Technical/Regulatory Guidance

Managed Aquifer Recharge Guidance

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Prepared By

The Interstate Technology & Regulatory Council

(ITRC) Managed Aquifer Recharge Team

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ITRC (Interstate Technology & Regulatory Council). 2023. Managed Aquifer Recharge Guidance MAR-1. Washington, D.C.: Interstate Technology & Regulatory Council, MAR Team. https://mar-1.itrcweb.org/.

The combination of climate change and growing demand for fresh water has resulted in an increase in the vulnerability and scarcity of freshwater supplies around the world. Managed Aquifer Recharge (MAR) is a process that is becoming an increasingly important method for improving and supplementing subsurface freshwater storage and ecosystems with an additional benefit of reducing flood risk, managing stormwater, mitigating subsidence, and controlling saltwater intrusion.

This Managed Aquifer Recharge guidance provides a basic understanding of MAR and its applications through the presentation of:

- A **model of the MAR process** illustrating the four key components of MAR and their interaction.
- An **overview of the applications of MAR** and the role in addressing climate change impacts through sustainability and resilience in water resources management.
- **Information on the key components of MAR** and the critical considerations for each component in the design of a MAR project.
- **Case studies** illustrating the various applications of MAR.

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1. Introduction

The combination of climate change and growing demand for fresh water has resulted in an increase in the vulnerability and scarcity of freshwater supplies around the world. The need for fresh water to grow crops and provide for the welfare of the general population, economic growth, and ecosystems is becoming more acute. In the past 50 years, the amount of water withdrawn for human use has tripled (Jordan 2016). Managed aquifer recharge (MAR) is becoming an increasingly important method for improving and supplementing subsurface freshwater storage and ecosystems with an additional benefit of reducing flood risk, managing stormwater, mitigating subsidence, and controlling saltwater intrusion.

This document is intended primarily for state regulators and stakeholders who may not be familiar with the opportunities and challenges associated with MAR. It provides a basic understanding of MAR concepts and example applications. It is important to realize that MAR is an area of active research and expanding practical applications, and that this management process is continuing to evolve with time.

1.1 What Is MAR?

MAR is defined as the purposeful recharge of water to aquifers for subsequent recovery or for environmental benefit (Dillon et. al 2009). Groundwater recharge is a natural phenomenon, and MAR can involve either enhancement or restoration of recharge in areas such as floodplains or introduction of recharge where not naturally present, such as arid environments. Aquifers can provide excellent natural reservoirs for freshwater storage and can be more effective and economical for long-term storage over surface water reservoirs. MAR is a water resources management tool that encompasses a wide variety of water sources, recharge methods, and storage management practices. It has a long history and is likely to see increased use as growing populations create greater demand for water and as a strategy for resilience to adapt to increased vulnerability of water supplies due to climate change (Dillon et al. 2022).

There are many forms of MAR, ranging from infiltration basins and injection wells to managed release from reservoirs coupled with stream channel modification. Each MAR project is designed and implemented based on important location-specific factors, including water rights, regulatory considerations, permitting requirements, source water characteristics, hydrogeologic factors, source water/aquifer interactions, engineering constraints, and economics. Whether a MAR project succeeds or fails is largely dependent on the thorough understanding of project-specific factors. The key elements encapsulating the project factors are intended use, source water, receiving aquifer, and recharge technologies (Figure 1-1. MAR Process Model—Key Elements and MAR Process Model—Recharge Technologies). These are discussed in detail in this document.

Historically, the primary reason to implement MAR has been to increase groundwater storage and alleviate overdraft of groundwater basins. With proper design and successful application, the benefits of MAR can be far-reaching including improving water supply resilience and quality, mitigation of saltwater intrusion, flood control, and freshwater fish habitat improvement (Kirk et al. 2020).

Technical considerations are covered extensively in this document and typically consider a broad range of topics, including permitting, engineering, chemistry, and hydrogeologic factors. Social considerations can range from local acceptance of recharging drinking water aquifers with treated municipal wastewater to flooding idle farm fields with available river flood flows. MAR projects can also have political/regulatory implications; for example, a water replenishment district or stormwater management agency may be required to pay for and maintain MAR projects. Regulatory considerations can range from the right to extract and use stored water to unintended consequences of MAR projects, such as raising the water table under sensitive structures or deep-rooted crops. As will be demonstrated in the case studies in this document, while there are common themes, each MAR application will have a unique set of circumstances that must be identified, understood, evaluated, and planned for.

