Groundwater

Issue Paper/

Planning for Managed Aquifer Recharge Projects

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Abstract

Managed aquifer recharge (MAR) involves the intentional recharge of water to aquifers for subsequent recovery or for environmental benefits. It is an increasingly common water resources management strategy but, despite its use for many decades, is unfamiliar to many. This lack of widespread understanding makes it essential that MAR projects are developed using a systematic, comprehensive and transparent approach. This paper outlines a proven and successful approach to planning and developing MAR projects. The process includes three steps, consisting of developing project objectives, developing evaluation criteria for potential MAR projects, and, after collecting and evaluating pertinent data, ranking potential projects against those criteria. Project objectives help define the data that should be collected and the evaluation criteria that are relevant to consider. Commonly used criteria include those relating to water supply, aquifer restoration, water quality and environmental protection. Key evaluation criteria that are discussed in more detail include the availability of water that would be used for recharge, the suitability of receiving aquifers to accept and retain the recharged water, and the compatibility of recharged water with the aquifer into which it is placed. Potential MAR projects can be ranked objectively by quantifying the evaluation criteria and assigning ranking scores to them. The potential project that best meets the project objectives will score the most favorably. Using a quantitative and objective process to evaluate and rank potential projects will increase support by project stakeholders and increase the likelihood that the project will be successful.

Introduction

Managed aquifer recharge (MAR) is becoming a water management option used increasingly throughout the world (Dillon et al. 2019; IGRAC 2022). It has been shown to increase water supply, serve as a buffer during drought periods, improve water quality, reduce sea water intrusion and enhance environmental flows among other benefits (Zheng et al. 2021). MAR projects can be expanded incrementally and have been found to be cost-effective compared to surface storage (Khan et al. 2008; Vanderzalm et al. 2022). Once water supply alternatives and their preliminary cost ranges have been evaluated and a MAR approach is selected, planning is an essential first step to undertake when developing projects that involve managed aquifer recharge (MAR). MAR is the intentional or purposeful recharge of water to aquifers for subsequent recovery or for environmental benefits (Zheng et al. 2021). MAR projects can recharge aquifers using surface facilities such as infiltration basins or canals, using subsurface facilities such as recharge or aquifer storage recovery (ASR) wells, or a combination of the two (ASCE 2020). Planning should be undertaken early during the feasibility phase of a MAR project. The outcome of MAR planning can range from determining whether a MAR project should be undertaken, to identifying the best sites to recharge an aquifer, to developing the conceptual design of the MAR project.

MAR planning often includes three steps: (1) develop project objectives, (2) develop criteria for the MAR project and gather available information for each criterion, and (3) evaluate that information against the criteria to identify the most feasible project (ASCE 2020).

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Although MAR has been in use for more than a century (Dillon et al. 2019), it is a less familiar water resources management strategy to many so it is particularly important to have a planning process that is systematic and objective. As with many complex projects, MAR planning is an iterative process that includes increasing levels of information and analyses as potential projects are identified and compared.

Due to the wide range of factors involved in MAR projects, it is also beneficial to include a variety of professionals including engineers, hydrogeologists, and those with expertise in water treatment, water distribution systems, applicable regulations, and possibly others. A key element for success is to ensure that engineers and hydrogeologists coordinate from the very beginning of the MAR project at the feasibility and planning stages on siting and design issues. Undertaking a thorough and robust approach to planning will increase the likelihood of a successful MAR project. The MAR planning process is summarized in this paper. Suggested sources that provide more detail on this process and on factors that should be considered include ASCE (2020), Pyne (2005), NRMMC (2009) and NRC (2008).

Developing Project Objectives

Care should be taken to describe the purpose of the proposed MAR project by clearly identifying its objectives. This step should be undertaken at the beginning of project planning and might be refined as more information is learned about the project components. The project objectives are important because they can help determine the information that should be collected during the feasibility study process, and serve as a guide for how project components are assessed according to evaluation criteria that are developed for the project.

