out of production (CV-SALTS 2016). A major anthropogenic source of salinity comes from cumulative evaporative losses of imported surface water for irrigation (CV-SALTS 2016, Pauloo et al. 2020). Other anthropogenic sources compounding the salinity problem in the Central Valley include water softeners, agricultural inputs (manures, synthetic fertilizers, and liming agents), source water for recharge such as recycled wastewater, local groundwater used for irrigation, and in coastal areas, seawater intrusion due to sea level rise and/or unsustainable pumping (Werner et al. 2013, Richardson et al. 2018). Groundwater salinization is exacerbated and accelerated as groundwater basins become disconnected from surface water outlets, since the only outflow of water is via evapotranspiration, and salts cannot be exported from the system (Figure 2) (Pauloo et al. 2021).

Natural sources of salinity come from the dissolution of salt bearing rocks (e.g., gypsum, calcium and magnesium sulfates and carbonates) when they come into contact with water (Schoups et al. 2005). Salinity levels in groundwater vary across the Central Valley depending on the local geology. For example, the west side of the valley has higher groundwater salinity due to more soluble, salt bearing materials derived from the Coastal Mountain Range, whereas the east side has lower salinity due to the less soluble, crystalline geologic materials from the Sierra Nevada Mountain Range (Schoups et al. 2005, Fuji and Swain 1995, Belitz & Heimes, 1990). Unlike nitrate contaminated groundwater, growers cannot pump and fertilize with salinized water and remediation opportunities, at least in inland sites, are limited and costly. Thus, both nitrate and salt contamination are a public health and economic concern for our groundwater dependent communities and agricultural economy.

FIGURE 2: **Conceptual model on how hydrologic basin closure and groundwater pumping interact to increase salinization of an aquifer system.** (A) Open basin, pre-groundwater development: surface and groundwater systems connect. Groundwater discharges dissolved solids into surface water which exits the basin. (B) Closed basin: groundwater pumping causes elimination of baseflow to streams. Lower groundwater levels cause subsurface inflow to drain adjacent basins. Pumped groundwater is concentrated by evapotranspiration (ET) when applied for irrigation. Salts migrate into the production zone of the aquifer, driven by vertical hydraulic gradients from recharge and pumping. Although these figures show two extremes (open and closed), partially-closed basins also exist. *Source: Figure 1 from Pauloo, R.A., Fogg, G.E., Guo, Z., and Harter, T. (2021). Anthropogenic Basin Closure and Groundwater Salinization (ABCSAL). Journal of Hydrology.*



AgMAR: Potential Benefits and Risks

California has seven million hectares (ha) of agricultural land, 3.6 million of which have been rated as "Excellent" or "Good" in the Soil Agricultural Groundwater Banking Index (SAGBI) for infiltrating large amounts of water to support recharge of underlying unconfined aquifers based on surface soil physiochemical properties (O'Geen et al. 2015). The potential benefits of AgMAR include: 1) raising water tables, which could improve drinking water access and decrease pumping costs to farmers; 2) enhancing streamflow and habitat for groundwater dependent ecosystems in downgradient gaining streams and downgradient areas with shallow groundwater (Foglia et al. 2012, Kourakos et al 2019, Ghasemizade et al 2019); 3) preventing further land subsidence that would obviate the need for associated infrastructure repair costs; and 4) increasing groundwater storage that could act as a buffer against future droughts (Bachand et al. 2014).

AgMAR could affect nitrate contamination in five ways: (1) mobilizing and flushing legacy and/or recently applied nitrate stored in the unsaturated (vadose) zone, to perched groundwater or groundwater stored in an unconfined aquifer, causing an increase in nitrate concentrations in groundwater that could be temporary or ongoing depending on current land management practices (Stinson 1999, Waterhouse et al. 2020); (2) diluting nitrate concentrations in groundwater if subsequent and sufficient quantities of flood water are applied and current root zone nitrate is managed efficiently to reduce loss (Bastani et al. 2019); (3) changing groundwater gradients and potentially altering direction of flow, which could move nitrate contaminated groundwater towards or away from drinking water wells; (4) exacerbating or diluting existing groundwater nitrate concentrations, depending on the amount of nitrate in the source water used for an AgMAR project (Bachand et al. 2016); (5) changing the redox status of the aquifer via incoming recharge water, potentially mobilizing or attenuating contaminants (i.e. oxic recharge water introduces oxygen into previously anoxic aquifers and reduces the ability of the groundwater to attenuate nitrate by transforming nitrate to dinitrogen) (McMahon et al. 2011).

In addition to nitrate, other salts could be affected in similar ways by AgMAR activities, with additional consideration of how the underlying geologic solubility will contribute to salinity under AgMAR. Furthermore, the degree of hydrologic basin closure will influence the efficacy of AgMAR on improving water quality in relation to salts (Pauloo et al 2021; Figure 2).

Nitrate contamination of groundwater is expected to worsen into the future due to nitrate build up in the vadose zone from historical applications of nitrogen fertilizer (Bastani and Harter, 2019). However, a combination of improved nutrient management and carefully implemented AgMAR projects could improve groundwater quality faster than under business as usual (Bastani and Harter 2019). As a key tool identified by GSAs to improve groundwater quantity, AgMAR should be implemented to maximize benefits to water quality and to manage risks. The effects of AgMAR on water quality is an area of active and emerging research and thus AgMAR projects should proceed cautiously and include all stakeholders (growers, water managers, communities and environmental justice and conservation groups) in the planning process, with a full understanding of the potential risks, benefits, and uncertainty in the outcomes. While pesticides and geogenic contaminants such as arsenic pose additional water quality concerns in MAR projects, this paper focuses specifically on water quality considerations for nitrate and salts related to AgMAR activities.

Drawing from the existing literature and expert scientific opinion, the following sections present management considerations to prevent or minimize negative water quality outcomes from AgMAR activities

AGMAR-SPECIFIC BEST AGRONOMIC MANAGEMENT PRACTICES

The highest priority to protect drinking water quality under AgMAR is to ensure current and future agronomic practices minimize any further leaching of nitrogen (N) below the root zone. AgMAR can represent a significant shift from standard agricultural irrigation practices by introducing large volumes of applied water that are above typical irrigation rates. Therefore, traditional grower practices should include additional considerations to account for new issues that may arise with this change in practice. Based on the currently available literature and most up-to-date science, this section contains current recommendations for adjusting agronomic practices at an AgMAR site.

