# Introduction to the Special Collection: Institutional Dimensions of Groundwater Recharge

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ABSTRACT Unsustainable management of groundwater basins has led to groundwater depletion, with impacts to human and environmental systems that will be exacerbated by the hydrologic effects of climate change. Increasing inflows to groundwater basins through managed aquifer recharge (MAR) is a mechanism that can help bring aquifers into sustainable balance, yet in spite of significant physical potential, MAR remains underused. Increasing emphasis on the technical aspects of MAR has served to improve knowledge of the science needed to implement MAR. However, water managers often express anecdotally that institutional elements are equally important determinants, challenges, and potential drivers of MAR. In this special collection, we examine the institutional elements that enable, or gate progress on, MAR by presenting and comparing examples of successful MAR implementation from around the United States. The case studies depict the deep connection between water management objectives of MAR and institutional contexts and design. The motivations for MAR in these case studies fall into four broad categories: water supply risk management, groundwater banking, addressing interconnected groundwater and surface water, and recharge for broader aquifer or environmental benefits. In each case study, these water management objectives help determine key managerial and administrative issues that need to be addressed and accordingly the institutional shape of a MAR project. Ultimately, empirical efforts such as this special section may help demystify this process and enable more rapid adoption and diffusion of MAR.
KEYWORDS groundwater, managed aquifer recharge, institutions, governance, recycled water

## INTRODUCTION

Groundwater pumping exceeds naturally occurring recharge in many regions of the world [1, 2]. The resulting impacts to groundwater systems adversely affect human and environmental systems. Climate change adds urgency, as the combination of more extreme flood and drought regimes coupled with intensifying demand further push groundwater resources out of balance [3]. In many or most groundwater basins, some reduction in groundwater extraction will be necessary to reduce outflows from stressed basins. Increasing inflows to these basins through managed aquifer recharge (MAR) is increasingly looked to as a mechanism to help bring aquifers into sustainable balance [4–6].

MAR entails the use of engineered or natural infrastructure to increase infiltration into an aquifer system [5, 7]. By increasing the amount of water entering an aquifer, MAR can be used to address a range of concerns related to groundwater abstraction, including increasing or stabilizing groundwater levels, augmenting the amount of water in storage, and mitigating or reducing the presence of other adverse aquifer conditions, including subsidence, water quality degradation, seawater intrusion, and depletion of interconnected surface waters [5, 8]. Addressing these concerns, in turn, can contribute substantially to social, economic, and environmental well-being. Water recharged to the aquifer can be used for extractive use, such as pumping to satisfy urban or agricultural water demands, or it can be used for in situ purposes, such as improving springflow or wetland conditions that support groundwater dependent ecosystems. Aquifer recharge can

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also aid in addressing concerns related to the temporal flows of water, including storing water to address variability in water availability or creating a lag in the timing of when water discharges to streams [9].

At present, MAR remains a relatively underused approach for managing groundwater [9]. Yet the potential importance of increasing recharge, combined with the untapped physical potential for recharge in many areas [7], points to significant opportunity for expansion of MAR.

Efforts to increase adoption of MAR in recent years have primarily focused on advancement of the technological aspects of MAR. Such efforts have included analysis and the provision of information on methods for recharge (see, e.g., [4–6]) and advancements in the tools used to analyze hydrogeology (see, e.g., [10, 11]). Progress has also been made in enhancing knowledge of the water quality aspects of MAR, including in identifying constituents of concern, tracing and evaluating contaminant transport, and promulgation of regulations related to water quality (see, e.g., [6, 12–15]). Finally, there has been increasing attention to the economics of MAR, including research seeking to identify economically suitable locations for MAR (see, e.g., [16]) and research estimating the factors influencing the cost of MAR (see, e.g., [17–20]).