The most common objective for an MAR project is to increase the available water supply, however a fairly recent trend is toward improving water supply reliability during droughts and emergencies. While these are important objectives, the project team should seek to develop other project objectives since doing so is likely to increase stakeholder support and increase the probability that the project will be approved. Examples of project objectives include those that pertain to water supply, water quality, aquifer restoration, and environmental protection. Table 1 provides a list of potential MAR project objectives and others can be found in Pyne (2005), Topper et al. (2004), USACE (2020), and Zheng et al. (2021). For ASR, 30 different objectives have been identified to date. Typically, three to five key objectives are selected. After key objectives are identified, they are typically ranked in order of importance, thereby guiding subsequent planning.

Table 1
Example Objectives for MAR Projects

Water Supply-Related
Provide seasonal to long-term storage
Improve reliability of supplies
Improve wellfield production
Defer expansion of water facilities
Maintain pressures in distribution systems
Maintain flows in distribution systems
Offset out-of-priority stream depletions
Sustain economic activity
Water Quality-Related
Improve groundwater quality
Reduce disinfection by-products of treated recharge water
Provide additional water treatment
Aquifer Restoration-Related
Restore groundwater levels
Reduce subsidence
Manage sea water intrusion
Environmental Protection-Related
Increase baseflow to streams
Maintain wetlands
Enhance riparian habitat
Stabilize surface water temperature
Control aquifer contamination
Protect human health

Developing Evaluation Criteria

The second step in MAR planning is to develop evaluation criteria, and these should be based on the project objectives. The criteria are developed in order to provide an objective and comprehensive means to evaluate the feasibility of various project components. The criteria should include, at a minimum, the suitability of potential water supplies that would be used as a source of recharge, and the hydrogeologic suitability of the potential recharge site or sites. These can be considered primary criteria since they would significantly limit the efficiency and cost-effectiveness of a potential MAR project. Other criteria include the timing and magnitude of anticipated water demand, and water quality, environmental, implementation and regulatory factors (Pyne 2005; ASCE 2020). These criteria will influence the design and cost of potential MAR projects. The evaluation criteria help determine the types of information that should be gathered and the level of detail needed to address each one.

Example criteria to evaluate potential MAR projects are listed in Table 2. The table shows categories of criteria that are commonly associated with MAR projects but these may or may not be applicable to a given MAR project depending on its size, type or setting. The example criteria shown in the table are qualitative and can be considered as topics with more detailed specific criteria that could be developed for each, as suggested by the descriptions provided in the table. Effort should be made to define criteria in quantitative terms to aid in the evaluation of multiple project sites, recharge methods or other project components. A few of the more important and more commonly used evaluation criteria are discussed below. Each of the example criterion listed in Table 2 are discussed in ASCE (2020).

Table 2
Example MAR Evaluation Criteria

Category	Criterion Topic	Description/Applicability
Water sources and demand	Availability of water	Whether water is available physically or institutionally; trends and variability
	Proximity of source water	Distance from water source to MAR site
	Source water quality	Compatibility of source water with aquifer water, treatment costs
	Water demands	Trends and variability in demand from MAR project under anticipated operation scenarios
Site hydrogeology	Hydrogeologic suitability	Whether aquifer characteristics will allow anticipated recharge
	Amount of available storage	Physical space in aquifer relative to demand; unsaturated pore space for unconfined aquifers, pressure head and porosity for confined aquifers
		Lateral velocity and direction
	Residence time	How long water will stay under dominion and control for aquifer setting
	Induced Seismicity	Likelihood of causing a seismic event
Environmental considerations	Waterlogging and nonbeneficial use	Where elevated water table conditions may affect soils and structures or be lost through evapotranspiration
	Habitat concerns	Possible effect on sensitive environments
	Effects on aquifer water quality	Effects of introducing water with differing chemistry
Implementation considerations	Proximity to existing infrastructure	Affects overall cost
	Proximity to demand	Affects overall cost
	Landownership and use	Affects cost and permitting
	Cost	Total cost to implement and maintain
	Site access and security	Affects cost and permitting; applies to protection of water supply
	Conditions surrounding site	Affect costs, permitting, and environmental considerations
Regulatory considerations	Permitting and other regulatory requirements	Affect cost and permitting

Source: Adapted from ASCE (2020).