Nitrogen Use and Irrigation Efficiency

Under AgMAR, using clean surface water for recharge must be accompanied by eliminating or minimizing nitrogen loading to groundwater through applied nitrogen, which can be accomplished by prioritizing recharge on crops with low nitrogen demand and avoiding nitrogen application in excess of crop demand (Bastani and Harter 2019 and 2020). The goal for nitrogen management with respect to AgMAR should be to reduce the amount of excess nitrate in the soil that flushes past the root zone and eventually into the groundwater. Field-specific adjustments will be necessary for all practices discussed below and will depend on yield goals, weather, soil properties, and irrigation systems (CDFA Fertilizer Guide, CDFA Fertilizer Adjustments.

Nitrogen Application: For nutrient management, the four "R's" of fertilization (Right Source at the Right Rate at the Right Time in the Right Place) are appropriate guidelines (Niederholzer 2012, Wang et al. 2015). These efforts attempt to better match nitrogen application with crop uptake in order to reduce the potential for excess amounts of nitrate to remain in the soil and subsequently leach toward groundwater. Methods such as fertigation and enhanced efficiency fertilizers (slow-release fertilizer and inhibitors) have been helpful in synchronizing applied nitrogen to crop uptake and thereby improving nitrogen use efficiency (Barakat et al. 2016). Fertigation, the process of applying nitrogen fertilizer through irrigation systems, can be done in many different types of irrigation systems (drip, sprinkler) and can better match plant uptake while reducing nitrate loss by applying low concentrations of nitrogen at high frequency with timing and amounts adjusted based on crop uptake needs (Gärdenäs et al. 2005, Barakat et al. 2016). Irrigation systems that deliver these low concentrations of nitrogen at high frequency directly within the root zone where uptake of nitrogen occurs tend to have higher nitrogen use efficiency and less nitrate lost than other systems (Gärdenäs et al. 2005, Barakat et al. 2016). End of season soil nitrate should be tested to assess the efficiency of fertigation practices and to better understand how much nitrate loading there could be during a subsequent AgMAR event (Gärdenäs et al. 2005).

Nitrogen applications should be applied for realistic yield goals so that over fertilization is avoided (CDFA Fertilizer Guidelines). Once a realistic yield goal is determined, accounting for nitrate in irrigation water, plant available nitrogen produced from organic matter (nitrogen mineralization) and residual nitrate in the soil can help adjust and reduce exogenous fertilizer inputs and thus lower the nitrate leaching potential. Although many factors influence nutrient cycling, lower application rates of nitrogen fertilizer can lead to decreased nitrate leaching from agricultural land (Gheysari et al. 2009, Harter et al 2017).

Nitrogen fertilization should be avoided directly before a planned AgMAR event, as this can increase the nitrate leaching potential (Baram et al. 2016). Fall application of nitrogen fertilizer in almonds may be reduced or avoided completely if July leaf nitrogen concentrations are above 2.8%, as research indicates that additional fall applied N had no effect on almond yield the following growing season (Doll 2012, Niederholzer 2012). Nitrate leaching can be reduced by minimizing recharge during the active growing season when nitrogen pools are greatest and focusing instead on dormant cropland or fallow fields.

Cover Crops: Practices such as cover cropping that scavenge residual nitrogen after a cash crop has been grown can help reduce nitrate leaching during the winter when rains normally flush nitrate from the root zone (Thapa et al. 2018). Cover cropping, when rotated with cash crops, improves the nitrogen retention of the agroecosystem as a whole (Thapa et al. 2018). Cover crops can either reduce nitrate leaching by absorbing residual nitrate in soils after harvest or by integrating nitrogen-fixing cover crops that reduce the need to apply chemical fertilizers. However, cover crops could be negatively impacted by anoxic conditions created by large applications of water, rendering them less effective at taking up residual nitrate (Barton and Colmer, 2006). If the cover crop is already established and plants are past their peak nitrogen uptake period, residual soil nitrate will be reduced in the field and nitrate leaching will be reduced under AgMAR. Future research should be conducted to test the timing of AgMAR in relation to the growth stage of a cover crop to best implement this management strategy under AgMAR and its ability to reduce chemical input needs and nitrate leaching potential. However, perceived reductions in yields due to cover cropping remain a barrier to adoption by many growers.

Water Use: Growers should also strive to improve water-use efficiency through improved irrigation management during the growing season to conserve water and reduce movement of nitrate below the root zone due to excess irrigation where plants cannot access it (Gheysari et al. 2009). Any irrigation system can be prone to inefficiencies if water applications exceed evapotranspiration demands (CDFA Fertilizer Guide, CDFA Fertilizer Adjustments). Improvements in water use efficiency will also have positive benefits on crop nitrate uptake and can improve nitrogen use efficiency during the growing season, thereby reducing the risk of residual nitrate leaching under AgMAR during the winter or dormant period (Barton and Colmer 2006). Region-wide trends toward increased irrigation efficiencies have in fact decreased summer return flows and recharge to groundwater (Niswonger et al. 2017, Sears et al. 2018), but focusing AgMAR outside of the growing season when there is no active crop fertilization could help reduce mobilization of nitrate from the root zone. In some cases, over irrigation of low nitrogen-use crops such as alfalfa during the growing season could help increase recharge without increasing nitrate leaching.

Optimizing AgMAR Project Area and Water Availability

Variability in yearly surface water availability has the potential to limit the effective implementation of AgMAR (Bastani and Harter, 2019). Excess flood flows are predicted to be intermittent and inadequate in quantity to sufficiently dilute nitrate with recharge water within the San Joaquin and Tulare Basins of the Central Valley, where high magnitude excess flood flows occur on average 4.7 out of 10 years and may need to be supplemented with imported surface water for dilution effects to occur (Kocis and Dahlke 2017, Bastani and Harter 2019, Bastani and Harter, 2020). In fact, Bastani and Harter (2020) found that AgMAR alone, given the insufficient frequency and amount of water available for recharge, did little to dilute nitrate concentration in groundwater.

The efficacy of AgMAR to reduce or at least not exacerbate nitrate concentrations in groundwater will depend on the availability, amount, and frequency of water for recharge. Baram et al. (2016) estimate that in an almond orchard with 70% nitrogen use efficiency, 60-100 kg/ha of excess nitrogen accumulates in the soil over a year and would require 0.68 to 1.0 meter (2.2 to 3.3 feet) of clean flood water to dilute nitrate concentrations below the MCL. AgMAR alone will not lead to substantive improvement in groundwater quality without concomitant improvements in agronomic nitrogen management and sufficient water for dilution (Bastani and Harter, 2019 & 2020). Thus, tools that measure or estimate the residual nitrate in the root zone should be developed to calculate the necessary amounts of water needed to dilute the propagating nitrate front to groundwater. This could then be compared with the likely amount of water available in any given year in order to determine if a site should be used for recharge.