Although the technical aspects of augmenting recharge are essential to deployment of MAR, barriers to deployment of MAR extend beyond this [9]. MAR is a strategy for managing water resources, and as such, the institutional aspects of MAR are also fundamental. For MAR to be implemented and contribute to improving groundwater sustainability, there needs to be a convergence on the intended vision of MAR, which drives how recharge will be achieved and the aquifer managed in practice, as well as a set of policies, processes, and procedures that guide operation of the MAR. Development of such systems is not trivial, as it involves design of institutions that dictate how entities involved in implementation will operate, navigate regulations, track and measure progress, and otherwise engage in the administrative practices necessary for management.

In this special collection, we examine the deployment of MAR in examples from around the United States to illustrate the range of institutional approaches used as well as how those relate to the drivers and objectives of MAR. The overarching impetus for this work is the recognition that water managers often anecdotally agree that institutional elements are as important, or more important, than technical challenges to MAR in many cases. In spite of this understanding, there has been no systematic examination of institutions for MAR, and as such, there is no basis for comparison of the institutional features that are necessary for development and operation of MAR. Consequently, entities considering MAR as a potential water management strategy have few priors from which to draw when building the case for and when designing MAR projects. The case studies in this special collection lay the foundational empirical groundwork for examining institutional aspects of MAR. Taken together, they illustrate a diversity of approaches to MAR. The case studies also depict the deep connection between water management objectives of MAR and institutional contexts and design.

## CASE STUDIES IN THE SPECIAL COLLECTION

The articles in this collection include nine case studies in which MAR has been successfully implemented and which can serve as examples for deployment of MAR in other locations. The cases span the continental United States (figure 1). Case studies for this collection were selected to reflect diversity across a variety of factors, including geography, source water, and method of recharge. Although the cases are predominantly located in Western states where water availability is uncertain and often stressed, one case, SWIFT, highlights the potential of MAR to help address water management challenges even where water quality rather than water supply is the primary concern. Cases were selected to illustrate diversity in source water, including surface water diverted from streams, stormwater runoff, recycled wastewater, and even, in the case of H2Oaks, groundwater from a different aquifer. Finally, the case studies cover a wide range of technical approaches to recharge. Infiltration ponds and injection wells were the most common, yet other methods of recharge include in-stream infiltration and the use of unlined irrigation canals during the off season.

The nine case studies include:

- **Arizona Water Bank** [21]—The Arizona Water Bank serves as a mechanism to both store Arizona's unused share of Colorado River water and to address groundwater depletion in central Arizona while also protecting Colorado River water users against future water shortages. Water is


**FIGURE 1.** Geographical distribution of case studies in this special section.

recharged to the aquifer through in-lieu processes, injection wells, and percolation basins.

- **Bear Canyon Recharge Project** [22]—The Bear Canyon project infiltrates surface water to the aquifer to store water for municipal supply during drought. Water is recharged to the aquifer through streambed percolation.
- **Eastern Snake Plain Aquifer (ESPA) Recharge Program** [23]—The Eastern Snake Plain Recharge Program recharges excess surface water to the aquifer, mainly during the winter months in order to protect stream flows and to reduce the potential for conflict between surface and ground water users. Water is recharged to the aquifer through percolation basins and percolation via unlined canals.
- **Groundwater Replenishment System** [24]—The Groundwater Replenishment System uses recycled wastewater for recharge with the dual purpose of forming a seawater barrier while also being augmenting groundwater supply. Water is recharged to the aquifer via injection wells.
- **Heyborne Ponds Recharge Project** [25]—The Heyborne Ponds Recharge Project infiltrates water available during winter flows via constructed wetlands in order to simultaneously support wildlife habitat, address threatened and endangered species recovery, and facilitate water availability for agriculture. Water is recharged to the aquifer through constructed wetlands.
- **Kern Water Bank** [26]—The Kern Water Bank stores water from California's State Water Project, the federal Central Valley Project, and the Kern River on behalf of its member water agencies, which can draw upon that water during times of shortage. Water is recharged to the aquifer through percolation basins.
- **Recharge Net Metering (ReNeM)** [27]—The Recharge Net Metering pilot project encourages development of groundwater infiltration projects on private or public land by offering a rebate on groundwater pumping fees based on the net increase in infiltration. Hillslope runoff is recharged to the aquifer through percolation basins.
- **Sustainable Water Initiative for Tomorrow (SWIFT)** [28]—The Sustainable Water Initiative for Tomorrow project recharges drinking water quality-treated municipal wastewater into the aquifer, reducing nutrient discharges from wastewater treatment plants and improving water levels in the regional aquifer. Water is recharged to the aquifer through injection wells.
- **Twin Oaks ($H_2$Oaks)** [29]—The $H_2$Oaks aquifer storage and recovery project pumps water