Availability of Water

This criterion includes information on when the source of water is available in terms of the timing and amount in relation to project demands. Potential sources of recharge water include rivers, streams, lakes, groundwater from other aquifers, reclaimed water or stormwater runoff. Each potential source will have its own pattern for the amount of water available and when it is available, from both a physical and legal perspectives. In arid regions surface water supplies often show extreme variability, and that will factor into how that water can be captured and stored before it is treated, if necessary, and recharged. It will be important to characterize each potential source with as much historic data as is available to understand the seasonal variability in flow and if long-term trends exist. Climate change projections of future flows should be included in the assessment of how reliable a given supply might be in future decades. Another factor to consider is the legal availability of the potential supply. In the Western United States, for example, many surface water supplies are fully allocated under the regulatory system of water rights administration, so while supplies exist physically, they may not be available from a regulatory perspective.

Hydrogeologic Suitability

This criterion is particularly important when evaluating the feasibility of potential MAR projects. It describes how readily the subsurface materials can accept recharged water. Successful MAR projects are sited where the infiltration rate for surface MAR facilities or the injection rate for subsurface MAR facilities such as wells is high. Those conditions would exist in a more permeable (higher hydraulic conductivity) aquifer, such as one consisting of sand or gravel. This becomes especially important when water used for recharge is available on a limited timeframe such as during stormwater runoff events. Aquifer recharge rates can be compared qualitatively among different sites using aquifer transmissivity. Hydraulic conductivity can be estimated from literature values that relate soil and rock type (for example, Heath 1989; Fetter 2001) or from existing studies undertaken in the region, and these may be sufficient for the initial stages of the planning purposes. However, as the planning process becomes more quantitative, more accurate estimates will be necessary using site-specific samples of aquifer materials that undergo geotechnical testing or from conducting aquifer pumping tests. The presence of low-permeability layers within the target aquifer zone, such as clay or shale, should be characterized as part of hydrogeologic analyses to aid in the design of the well screened zones of wells used for recharge and extraction.

Hydrogeologic suitability includes the vadose zone, the partially saturated zone above the water table, for those MAR projects that recharge water at the surface through structures such as infiltration basins or canals. In arid regions, the vadose zone may be quite thick, so low-permeability layers such as clay or caliche could result in creating perched water zones that would prevent the infiltrated water from reaching the target aquifer. If the low-permeability zones are close enough to the land surface and laterally extensive then groundwater mounding could occur. Mounding would eventually reduce infiltration rates as the water table mound approaches the base of the infiltration structure and could have an adverse impact on nearby structures and vegetation. Cyclic operation of recharge ponds, including dry periods between recharge periods to remove fine-grained materials that accumulate at the base of the ponds, can be effective in maintaining satisfactory infiltration rates (ASCE 2020).

For MAR projects that recharge water through ASR wells, other hydrogeologic criteria apply. These include but are not limited to leakance through confining layers, well interference, geochemical reactions, air binding of storage aquifers, well clogging due to particulates, entrained air and microbiota, inappropriate materials of construction, and inappropriate well design.

Water Quality and Aquifer Compatibility

These criteria include the quality of the source water and its compatibility with the groundwater in the target aquifer. They relate to physical or geochemical reactions that could reduce the ability of the subsurface to accept recharge water. Physical reactions include clogging the beds of surface infiltration facilities or clogging the well screen and adjacent aquifer materials due to high concentrations of suspended solids, entrained air or turbidity. These clogging mechanisms can be managed by characterizing the total suspended solids (TSS), turbidity and oxygen content of the source water and then incorporating any pretreatment processes into the design of the MAR facility (ASCE 2020). Clogging can be minimized at surface MAR facilities by including settling basins upstream of the recharge basins. In some situations, chemical pretreatment may be more cost-effective. For subsurface recharge, filtering and pretreatment of the source water is particularly important to keep the recharged water as free of suspended solids and entrained air as possible.