The AgMAR project area should be optimized such that the spreading area is not too large in proportion to the amount of surface water available. A dedicated recharge site of appropriate size will minimize the area impacted by increased nitrate leaching potential under AgMAR. Continual availability and application of water annually for recharge will greatly help in reducing groundwater nitrate contamination, as long as other best management practices are implemented such as reducing or eliminating nitrogen loading at the site.

AgMAR programs should prioritize sites that can recharge in longer-duration single-flooding events instead of short, pulsed flooding events. If crop and site-specific flooding tolerance is sufficient, long duration flooding events can decrease mineralization potential (the conversion of organic nitrogen to plant available nitrogen), increase denitrification potential (the conversion of nitrate à nitrous oxide àdinitrogen gas), and decrease overall nitrate loss to the subsurface (Murphy et al. in Prep). However, incomplete denitrification, where nitrate is converted to nitrous oxide instead of completely converting to dinitrogen could be an unintended negative externality of an AgMAR activity. As nitrous oxide is a potent greenhouse gas, more research is needed to understand how AgMAR will affect the entire nitrogen cycle (Kennedy et al. 2013).

Sandy, coarse textured sites with high infiltration rates are often rated as excellent recharge sites, with a relatively high recharge potential in existing AgMAR soil suitability indexes (O'Geen et al. 2015). While denitrification and mineralization potential tend to be lower at these sites, they may be strong candidates for long-term dedicated AgMAR sites, based on their dilution effect potential and high recharge capacity.

TABLE 1: Summary of best AgMAR-specific agronomic practices to reduce nitrogen leaching below the root zone.

Nitrogen Applications	**Follow 4 R's of fertilization** (Right Source at the Right Rate at the Right Time in the Right Place)
	Adjust N application rates based on realistic yield goals (crop uptake), nitrate in irrigation water, nitrogen mineralization from organic matter, and residual nitrate in soil.
	Use fertigation (delivery of N through irrigation systems) to target low-concentration, frequent applications directly to root zone.
	Use controlled-release fertilizers and nitrification inhibitors or split applications.
	Test end-of-season N to evaluate uptake efficiency during growing season.
	Reduce or eliminate fall N applications if dormant crop needs can be met with residual soil N.
Water Use	**Avoid excess irrigation during the growing season,** which can move N below root zone.
Cover Crops	**Use cover crops** to scavenge residual N after harvest and/or reduce the need for synthetic N applications.
Recharge Management	**Do not apply N directly before a recharge event.**
	Focus recharge on fewer acres when surface water is limited to decrease nitrate and salt leaching potential.
	Recharge in longer-duration flooding events (rather than short, pulsed events).
	Maximize recharge in dormant/fallow periods when N is not actively applied.

Decreasing Groundwater Salinization Potential

Salinization of groundwater basins is particularly pernicious as its effects are slow to detect, long term, and expensive to remediate. Groundwater-surface water connections allow for water, and the salt it carries with it, to exit the basin via surface waters. Over-pumping of groundwater resources can result in groundwater becoming disconnected from surface water, resulting in increased salinization due to water exports being dominated by evapotranspiration (Pauloo et al. 2021). This output leaves salts behind without a way for them to be exported out of the basin and effectively turns the system into a salt sink. Reconnecting basins to surface water via AgMAR and other types of managed aquifer recharge could eventually help alleviate groundwater salinization, although it may take decades to hundreds of years to achieve depending on the extent of overdraft in a basin (Pauloo et al. 2021). Incorporating the following practices now can establish a system where groundwater salinization is mitigated over the long term.

AgMAR projects must prioritize the use of low-salinity water for recharge, in order to decrease salt loading (Bachand et al. 2014, Pauloo et al. 2021). Surface water resources during high flow events are often low in salinity, making them potentially ideal sources of water for AgMAR. However, if the source water is high in salts, such as municipal recycled water, it can be blended with clean water to reduce salinity levels before being applied during an AgMAR project (Water Environment and Reuse Foundation, 2017).

As mentioned in the site selection process, AgMAR sites should be located where there is not a history of saline soils or salinity contamination issues. Sites with a historically high water table due to an underlying impermeable layer are prone to salinization via evapotranspiration. When possible, sites should also be located where the underlying geologic materials are not sources of potentially significant amounts of soluble salts.

Similar to nitrate leaching mitigation, an important piece of decreasing salt leaching potential is to maximize the dilution effect at AgMAR sites (Bastani and Harter 2019). Prioritizing a site that can recharge a large amount of water, through a relatively small surface area will decrease the number of interactions between soil volume and the recharged water, reducing dissolution reactions and could decrease groundwater contamination potential.

SITE ASSESSMENT CONSIDERATIONS TO PREVENT OR MINIMIZE WATER QUALITY RISKS UNDER AGMAR

The aim of AgMAR is to help improve groundwater sustainability by increasing groundwater reserves while protecting water quality. The following considerations take into account regional- and field-scale characteristics that can help guide an initial site assessment to determine water quality risks associated with recharging on particular field sites.

Regional-Scale Considerations

Hydrogeology: Generally, groundwater moves slowly, carrying dissolved contaminants as it flows (EDF 2019, Winter et al. 1998). As groundwater levels rise or decline in response to recharge or pumping activities, the magnitude and direction of groundwater flow and the contaminants it carries can change (EDF 2019). The rise and fall of water tables, as well as changes in lateral and vertical movement and mixing, will also change the interaction between groundwater and the overlying sediments in the vadose zone and therefore what is dissolved in the groundwater (Winter et al. 1998). Because groundwater quantity and quality are inextricably linked, regional trends in groundwater quality and quantity should be assessed when evaluating potential AgMAR site locations to anticipate how groundwater levels will change and influence the movement of contaminants. An understanding of relative flow rates and direction will impact site evaluation plans as well, allowing for the identification or placement of useful monitoring well locations (EDF 2019). An assessment of regional pumping activities will increase the understanding for the potential acceleration of flow paths and their dominant direction. This can inform expectations on the timeline at which the impact of an AgMAR site may be seen in groundwater monitoring networks (e.g., Bastani et al., 2019, 2020).