from the Edwards Aquifer and transports it to another aquifer, the Carrizo, for storage. Stored water is then withdrawn to meet municipal demand during periods of extended drought and support endangered species protection. Water is recharged to the aquifer through injection wells.

In keeping with the aims of this special collection, each article provides an overview of the motivation and goals of the MAR project as well as details on the institutional aspects of the project. Each article begins with a synopsis of the historical context that led to the development of the project, including relevant groundwater management issues and the legal and regulatory environment for water management. A description of the MAR project then follows, including institutional and technical details related to recharge, monitoring and accounting for water, and, where relevant, recovery of recharged water. Each article then depicts the institutional arrangements for managing operations of the case study MAR project, including the administrative and decision-making bodies as well as budgetary and financing practices. The articles then conclude with discussion of key factors contributing to successful implementation of the project and factors that may affect operations of the project into the future.

## METHODS FOR THE CASE STUDIES

Source materials for the case studies include academic articles, legal and regulatory information, and other publicly available reports and documents. We also conducted over 30 interviews with key players involved in the management and operation of each of these projects, including project implementers, government officials, and consultants. Interviews were semistructured and questions tailored to fill in gaps in knowledge about the case studies and settle areas of uncertainty based on our textual research.

Draft versions of the case studies were refined through a collaborative process including through discussion and review during a major symposium held at UC Berkeley in September 2019 and through review by members of the symposium's Technical Advisory Committee [30]. The symposium was structured to highlight each case study in greater detail and subject them to comparative comment by expert panels. A second event immediately following the symposium brought together a smaller group of invited specialists for a facilitated discussion of emerging themes and observations from both the symposium and the case studies, which inform this special section. Key observations and lessons learned from both the case studies and the symposium proceedings are discussed below.

## DISCUSSION

The case studies in this collection illustrate the diversity of institutional structures utilized in deployment of MAR. Table 1 summarizes key characteristics of each case study. Across the cases, MAR projects were implemented both individually by a single entity and by multiple entities working together. MAR projects that were implemented by multiple entities include collaboratively implemented centralized projects and distributed projects with multiple, typically smaller, recharge locations, often by differing entities. A local public water agency (water district, canal company, sanitation district, etc.) was involved in implementation of each of the cases, though state-level agencies, private landowners, nonprofits, and tribal entities are also involved. Institutional structures for each case study also involved some form of monitoring and tracking of recharge activities. The institutions utilized in the case studies appear to be tightly connected to two elements: (1) the water management objective for implementing of MAR and (2) whether multiple entities are involved in implementation of the MAR project.

### *Water Management Objectives for MAR*

Although each of the MAR projects described in the case studies provide multiple water management benefits, four broad categories water management objectives existed across the projects: supply risk management, groundwater banking, addressing the relationship between interconnected surface and groundwater, and achieving broader aquifer and environmental benefits.

The first category—supply risk management—encompasses the objective of increasing or restoring groundwater supplies to hedge against variability in supply availability. The Bear Canyon Recharge Project, $H_2$Oaks, and the Groundwater Replenishment System all fall into this category.