Geochemical reactions include precipitation of minerals that can also lead to clogging of the well screen, filter pack or pore spaces in the aquifer adjacent to the well being used for recharge. Geochemical reactions can also include chemical dissolution of aquifer materials which can result in mobilization of contaminants such as arsenic and nitrate into the mixing zone for source and native groundwater.

Many ASR wells store water in deep, brackish or saline aquifers at depths up to about 3000 ft. (900 m). Geochemical reactions can also include clay swelling when fresh water is stored in a previously brackish aquifer containing sodium montmorillonite clays which can permanently clog a well in a few hours. Microbial activity can also clog a well, such as with growth of iron bacteria in carbon steel used as casing. Solutions exist for each of these potential issues, however they are less likely to be recognized and resolved in advance unless engineers and hydrogeologists are coordinating from the very beginning of each project. Many ASR projects include continuous wireline coring and core analysis, followed by geochemical modeling, prior to designing wells and wellhead facilities.

Gaining an understanding of the potential for physical and geochemical reactions between the source water and recharge water is extremely important during the planning phase of an MAR project. Doing so will provide insight into the system design, water pre-treatment, and maintenance activities that will be needed to minimize clogging and maintain desired recharge rates. It can be very expensive or altogether infeasible to restore the infiltration rate of the vadose zone beneath a surface MAR facility or to regain the original transmissivity around a recharge well once they are clogged, so every effort should be made to avoid these situations.

To understand the likelihood of these reactions it is necessary to characterize the water quality of the source water that is to be used for recharge, the quality of water in the aquifer being recharged, referred to as native water, and interactions that might occur during recharge. It will be necessary to collect samples of the proposed source water and, for projects involving subsurface recharge, samples of native water and have them analyzed for an array of inorganic constituents along with physical parameters including pH, Eh, dissolved oxygen, and turbidity (ASCE 2020). If possible, the materials in the target aquifer zone should also be collected and analyzed since they can also serve as a source of reactions with recharged water. The quality of source water can vary considerably over time due to seasonal inflows and to increases in turbidity with higher flows. To understand the range of possible reactions with native groundwater, samples of source water should be collected at different times of the year and at different flow rates. Depending on its age, older water quality data from the source and native water may not be representative of current conditions, and data collected from investigations of contamination may be biased toward poor water quality. The water quality of the source water and native water should be evaluated in a geochemical mixing model such as PHREEQC (Parkhurst and Appelo 2013) or Geochemist's Workbench (Aqueous Solutions LLC 2022) to determine what reactions are likely and thus what water quality treatment will be required.

The design, operations and maintenance components of a successful MAR project can vary greatly in complexity and cost, and minimizing adverse reactions between the recharge water and the subsurface can be a key aspect affecting those costs. Since project cost often determines the overall feasibility of an MAR project, understanding the compatibility of the source water and the target aquifer is an essential part of MAR planning and design.

Selecting the MAR Project

The third step in MAR planning is to identify the project site and the project components that appear to be most feasible to implement. This feasibility evaluation will be based on an analysis of available information that is considered within the context of the criteria developed previously. It is an iterative process drawing on successively more detailed information and analyses. The initial data analysis might show that there are many locations and project components that may be feasible, resulting in a large number of possible MAR projects. To reduce the possible projects to a smaller number that could be evaluated in more detail, a scoring or ranking process should be developed and employed.