Community Water Access: Current research regarding the extent of domestic well vulnerability in unconfined aquifers across the California Central Valley has mapped areas of high risk for well failure (defined here as wells that lose access to water due to water levels dropping below the screened interval of the well) under various groundwater management scenarios (Pauloo et al. 2020). Shallow domestic well failures are predicted to occur even with efforts to minimize pumping and increase recharge, leaving some people without access to water unless wells are drilled deeper (Pauloo et al. 2020). Planning agencies should assess and map drinking water wells that can benefit from Ag-MAR water replenishment but where water quality may be impacted by recharge activities. AgMAR could be prioritized in areas most vulnerable to well failure, with special care to protect drinking water quality as long as a community is engaged in the process and determines this would be the best action for them. Short-term water quality degradation may occur before long-term improvement is realized, and thus it is important that stakeholders understand this risk and can advocate for other sources of clean water. Many resources have been developed to help guide GSAs in substantively engaging communities in GSP planning and activities (DWR 2018, UCS 2017).

Existing Groundwater Quality (Contaminant Sources, Transport, and Fate): AgMAR represents a shift away from the standard agricultural hydrologic regime by introducing much larger water applications relative to irrigation practices, which are typically implemented to increase irrigation water use efficiency and reduce nitrate leaching. This has the potential of causing local degradation of groundwater due to accelerated leaching of legacy and ongoing applications of nitrate stored in the vadose zone (Bachand et al. 2014, Gheysari et al. 2009, Waterhouse et al. 2020). For example, in both column lab studies and field studies of sandy soils, 80-90% of nitrate was lost from the top meter after being flooded with ~60 cm of water (Murphy et al. In Prep).

Special caution should be taken if AgMAR activities are planned in areas where groundwater currently maintains good or marginal water quality (see water quality thresholds side bar) in the aquifer being recharged. A flush of legacy nitrate from initial recharge activities may subsequently be diluted with further dedicated recharge efforts (Bastani et al. 2019), with relatively clean recharge water compared to aquifer water quality. However, current land management (especially agronomic) practices will need to be planned, implemented, and monitored to ensure that excess nitrate is not continually introduced, and that the AgMAR system will be designed so that enough recharge water is available to ensure that overall dilution is occurring.

Areas with already degraded groundwater quality (in excess of the Maximum Contaminant Level) may have the highest potential net benefit from AgMAR compared to areas not yet experiencing degraded water quality, since the introduction of more water may dilute existing nitration concentrations. Thus, consideration of establishing AgMAR locations in areas where the dilution effect could potentially improve the underlying groundwater quality may be prudent.

General guidelines for water quality thresholds for nitrate in drinking water: (Balaz et al., 2011):

Good water quality: below 5 mg NO_3^- N/L
Marginal water quality: 5-10 mg NO_3^- N/L
Poor water quality: above 10 mg NO_3^- N/L (Maximum Contaminant Level - MCL)

Geochemistry: The geochemistry of both the underlying aquifer and geologic sediments in the soils and vadose zone may impact the site selection process. Some geologic sediments are more susceptible to dissolution and contribute higher levels of salts (and in some cases nitrate from geologic nitrogen) compared to others (Strathouse et al. 1980, Schoups et al. 2005, Fuji and Swain 1995, K.R. Belitz & Heimes 1990, Pauloo et al. 2021). Igneous and metamorphic rocks of the Sierra Nevada Mountain ranges like granite and diorite are more resistant to weathering and are relatively salt-free. In contrast, sediments from the coastal range consist of shales and other fine-grained rocks that are more easily weatherable and higher in salts, but often also lower in permeability. Careful evaluation of geochemical reactions will be needed to evaluate the potential for recharge salinization where AgMAR with small amounts of water over large areas of such lands is to be attempted (EDF 2019).

Furthermore, some groundwater that is anoxic (<0.5 mg O_2/L) attenuates nitrate via denitrification. Denitrification is the reduction of nitrate to dinitrogen gas, usually mediated by microorganisms (although abiotic mechanisms have been identified), and represents a permanent sink of nitrate (Butterbach et al. 2013). Most groundwater in the Central Valley is oxic, but anoxic zones do exist, predominantly in the valley trough and in areas where high groundwater levels historically interacted with carbon in the topsoil (Landon et al. 2011, Ransom et al. 2017, Jurgens et al. 2020). Furthermore, Landon et al. (2011) found that increasing nitrate trends were less prevalent where anoxic groundwater conditions existed. Introducing oxic recharge water into anoxic groundwater could diminish the attenuating capacity of denitrification in these aquifers. However, further research is needed to understand the interaction between AgMAR recharge water, oxygen depletion as it travels through the vadose zone, and nitrate attenuation in the subsurface.

Field-Scale Considerations

Field-scale site-specific properties will impact the relative nitrate leaching potential, recharge capacity, and long-term sustainability of an AgMAR site.

Land Use and Management: One of the most important considerations for AgMAR is the current and historical land-use practices of a potential recharge site. This will help estimate the amount of nitrate, or nitrogen loading, expected to reside in the root zone and vadose zone that could be mobilized under AgMAR (Harter et al. 2012 & 2017, Van Meter et al. 2016, Ascott et al. 2017, Waterhouse et al. 2020).

Current Land Use: Current and future land use is arguably one of the most important variables to consider when assessing potential sites for recharge. Crops that have low nitrogen needs (such as legumes and grapes) are ideal as potential AgMAR sites and should be prioritized above other crops that need more nitrogen inputs (O'Geen et al. 2015, Bastani and Harter, 2019, Waterhouse et al. 2020). Potential AgMAR sites with current or planned high or medium nitrogen demand crops may want to consider a transition to low nitrogen demand crops, if economically feasible, before implementing AgMAR in order to reduce nitrogen loading to the aquifer (Bastani and Harter, 2019).