The second category—groundwater banking—also serves a water supply function but operates by a specific mechanism. Water banking generally has the objective of storing water on behalf of a specific entity, so that the entity recharging water into an aquifer has the exclusive right and ability to withdraw it later. Groundwater banks operate much like a financial bank, with members able to make

**TABLE 1.** Summary of Key Characteristics of Each Case Study.

| Case | Water Management Objective | Implementing Actors | Structure for Implementation | Accounting |
|---|---|---|---|---|
| Arizona Water Bank | Primary: Supply risk management | Multientity: State government agencies, local water agencies, municipalities, and tribal entities | Distributed | Tracks recharge through a system of long-term storage credits |
| Bear Canyon Recharge Project | Primary: Supply risk management | Single-entity: local water agency | Centralized | Measures inflow and pumping. Uses that information to track total storage |
| Eastern Snake Plain Aquifer Recharge Program | Primary: Address interconnected surface waters | Multientity: State governmental agencies, local water agencies, and districts | Distributed | Tracks diversions, calculates recharge, and monitors aquifer levels |
| Groundwater Replenishment System | Primary: Broader aquifer or environmental benefits<br>Secondary: Supply risk management | Single-entity: Regional water district | Centralized | Measures water injected for recharge, receives reports on pumping. Combines the two to tracks storage |
| Heyborne Ponds Recharge Project | Primary: Address interconnected surface waters<br>Secondary: Supply risk management | Multientity: Landowner, local water district, and nonprofit | Centralized | Measures diversions, calculates infiltration, and lagged stream outflows. Uses that information to receive augmentation credits for water that reaches the river |
| Kern Water Bank | Primary: Supply risk management | Multientity: Local water agencies | Centralized | Tracks diversions of water for recharge and recovery pumping. Uses this information to calculate storage separately for each participating agency |
| Recharge Net Metering | Primary: Broader aquifer or environmental benefits | Multientity: Local water district, landowners, and third-party certifiers | Distributed | Infiltration measured by third-party certifiers |
| Sustainable Water Initiative for Tomorrow | Primary: Broader aquifer or environmental benefits | Single-entity: local water sanitation district | Centralized | Measures water injected via wells |
| $H_2$Oaks | Primary: Supply risk management<br>Secondary: Broader aquifer or environmental benefits | Single- became multientity, local water agency, joined by state agency | Centralized | Measures water injected for recharge and groundwater pumping. Uses that information to track storage |

withdrawals and deposits. Case studies in this category include the Kern Water Bank, which stores water on behalf of its private members, and the Arizona Water Bank, in which the state stores water on behalf of a range of entities within Arizona, as well as for California and Nevada.

The third category of management objectives is present where addressing the relationship between interconnected surface and groundwater heavily influences the goals and design of the project. Such MAR projects often seek to reduce the impacts of groundwater pumping on interconnected surface water flows. In the Heyborne Ponds Recharge Project, MAR was used to support wildlife habitat, to retime flows of surface water to support an interstate agreement, and to allow local groundwater users to offset depletions to the river caused by their groundwater pumping. In the ESPA Recharge Project, a regional recharge program seeks to guarantee surface water flows in the Eastern Snake Plain and reduce conflicts between surface and groundwater users.

The final category of management objectives—recharge for broader aquifer or environmental benefits—arises from recognition of near-term physical threats to aquifer health. Although water supply may be improved as a result of such MAR projects, the primary focus is achieving a wider set of benefits from improving aquifer conditions. In the Recharge Net Metering case study, distributed recharge projects return water to the basin, motivated by a broader mandate to ameliorate the negative effects of seawater intrusion on the quality of their groundwater supplies. The SWIFT case study is motivated in part by reducing discharge of treated wastewater effluent and its impacts on coastal water quality, but structured such that its benefits also include increasing pressure in the local confined aquifer system to help address groundwater overdraft, seawater intrusion, sea-level rise, and improve conditions in local wells.