A two-step screening or ranking process can be employed to eliminate potential MAR projects. The initial step has been referred to as a viability assessment (NRMMC 2009) or a fatal flaw analysis (OWRB 2010) and can be applied to potential MAR locations and project components. The project team will need to determine what criteria should be used in the initial screening step but in most cases the hydrogeology and aquifer conditions in a candidate aquifer would be the criteria included (ASCE 2020). The kinds of questions to include in the initial screening include whether there is a reliable supply of source water that is available legally or institutionally, if the project site is acceptably close to the source water and to areas of demand to minimize construction impacts and cost to bring the water to the recharge site, if the target aquifer is suitable to store and recover recharged water, and if treatment costs are acceptable. A negative answer to any of those questions would eliminate the candidate project from further consideration.

The second screening step involves a more detailed and quantitative assessment. The result of this step reduces the number of potential MAR projects to a small number, allowing them to undergo more detailed field investigations and analyses. To conduct this step each criterion should be defined by a range of values that are measures of those criteria, and then a numeric ranking should be assigned based on where a given MAR project fits within the criteria range. As an example, if proximity of a project to demand were a selected criterion and the range of possible scores was 1 to 5, then proximity of less than 2 km (1.2 mi) might get a score of 5 and proximity greater than 10 km (6.2 mi) might get a score of 1 (ASCE 2020). In this example the higher criteria scores indicate a more favorable project attribute. An example screening table that was used to evaluate potential MAR projects in eastern Colorado is shown in Table 3. As a useful retrospective analysis, Zheng et al. (2021) provide a rating table for 28 existing MAR projects, using criteria that include hydrologic, water quality, environmental, economic and implementability factors.

Defining the criteria quantitatively and assigning ranking scores will be based on the available data, but will be an iterative process involving professional judgment and input from project stakeholders. It will be important to define the criteria ranking scores clearly so that independent parties will end up with similar scores for the candidate MAR projects, or at least a similar overall ranking of those projects relative to each other. The criteria that are used in this evaluation step should cover a wide range of considerations that relate directly back to the project objectives (Table 1).

In many cases the criteria may not be of equal importance. To account for that, the criteria ranking scores could be assigned weighting factors with larger weighting values representing the more important criteria. The weighted scores for a criterion would be the ranking score multiplied by the weighting factor. The weighted score for a candidate MAR project would then be the sum of the weighted scores for the individual criterion. If criteria ranking scores are also assigned with higher scores representing a more favorable project attribute, then the MAR project with the highest overall score can be said to best meet the project objectives and will therefore be more likely to be a successful project.

If developed thoughtfully, this second and detailed ranking step will be seen as being unbiased and the projects that are retained will be viewed more favorably by the project stakeholders.

Summary

MAR projects are used increasingly as a water resources management strategy to achieve a variety of water supply, water quality, aquifer restoration, and environmental protection objectives. Although MAR projects have been undertaken for many decades, these types of projects are less familiar to many in the water resources, regulatory and public arenas. As a result, it is particularly important that MAR projects undergo a thorough and objective planning process so that the proposed projects will have a greater likelihood of being successfully implemented.

MAR planning often includes three steps: (1) develop project objectives, (2) develop criteria for the MAR project and gather available information for each criterion, and (3) evaluate that information against the criteria to identify the most feasible project. Project objectives help determine the information that should be collected during the feasibility study process, and are used to assess project components according to evaluation criteria that are developed for the project. The second and third steps are done using an iterative process in which increasingly more detailed data and analyses are performed on the remaining potential projects. Increasing the available water supply is a common objective for MAR projects, but other objectives should be developed that relate to water supply, water quality, aquifer restoration and