Historical Land Use: Depending on soil type, as well as historical fertilizer applications and irrigation practices, legacy nitrate is either gradually making its way through the vadose zone or has already entered groundwater, as indicated by current levels of nitrate contamination. Estimates of water travel time (based on vertical conductivity) from the surface to the water table could help provide an understanding of how much historically applied nitrate has already flushed into the groundwater and how much still resides in the vadose zone and could be susceptible to leaching via AgMAR. Unfortunately, even as current nitrogen management has improved, legacy nitrate will continue to leach into groundwater due to past inefficient nitrogen management, potentially worsening water quality into the future (Bastani and Harter, 2019). While recharge may influence the timing of when nitrate enters the groundwater, potentially causing temporary increases in nitrate levels, it will not influence the total amount of legacy nitrate that ultimately will enter the groundwater. Thus, while legacy nitrogen is a concern where groundwater quality is not currently above the MCL, already-degraded groundwater quality could be improved potentially more rapidly under AgMAR, even in the presence of large amounts of legacy nitrate. These projected AgMAR improvements will only be realized if current agronomic practices reduce nitrate leaching below the root zone by following nutrient management guidelines and improving nitrogen use efficiency.

Nitrogen loading is based on a reasonable estimate of the nitrogen mass balance of a site and can be developed to provide an idea of how much legacy nitrate is stored in the vadose zone, and determine where the risk of excessive nitrate leaching under AgMAR is acceptably low (Harter et al. 2012 & 2017, Baram et al. 2016). Nitrogen mass balance is calculated using nitrogen inputs (chemical fertilizers, organic fertilizers such as manure, biosolids, atmospheric nitrogen deposition, and nitrogen in irrigation water) and subtracting nitrogen outputs (crop nitrogen uptake removed during harvest, atmospheric losses, and runoff) and the difference can be used as a proxy for nitrate lost below the root zone (Harter et al. 2012). Useful data when calculating the nitrogen mass balance includes the history of nitrogen applications, crop yields and relative nitrogen uptake, weather data, irrigation type and typical yearly irrigation rates. A farmer's nutrient management plan could also provide a good assessment as to how efficiently nitrogen is being managed, both currently and in the recent past.

If resources and time are limited, the historical nitrogen loading rate can be estimated by referencing the Potential Groundwater Loading from All Sources Map (Harter et al. 2017 http://ucd-cws.github.io/nitrate/maps/). For general purposes, a site can be classified into three risk categories (Bastani & Harter 2020):

Below 35 kg N/ha/yr: Low nitrogen loading site
Between 35-100 kg N/ha/yr: Medium nitrogen loading site
Above 100 kg N/ha/yr: High nitrogen loading site.

Nitrogen stored in the vadose zone is determined by historical land use and can be a large reservoir of nitrate. Therefore, sites that have been in low nitrogen crop production historically present a lower risk than sites that have historically required more nitrogen. When considering site selection, agricultural land with a history of low nitrogen intensity crops is likely to be preferred over those with a crop history that suggests high rates of nitrogen application.

In cases where there is a high amount of historical nitrogen loading and further evaluation is needed, the most rigorous approach to evaluating this risk is to perform site-specific soil and subsurface sampling for nitrate and salts in multiple locations to account for field-scale heterogeneity (Harter et al. 2002). One example of applying this technique is to take soil cores at multiple locations at an AgMAR site, up to several meters in depth. This analysis allows for an evaluation of both a field site's baseline levels of nitrate leaching potential and the scope of existing field scale heterogeneity, which can help determine parts of the field that have higher infiltration rates than others. This site-specific evaluation is time consuming and expensive, and may not be needed if available data indicates that historical nitrogen loading rates have been low.

Table 2 serves as a means of classifying sites according to relative risk by evaluating legacy nitrogen loading along with existing groundwater quality. Though not illustrated in the figure, it is important to note that past irrigation practices will also influence legacy nitrogen loading, where a history of flood irrigation might mean there is less legacy nitrogen than a site that has drip irrigation.

TABLE 2: Site Prioritization. This table can help prioritize sites according to relative risk by evaluating local groundwater quality and legacy N loading.

GROUNDWATER QUALITY	LEGACY N	RELATIVE RISK FOR NITRATE LEACHING	CONSIDERATIONS
Good/Marginal	Low	**Low risk** recharge site.	Use clean water for recharge.
Good/Marginal	Medium	**Medium risk** site for continued rise in nitrate concentrations, with or without recharge.	Use clean, abundant, reliable water for recharge. Impacted communities must be decision makers. Develop a monitoring program and contingency plan.
	High	**Highest risk** site for continued rise in nitrate concentrations, with or without recharge. *	
Poor	Low	**Low risk** recharge site.	Recharge may improve conditions. Use clean water for recharge.
	Medium	**Medium-low risk** site for continued rise in nitrate concentrations, with or without recharge	Use clean, abundant, reliable water for recharge. Impacted communities must be decision makers. Develop a monitoring program and contingency plan.
	High	**Medium risk** site for continued rise in nitrate concentrations, with or without recharge.	

** A site with a history of high nitrogen loading and local good/marginal groundwater quality may indicate that legacy nitrogen has not yet traveled to the aquifer. If this is the case, recharge may mobilize a new flush of legacy nitrogen into the groundwater, which may or may not be diluted depending on many variables. An assessment of short-term and long-term impacts to nearby downgradient domestic or public water supply wells is recommended.*

While we do not recommend categorically excluding any cropland site for recharge, at this time we recommend avoiding using sites for AgMAR that have significant organic nitrogen in the vadose zone (e.g. manure lagoons, animal corral areas) as they pose a significant additional risk to groundwater quality. At these sites, AgMAR would lead to potentially large mineralization of organic matter to inorganic nitrogen, such as nitrate, and subsequent nitrate leaching. AgMAR at such sites is not generally recommended.

Crop Suitability: Crops should be chosen to be able to withstand inundation and not significantly impact yields (O'Geen et al. 2015, Dahlke et al. 2018b). Negative effects on crop physiology and yield can negatively affect nitrogen uptake and the overall nitrogen mass balance of the field potentially leading to more nitrate loss (Heinrichs et al. 1972). AgMAR water applications may be managed to minimize saturated anoxic conditions and alleviate negative crop physiological response.

Soil Conditions and On-Site Hydrogeology: In addition to historical anthropogenic influences such as fertilization rates, physical properties of the soil and underlying materials at an AgMAR site have the potential to impact contaminant leaching and other important considerations, such as infiltration- and recharge capacities (Sogbedji et al. 2000, Arronson et al. 2001, O'Geen et al. 2015, Waterhouse et al. 2020). Sandier surface soils and underlying sediments allow for fast conveyance of water to deeper depths, but they limit the potential for attenuation of contaminants and can move contaminants more rapidly to the aquifer via preferential flow. Site-specific geophysical imaging of the deeper subsurface sediment layers can help in understanding how and the rates at which recharge water and the contaminants it carries with it will move toward the aquifer (Behroozmand et al. 2019). However, these techniques can be cost prohibitive.