The water management objective is an important consideration for the institutional aspects of an MAR project, as it determines the key managerial and administrative issues that need to be addressed. Figure 2 describes some of the key considerations for each category of water management objective, as illuminated by the case studies. All projects required institutional structures that enabled benefits to be captured by participating such as those who advocate for and fund a given project. Although many MAR projects have co-benefits that can accrue to entities other than those conducting the recharge, other MAR schemes have arrangements that seek to prevent free ridership.

Tracking and accounting of flows, storage, or recharge benefits are essential for clarity, especially given the invisible nature of groundwater resources and the opacity of the effects of MAR projects on groundwater conditions. For projects seeking to use MAR for supply risk management, tracking and accounting are important to ensure that expectations are met once recharged water is needed, and particularly where groundwater is comingled in aquifers accessed by multiple parties. Projects seeking to use MAR for groundwater banking also have to contend with tracking of flows across a larger number of entities and with quantifying potential reduction in stored water over time due to subsurface outflows or other causes. In contrast, projects seeking to use MAR for addressing interconnected surface and groundwater flows ideally track transport and discharge of recharged water to surface water bodies. Projects implementing recharge to accrue broader aquifer and environmental benefits must address ways motivate action when the direct impacts on storage or flows is not the main consideration, and it remains an open question whether it is feasible, or even necessary, to directly quantify or estimate the range of benefits. These functions all rest heavily on relevant institutional capacity.

### *Multientity MAR Projects*

The number of entities involved in implementation and how those entities will benefit from the project appears to be another key factor influencing the institutional structure of MAR projects. In each of the cases in which multiple entities were involved in implementation, institutional structures were created to set the expectations of the parties involved, track their actions, and have an accounting system that serves to distribute some form of benefits across the parties. Each of the case studies set up a unique institutional structure to achieve these. In the case studies of centralized MAR projects, the entities involved created formal agreements that specified responsibilities as well as how benefits would be allocated. For example, entities involved in the Heyborne Ponds Recharge Projects contractually agreed to a division of the operating costs and augmentation credits. The Kern Water Bank operates similar to a financial bank, with a predetermined set of rules of participation and separate water and financial accounts for each member. In the case studies of distributed MAR projects, an oversight and

**Overarching Considerations of All Projects**

- What natural infrastructure exists, what additional infrastructure will be needed to enable successful recharge, and what are the logical existing or new institutions necessary to construct and manage it?
- How will capital, operations and maintenance costs be funded or financed?
- How will rights be secured for water recharge and for withdrawal?
- How will inflows, outflows, and storage be tracked?
- What policies will be in place to manage the timing, quantities and operations of recharge and withdrawal?
- What are the key regulatory requirements for a project, and how can they be efficiently navigated?
- What third party impacts might occur, and how can they be accounted for and mitigated?
- What existing organizations have an interest in the project?
- What is the appropriate level of stakeholder engagement?

**Supply Risk Management**

- How will recharge and subsequent extraction be managed jointly with other supplies?
- How frequently and what amount of water will be recharged and withdrawn?
- How will rights be secured for water recharge and for withdrawal?
- How will recharged water be protected from capture by other entities?

**Groundwater Banking**

- What are the requirements for participation in the groundwater bank - who can "deposit" and who can "withdraw" water?
- Will banked water be marketable, and under what conditions?
- How will hydrologic losses or impacts to neighboring users or interest groups be accounted for?
- How will recharged water be protected from capture by entities outside of the bank?

**Addressing Interconnected Surface and Groundwater**

- How will groundwater outflows to surface water be reflected in the management and accounting system?
- How will recharged water be protected from capture before it reaches its outflow?
- What will be the implications of recharge groundwater and surface water rights?
- How will ecological and hydrologic benefits be defined, quantified, and tracked?

**Recharge for Broader Aquifer or Environmental Benefits**

- What will incentivize investment in recharge?
- How will ecological and hydrologic benefits be defined, quantified, and tracked?
- How can targeted benefits fit within applicable water rights frameworks for beneficial use?