Table 3
Example Scoring Measures

Evaluation Criteria	Criteria Description	Scoring Measures: High 10	9	8	Medium 7	6	5	4	Low 3	2	1
Hydrogeologic considerations											
1. Aquifer storage capacity	Available capacity for recharge	>0.6 m^3/m^2			0.1–0.6 m^3/m^2				<0.1 m^3/m^2		
2. Hydrogeologic suitability	Potential rate of aquifer recharge;										
• Unconfined aquifers	Estimated from aquifer K values	>10 m/day			1.0–10.0 m/day				<1.0 m/day		
• Confined aquifers	Estimated from aquifer T values	>300 m^2/day			100–300 m^2/day				<100 m^2/day		
3. Residence time											
• Unconfined aquifers	Duration recharged water is in aquifer	>1 year			4 months–1 year				<4 months		
• Confined aquifers	Subcrop proximity to alluvial aquifers	>5 km			1.6–5 km				<1.6 km		
Environmental considerations											
4. Water quality	Aquifer water quality with respect to state standards, soil leaching potential	No standards exceeded; minimal leaching potential (pot)			Limited areas where standards exceeded; minor leaching pot				Large areas where standards exceeded; strong leaching pot		
5. Habitat concerns	Presence of threatened and endangered species habitat; effect on wetlands	Minor area of T&E habitat; no effect on wetlands			Some T&E habitat; some wetlands affected				Much T&E habitat; wetlands affected		
6. Waterlogging and nonbeneficial use	Potential to create high water table and increased ET by phreatophytes	Low concerns for waterlogging effects			Medium concerns for waterlogging effects				High concerns for waterlogging effects		

Table 3
continued

		Scoring Measures									
		High			Medium				Low		
Evaluation Criteria	**Criteria Description**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
Implementation considerations											
7. Landownership and land use considerations	Proportion of area with accessible public land, multiple jurisdictions	Many areas of public and nonurban land			Some areas of public and nonurban land				Mostly private and/or urban land		
8. Existing infrastructure	Proximity of infrastructure (pipelines, ditches, etc.) and available capacity	Suitable infrastructure <10 km from area			Suitable infrastructure 10–30 km from area				Suitable infrastructure >30 km from area		
9. Proximity to areas with demand	Recharge areas nearby to areas of projected unmet demand in 2030	Near areas with demands >4000 m^3/year			Near areas with demands of 2000–4000 m^3/year				Near areas with demands <2000 m^3/year		
10. Implementation costs											
• Unconfined aquifers	Relative land costs for construction	Low cost			Medium cost				High cost		
• Confined aquifers	Depth to aquifer and proximity to existing high-capacity wells	<75 m; many wells in area			75–300 m; few wells in area				>300 m; no wells in area		

Note: Criteria 2, 3, and 10 have separate definitions and scoring measures for unconfined and confined aquifers.
Source: Adapted from CWCB (2007)

environmental protection. Having multiple objectives is likely to increase stakeholder support and increase the probability that the project will be approved.

The evaluation criteria are developed to provide an objective and comprehensive means to evaluate the feasibility of various project components. Criteria should include different aspects describing the suitability of the water used as a source of recharge, the hydrogeologic suitability of the potential recharge sites, and criteria pertaining to water demand, water quality, environmental, implementation and regulatory factors. Several criteria topics representing multiple specific criterion that are included in most evaluations of potential MAR projects are discussed in more detail. These include availability of water, hydrogeologic suitability, and the reactions that might occur between the recharge water with aquifer due to differences in water quality.

Evaluating a potential MAR project against the criteria is best done as a two-step process to eliminate potential projects that score less favorably and thus are less likely to be successful. The first step is an initial screening that poses fundamental but important questions about the source water, the proximity of the potential project to sources of water supply and demand, the suitability of the target aquifer, and whether pre-treatment costs are acceptable. Potential projects that are not eliminated from further consideration should then undergo a more detailed and quantitative screening process. This more detailed process involves defining each evaluation criterion in quantitative terms, and then assigning a range of evaluation scores that describe how well the proposed project meets those criteria. The criteria rating scores can be assigned weighting factors, if needed, to allow the individual criterion to better represent their relative importance. Defining the criteria quantitatively, assigning ranking scores and criteria weighting factors will be an iterative process. It should include the input of project stakeholders so that the results of the evaluation will be deemed transparent and objective. The MAR project with the most favorable evaluation score will have the highest likelihood of being a successful project.

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