Soil type affects the inherent fertility of a site. Lighter textured soils, such as sandy soils, are more prone to nitrate leaching if nitrogen inputs are larger than nitrogen outputs from crop uptake. On the other hand, sandier sites allow for higher infiltration rates of recharge water under AgMAR and, in addition to being less prone to anoxic conditions in the root zone, could allow for a more immediate dilution effect on the incoming nitrate to groundwater compared to heavier textured soils, if appropriate nutrient management plans are developed and followed (Bachand et al. 2016). Heavier textured soils tend to have a lower nitrate leaching potential, but also have higher native fertility and yet, they can still be overfertilized if a proper nutrient management plan is not in place and the inherent fertility is not incorporated into that plan. The fertility and nitrate leaching potential of a site must be weighed in balance with the infiltration and recharge capacities of a site. Surface soil type affects the ability by which an AgMAR project is able to convey water and contaminants to the deeper subsurface and eventually the aquifer.

Optimizing a site based on its soil texture, nitrate leaching potential, recharge capacity (dilution effect potential), water quality of the recharge water, and water availability for AgMAR will be crucial to minimize nitrate leaching and maximize the quantity of groundwater recharge from an individual site. Nutrient management plans that take into account the inherent fertility of the site and plan for realistic yield goals can help in this optimization.

TABLE 3: Summary of regional-scale and field-scale considerations for AgMAR.

Regional-Scale Considerations	**Groundwater Hydrogeology**	**Assess groundwater gradients,** including effects of regional pumping and recharge, to help predict when and where impact of AgMAR activities might be expected.
	Community Water Access	**Assess and map drinking water wells** that may be impacted by recharge activities. In close coordination with communities, consider prioritizing recharge in areas where wells are already vulnerable to drying up and/or are already contaminated, with special care taken to protect drinking water quality.
	Existing Water Quality	**Assess existing groundwater quality.** Further actions should depend on conditions (see text for details).
	Geochemistry	In the west side of the Central Valley, **recharge should be focused on higher intensity of recharge on smaller areas of land** to minimize water/sediment interactions.
Field-Scale Considerations	**Existing and Planned Land Management**	Assess historical and current land-use practices of a field site to estimate amount of legacy and ongoing nitrate expected in the vadose zone. **Prioritize sites with crops that have low N demand** and leaching potential, and that have an active nutrient management plan.
	Crop Suitability	When recharge is conducted on active farmland (i.e. perennial), **recharge should be applied on crops that can tolerate soil saturation** without significant impact on crop health, which can reduce the plant's ability to update N and leave more N vulnerable to leaching.
	Soil and on-site hydrogeologic Conditions	**Sandy, coarse-textured soils may be the best candidates** for recharge - when paired with adherence to a good nutrient management plan, suitable low N crops and a land use history of low N loading.

CONSIDERATIONS FOR RISK EVALUATION, MONITORING PROGRAM, AND CONTINGENCY PLANS

The potential for AgMAR to impact groundwater quality necessitates that risk evaluation, monitoring, and contingency plans be incorporated into planning efforts that are considering recharge projects. Community engagement is essential in this process as an opportunity for the concerns and questions of all stakeholders to be considered and addressed through management actions. Due to the disproportionate effects groundwater overdraft and contamination have had on disadvantaged communities, it is necessary to engage them and prioritize their concerns and needs. Holding workshops or webinars for community members and growers to learn about potential risks, benefits, options, and costs of recharge projects is one way to ensure all parties are able to self-advocate and participate in this process. An exhaustive summary of a risk evaluation, monitoring program, and contingency plan is beyond the scope of this white paper; however, a summary of some key considerations is given here and resources for more detailed plans are listed in the references section (CWC guide, DWR 2016, NCWA 2017, EDF et al. 2019).

Risk Evaluation

GSAs should take all necessary precautions to avoid new contamination or exacerbate already contaminated groundwater. All potential contaminants must be taken into account (nitrate, salts, geogenic, pesticides, emerging contaminants of concern) to have a more holistic understanding of the potential for contamination, type of contamination, and the potential for contaminants to interact with each other to deleteriously affect water quality (EDF 2019, CWC Guide). For example, nitrate can interact with uranium, making the latter more mobile in an aquifer; thus, if an aquifer has been relatively nitrate-free and has uranium-containing sediments, introducing nitrate in the aquifer could worsen two contamination issues (EDF 2019).

Predicting the effects of a management activity such as AgMAR at the individual well scale is computationally expensive and data intensive, and in most cases does not provide a GSA with sufficient insight to manage recharge throughout the basin. It may be more effective to conduct mass balance calculations at the GSA or basin-wide scale. Simple mass balance calculations are useful tools in assessing the risk of contaminant loading to groundwater due to recharge and/or pumping activities (Baram et al. 2016, Harter et al. 2017, Bastani and Harter, 2020). The maps developed by Harter et al. (2012, 2017) are a good first estimate in assessing risk of nitrate contaminant loads to groundwater on the regional scale. Other indicators, such as groundwater age can serve as a proxy for how quickly a system will respond to an AgMAR activity. Oxygen status can indicate shifts in groundwater redox status, which can determine what contaminants may be present, released, or chemically transformed into more or less harmful products.

Mass balance approaches are relatively transparent and easy to implement. However, they are prone to higher levels of uncertainty due to the spatiotemporal variability in nitrate concentrations at the field scale (Healy and Scanlon, 2010). More complicated process-based models can describe the uncertainty in estimates, but they require high levels of expertise to be appropriately implemented and are less transparent to non-experts. Baram et al. (2016) found that at larger spatiotemporal scales (annual timescale and regional scale), mass balance approaches and a process-based model (e.g., HYDRUS) estimated nitrate leaching on the same order of magnitude in an almond orchard. Simpler process-based models, when appropriately defined, parameterized, and upscaled, can help in regional decision support tools. Upscaled models require less temporal and spatial detail and are thus less computationally intensive, and can help understand the distribution, variability and trends of water quality across an ensemble of wells in a given area (Bastani and Harter, 2020).

For example, the Central Valley Irrigated Lands Regulatory Program (ILRP) agricultural water quality coalitions, under the Management Practices Evaluation Program (MPEP), have developed the Central Valley Soil and Water Assessment Tool (along with HYDRUS), a process-based model that is being calibrated and validated across the Central Valley to understand how changes in management affect water quality. This, along with the approach taken in Bastani and Harter (2020) could be a model for how Nutrient Management Zones and GSAs could approach determining the effect of AgMAR on nitrate leaching to groundwater and the resulting water quality (Northern MPEP GCC workplan 2018, SSJV MPEP 2019).