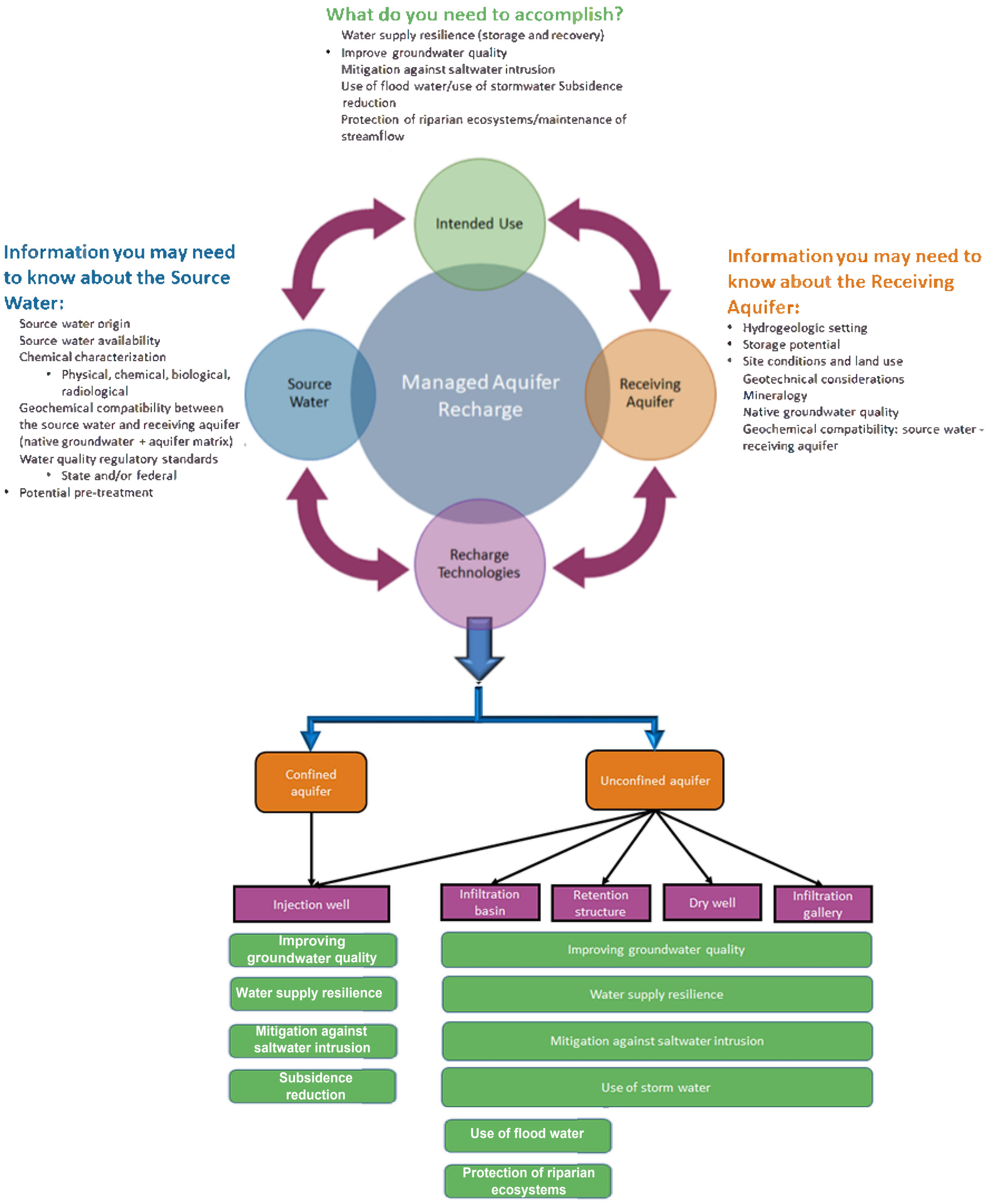

Figure 1-1. MAR Process Model — Key Elements

1.2 Purpose/Scope of MAR Guidance

This document synthesizes the current knowledge of MAR, including intended uses, recharge technologies, and technical background, and provides guidance and a framework for considering key elements, such as intended use, source water, effects on the receiving aquifer, and recharge technologies when implementing a MAR project. This guidance document generally follows the flow of typical MAR projects as depicted in the MAR Process Model (Figure 1-1). This process typically starts with identifying the objectives of the MAR project, followed by identifying a source of water and developing an understanding of the subsurface conditions and whether MAR is feasible to implement. Provided MAR is hydrogeologically feasible, the project then addresses site characteristics followed by selection of the appropriate MAR technology. Water rights law and other considerations are beyond the scope of this document but must be considered in any MAR project.

1.2.1 Audience

This document is designed to assist regulators, both state and federal, as well as environmental consultants, local government officials, and other stakeholders to understand the basic principles of MAR projects and highlight key issues and challenges in undertaking and operating MAR projects. This document depicts MAR project considerations through an overview, fact sheets, and several case studies that inform about challenges often encountered when implementing MAR projects and provides the reader with lessons learned.