**FIGURE 2.** Considerations for the institutional design of MAR projects, by Water Management Objective.

certification process was utilized. The Arizona Water Bank relies on the state of Arizona's permit and certification process for entities seeking to conduct recharge. For the ReNeM project, a third-party certifier monitors infiltration. In the ESPA, the Idaho Water Resources Board sets up individualized contracts with canal and irrigation companies that conduct recharge.

In sum, the institutional aspects of MAR in each case study are a reflection of the water management objectives of the project and the implementing entities. Although similarities exist across the nine case studies, the diversity of institutional structured used for MAR suggests that contextual conditions influence MAR project design. As with many other types of water resource projects, there exists no generic institutional template that fits the wide variety of contexts for MAR. The resulting need for bespoke institutional design is clear and unsurprising. But given the relative novelty of MAR as an emerging approach, learning from those who have succeeded thus far is crucial. This finding highlights both the value of this collection and the need for more intensive research and analysis that can provide guidance to prospective implementers of MAR.

## CONCLUSION

The case studies in this collection reflect instances of successful implementation of MAR around the United States. In each, implementers were able to overcome two of the most important hurdles to achieving functioning MAR projects—developing the physical and technical means to recharge water and designing the institutional structures needed to harness MAR for broader water management objectives. Although the approaches to MAR vary across the cases, a notable similarity is that in each, MAR was a creative strategy that enabled the project implementers to address an ongoing water management problem of concern. In all of the cases, the MAR project provides multiple benefits. Further, in at least three of the case studies (the Arizona Water Bank, Groundwater Replenishment System, and $H_2$Oaks), use of the MAR project was extended beyond its initial purpose to address emerging issues of concern and to provide social and political benefits to entities beyond those implementing the project. These findings highlight not only the value of MAR but also its flexibility as a water management strategy.

MAR is physically possible in many, although not all, stressed groundwater basins around the world. MAR has a great potential to shift how groundwater resources are managed. This collection of case studies demonstrates pathbreaking efforts to deploy MAR. The case studies strongly support the anecdotal observation and overarching conclusion that institutional factors are as or more important, and as or more difficult to solve, than physical and technical ones in many places. They also support the notion that with motivation and creativity, project proponents can generate institutional innovations to overcome both sets of challenges. Ultimately, empirical efforts such as this special section may help demystify this process and enable more rapid adoption and diffusion of MAR.

## CASE STUDY QUESTIONS

We invite the reader to evaluate the topic through cross-cutting questions comparing aspects of the case studies.

- What institutional elements are most important as baseline requirements across the case studies? What institutional elements serve as the most important incentives or barriers across the case studies?
- What is the role of monitoring and accounting across the case studies?
- Many MAR projects are implemented jointly by multiple entities. What types of policies and procedures need to be in place to ensure such projects can be deployed and operated successfully?
- MAR projects are by their nature typically local installations with local benefits, yet many of the projects in the case studies involve nonlocal actors and have nonlocal effects. In which case studies were nonlocal actors involved, and what was their role? Under what circumstances might nonlocal parties be particularly useful for facilitating deployment of MAR?
- The case studies in this collection span multiple states. Are there any notable variations in state laws and policies that influenced how the institutional structures for each MAR project were designed?
- In several of the case studies, project implementers were concerned about stakeholder approval. What concerns might stakeholders have about implementation of MAR? What steps can project implementers take to ensure project support?

- The MAR projects in the case studies were implemented by a diverse set of entities. What types of actors were involved in the cases and how might their prior experiences and capacities (e.g., technical, managerial, financial) have contributed to their successful implementation of MAR?

- Might lessons from some cases in this series have potentially informed efforts in other cases in this series? How? What are the common lessons across the diverse case studies that can inform future efforts to implement MAR?

## AUTHOR CONTRIBUTIONS

KM, AM, and MK wrote this article. MK and AM conceptualized and supervised the research project. AM developed the research methodology. MK acquired funding and administered the project.

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## COMPETING INTERESTS

The authors have declared that no competing interests exist.

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