Monitoring Network and Program

A well monitoring program is essential in order to track potential beneficial and detrimental water quality effects of recharge projects. Installing new monitoring wells for every AgMAR project is not financially feasible nor realistic. Instead, the local GSA or irrigation district should first determine if existing agricultural, domestic, and monitoring wells are suitable for their monitoring program by assessing factors such as well location, depth to water, proximity to drinking water wells, groundwater gradients and accessibility.

The GSA should map and assess all drinking water wells that could be impacted by recharge activities. CV-SALTS, the Irrigated Lands Regulatory Program (ILRP), the State Water Resources Control Board Groundwater Ambient Monitoring and Assessment (SWRCB GAMA) and the Central Valley Groundwater Monitoring Collaborative all plan to have trend monitoring programs with the objective of compiling and integrating data from a range of sources. These efforts will provide publicly accessible information on current groundwater quality conditions relevant to irrigated agriculture, as well as develop long-term groundwater quality information that can be used to assess the impacts of agriculture and management programs on water quality. Using this data, GSAs can identify high priority wells to monitor, which can then inform how a robust monitoring network should be designed. Although an invaluable resource in assessing and tracking water quality statewide, GAMA admittedly contains a fair amount of incomplete information. For instance, records of older wells may not contain the depth to which they have been drilled and/or screened and naming conventions are not always aligned, leading to confusion about locations and characteristics of wells and the soils in which they are drilled. GSAs might consider how they could potentially fill in these gaps through on-the-ground monitoring and diligent record keeping aligned with standardized methodology.

Groundwater data from industries regulated under CV-SALTS and the ILRP will soon be uploaded into another state database, Geotracker, which may provide invaluable information on shallow groundwater conditions. GSAs should also coordinate with these programs in establishing local monitoring networks in order to share knowledge and fill in data gaps. Similarly, GSAs could work with local non-profits already conducting evaluation of wells to prioritize monitoring of potentially affected domestic wells. Finally, GSAs can install a limited number of monitoring wells in carefully selected areas, prioritizing locations by using a robust risk assessment to identify high risk AgMAR sites and conduct regional trend analyses to detect changes in groundwater quality.

In general, monitoring wells should be located or built along the groundwater flow path in between the AgMAR site and any potentially impacted wells to allow for sufficient time to trigger an early warning and enactment of contingency measures (EDF 2019, CWC Guide). However, it must be noted that AgMAR can create a local groundwater mound or perched water table in the shallow unconfined aquifer that is sufficient to supply a domestic well but is separate from the regional water table. Thus, in order to effectively monitor contaminant transport, monitoring wells must be screened to a depth that captures this shallow groundwater supply.

Furthermore, temporal variation in recharge fluxes may complicate monitoring efforts. Sampling frequency should be robust enough to capture temporal changes in contaminant concentrations but there are still no guarantees that an increase in a contaminant of concern will be captured. Remote sensor technologies are being developed for continuous, automated groundwater level monitoring, but this has yet to be coupled with groundwater quality measurements. This type of monitoring could provide useful information for predicting water quality changes if incorporated into models (Calderwood et al. 2020).

Contingency Plans

Contingency plans should be developed by GSAs prior to implementing AgMAR programs in order to mitigate any potential negative water quality outcomes - especially near disadvantaged communities where technical, financial, and managerial capacity to respond to adverse consequences to drinking water quality are limited (CWC Guide, DWR 2016, NCWA 2017, EDF et al. 2019). Contingency plans should be developed in partnership with local communities and community-based organizations to identify and coordinate preferred alternative water supplies for a community in case the monitoring program detects negative impacts to water quality from AgMAR activities. Thresholds for water quality below the MCL should be developed with community involvement so that once a threshold is reached within a monitoring well the contingency plan will be triggered (for example, 70% of the MCL) (CWC

Guide). Furthermore, for sites located in the Central Valley, GSA and community coordination with the appropriate CV-SALTS Management Zones is recommended to understand and coordinate with the short-term and long-term plans for alternative water sources under that regulatory program. Alternative short-term sources of water could include bottled and/or tanked water or installation of point-of-use water filters. Longer-term solutions should be considered as well, including the potential of connecting impacted well users to nearby municipal systems, identifying funding sources for deepening wells to access clean water, remediating the contaminated water, or establishing new, small public water systems in the affected area. Although GSPs are not directly involved in CV-SALTS and other water quality mitigation efforts, recharge activities could impact water quality, either beneficially or detrimentally, and thus coordination with CV-SALTS, ILRP and other applicable regulatory programs is recommended.

TABLE 4: Summary of steps to develop a monitoring program and contingency plan.

Risk Evaluation	**Assess potential for mobilization of any contaminants** (not just nitrate and salts), due to potentially compounding effects of chemical interactions (such as uranium mobilized by presence of nitrate).
	Conduct mass balance as a first step to estimate risk of contaminant loads to groundwater.
	Work with hydrogeologists and engineers to develop a simple process-based model to aid regional decision support tools.
Monitoring Well Network	**Identify and map drinking water wells** that could be impacted by recharge activities. Use data gathered from regional- and field-scale considerations (Table 3) to prioritize the monitoring of drinking water wells that could be impacted by recharge activities.
	Examine data from local wells to evaluate their potential to be used concurrently as monitoring wells and/or to establish baseline conditions –based on location, proximity to drinking water wells, depth to water, well screen depth, groundwater gradients, and accessibility, among other considerations.
	Coordinate monitoring efforts with nitrate-related regulatory programs such as ILRP coalitions, Central Valley Dairy Representative Monitoring Program, and Nitrate Management Zones.
	Coordinate monitoring efforts with NGOs and others that are monitoring drinking water wells.
	Install new monitoring wells if needed, in coordination with the network outlined in the GSP, to fill in data gaps and prioritize monitoring drinking water wells in the area of influence.
	Locate monitoring wells along the flow path, and at the appropriate depth, between AgMAR sites and area of influence. Note that groundwater flow directions can be highly variable and multi-directional, depending on seasonal conditions and pumping activities.
	Distance of monitoring well to drinking water well(s) should allow for **sufficient time to trigger early warning and enactment** of contingency plan.

Well Sampling Plan	**Frequency of well sampling** should be robust enough to capture changes in contaminant concentrations due to recharge activities.
	Consider different types of constituents to measure, including contaminants of concern as well as other water quality factors such as pH.
Contingency Plan	**Partner** with local communities, community-based organizations, ILRPs, and CV-SALTS Management Zones to identify and coordinate potential alternative water supplies. • **Short term**: Bottled and/or tanked water; point-of-use water filtration/treatment systems. • **Long Term:** Connect to nearby municipal systems, deepen drinking water wells, establish new small public water system, remediate contaminated water.
	Develop water quality thresholds with potentially affected communities, ILRPs, and CV-SALTS Management Zones. Once a threshold in a monitoring well is reached (e.g. 70% of MCL), contingency plan is triggered.

EMERGING AND FUTURE RESEARCH NEEDS

Future field scale research should focus on identifying best practices for management of soil to avoid unintended consequences of nitrate leaching and maximize potential benefits for both groundwater quality and quantity. The California Healthy Soils Initiative is actively engaging landowners and providing guidance on emerging soil health research, by exploring the benefits of soil health practices on water quality. Research suggests practices such as crop rotation, no-till, and increasing organic matter by applying carbon amendments can be beneficial for water quality in certain systems, but more research is needed in how these effects vary by soil type, climate, cropping system, and water availability. While there is robust scientific evidence for the reduction in nitrate leaching under cover cropping, field trials should be conducted to understand the interaction between cover cropping and AgMAR. For example, understanding the right time to apply AgMAR flood flows to avoid reducing the nitrogen retention benefits of cover crops would be a useful addition to the growing body of research. Synergies between soil health practices and AgMAR may exist but definitive research is sparse.

Because AgMAR represents a shift away from the typical irrigation and rainfall patterns, the effects on the entirety of the nitrogen cycle should be assessed and losses of nitrogen to the environment reduced. Unintended externalities, such as an increase in nitrous oxide emissions (a potent greenhouse gas), should be avoided through a deeper understanding of how AgMAR will affect denitrification (the conversion of nitrate à nitrous oxide à dinitrogen gas). Research on denitrification and AgMAR should address the question: Can AgMAR be managed to promote the pathway of complete denitrification (nitrate à dinitrogen gas)? The conversion of nitrate to dinitrogen gas avoids the creation of a greenhouse gas and represents a permanent sink of nitrate benefitting groundwater quality. In dedicated recharge basins, Gorski et al. (2020) found that reactive carbon barriers, acting as a bioreactor, increased denitrification of nitrate in the incoming recharge water at certain infiltration rates. However, more research should be conducted on the efficacy of carbon amendments or other techniques in removing residual nitrate in the soil. Research of this nature should expand its scope to explore similar opportunities in AgMAR settings – could increasing carbon in agroecosystems through high carbon amendments or other techniques increase denitrification of soils under AgMAR?

Furthermore, AgMAR has been shown to stimulate microbial activity in the rootzone, and increase nitrogen mineralization following flooding events (Murphy et al. In Prep). Nitrogen mineralization (the conversion of organic nitrogen to plant-available nitrogen) can be affected by water cycles. Pulsed, low-magnitude flooding events may mineralize organic matter and create new nitrate in between water applications that could be leached during the next flooding event, thereby increasing the nitrate leaching potential of an AgMAR site (Murphy et al. In Prep). More research is needed to provide guidelines to AgMAR project managers on how to manage their water applications so that nitrate leaching potential is minimized throughout a flooding season.

Additionally, an increase in high carbon, low nitrogen amendments can immobilize nitrate in the microbial biomass, preventing leaching when water is applied – however, large uncertainty remains on the magnitude and temporal dynamics of this process and more explicit research is needed. Other practices like crop rotations could reduce the need for external N inputs but perceived risks associated with potential yield loss remain a barrier to adoption.

At the landscape scale, emerging research is showing the long-term economic feasibility of establishing "agricultural protective buffer zones" of low N crops (i.e. alfalfa and wine grapes) around contaminated drinking water wells, which could help reduce nitrate transport under AgMAR in these areas (Mayzelle et al. 2015). While, Bastani and Harter (2019) found that the combination of low N "buffer zones" and AgMAR did improve water quality, improvements took a decade to be realized and large upfront costs of transitioning land from higher value crops could present barriers to implementation.

Finally, decision support tools for AgMAR are greatly needed. Leveraging existing data to delineate time of travel zones around a drinking well could help improve predictions on the travel time of nitrate to reach a well under various scenarios. Open source, transparent, and easy-to-use tools that can help in site selection, determine how much water is needed to dilute nitrate loads from specific fields, and predict how well water quality will be impacted would greatly improve the beneficial outcomes of AgMAR.

CONCLUSION

AgMAR is a promising managed aquifer recharge approach for bringing groundwater basins back into sustainable use and could benefit groundwater quality. Nitrate contamination of groundwater will continue to worsen into the future under business as usual, presenting an opportunity to manage AgMAR to accelerate the improvement in groundwater quality if managed appropriately. Recharge on land with legacy nitrogen loading may pose an increased risk to the underlying aquifer by creating a temporary spike in groundwater nitrate levels, but sufficient and relatively nitrate-free flooding applications could decrease nitrate levels more quickly than under business as usual. In order to achieve these groundwater quality benefits, steps must be taken to improve current nitrogen use efficiency and reduce current nitrogen loading from agricultural management practices. Nutrient management plans provide the backbone of ensuring current management practices are nitrogen-efficient and emerging research can help elucidate practices that increase nitrogen retention, from precision nitrogen applications (matching nitrogen supply to plant nitrogen demand) to leveraging soil health practices that retain nitrogen.

GSAs, in coordination with affected communities, should consider and prepare for any potential negative impacts of AgMAR on groundwater quality to avoid exacerbating already contaminated groundwater or creating new contamination in previously uncontaminated groundwater. Unintended nitrate and salt contamination under AgMAR could have negative impacts on human health and agricultural productivity. To manage this shared resource, all stakeholders' concerns, input and engagement are needed, including those who historically have not been able to participate in water management decisions. This white paper summarizes the current state of scientific knowledge on how to avoid or minimize nitrate and salt contamination of groundwater under AgMAR management, considering all stakeholders' interests. With emerging research on the impact of AgMAR on nitrogen cycling, transport, and fate, all stakeholders – including scientists, growers, water managers, groundwater dependent communities, and community-based organizations - can continue to improve the management of our groundwater resources.

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