1.2.2 What the Document Is and Is Not Intended to Cover

MAR is the purposeful recharge of aquifers to increase water supplies for subsequent recovery or environmental benefit. This document provides discussion of the major elements of a MAR project focusing on the intended use of the project, issues related to source water, the receiving aquifer, and recharge technologies used in a MAR project. Case studies are provided to help address lessons learned from ongoing MAR projects.

As stated before, water rights will not be discussed in detail, but are an integral part of any MAR project. Similar to water rights, civil and mechanical engineering and alternative analysis is only briefly discussed in this document. The process and effort required to complete an engineering feasibility study, alternatives analysis, preliminary engineering report, and engineering design with plans and specifications are beyond the scope of this effort. For the purposes of this document, the following engineered infiltration or injection systems are not typically implemented to purposely recharge an aquifer and are therefore not considered to be MAR applications:

- disposal injection wells (for example, underground injection control (UIC) Class I and Class II wells)
- open-loop geothermal systems
- solution mining (UIC Class III wells)
- septic system infiltration drainfields
- CO_2 sequestration (UIC Class VI wells)

1.3 Key Terms and Definitions

There are several key terms that are used routinely in discussing MAR applications. Key words and phrases are presented here and supplemented with the glossary near the end of this document.

Advanced treated water (ATW)—Wastewater that has been thoroughly treated by advanced treatment processes to reduce contaminant concentrations (including virus and pathogen reduction) to meet regulatory limits. This water often contains such low levels of impurities (for example, total dissolved solids (TDS)) that it requires conditioning before it can be recharged, as is the case in the use of reverse osmosis.

Aquifer storage and recovery (ASR)—A water resources management technique for storing water underground during periods when there is excess water and recovering that water later, typically facilitated by ASR-specific wells. ASR wells can be used for both the injection of source water and recovery of groundwater.

Aquifer storage transfer and recovery (ASTR)—An ASTR system uses separate injection wells and extraction wells, allowing the injected water to migrate or transfer from the injection area prior to extraction.

Environmental justice — The fair treatment and meaningful involvement of all people, regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies (USEPA 2023c).

Geochemical compatibility—A measure of the degree to which the source water, aquifer matrix, and native groundwater chemical characteristics will minimize adverse chemical reactions from occurring that could degrade water quality or reduce the recovery of stored groundwater.

Groundwater storage—Water that is stored in an aquifer, whether it is available for extraction or not.

Hydrogeologic conceptual model—Hydrogeologic framework that forms one of the foundational pillars in planning and designing the MAR project. The hydrogeologic conceptual model typically consists of a report that provides the hydrogeologic setting (hydrostratigraphy), receiving aquifer physical characteristics (for example, depth to water, permeability, storage coefficient, degree of confinement), receiving groundwater quality, groundwater flow characteristics (directions, rates, volumes, variability), nearby public and private groundwater users, and groundwater/surface water connections.

Injection wells—As used in this document, an injection well, also referred to as a recharge well, is a bored, drilled, or driven shaft or a dug hole where the depth is greater than the largest surface dimension used to directly supply water into the saturated zone or aquifer(s) for the purpose of recharge or replenishment.

MCL—Maximum Contaminant Levels are standards set by USEPA for drinking water quality. An MCL is the legal threshold limit on the amount of a substance that is allowed in public water systems under the Safe Drinking Water Act.

Monitoring—Monitoring is required for MAR projects and often includes routine testing of source water quality and flow rates and performance monitoring of the MAR system, including groundwater quality and groundwater elevations. Baseline groundwater monitoring is also commonly required to establish preproject surface and/or groundwater conditions.

Recharge technology—Any method used to introduce source waters into an aquifer. Technology can range from relatively passive methods, such as farm-flood infiltration, to more intensive methods, such as injection wells.

Recycled water—Treated wastewater that is reused for a new purpose, such as irrigation, potable water supply, or groundwater supply, among others. Sources of wastewater include but are not limited to municipal, industrial, and agricultural wastewater. As used in this document, the term “reclaimed water” has the same meaning as “recycled water.”

Residence time—Length of time recharge water resides in an aquifer before it is extracted. Residence times can be mandated by regulatory agencies to ensure pathogens and other contaminants are filtered from the recharged source water prior to being removed from the subsurface and served as drinking water.

Source water—Source water intended for use as recharge. This can range from transient sources, such as captured available flood flows, to more consistent sources, such as treated water originating from a wastewater treatment plant. Source water availability and quality are key components in the design and implementation of MAR projects. Source water quality can be highly variable and may require treatment or design constraints to improve water quality prior to use in recharge.

UIC—Underground injection control.

Vadose zone—The unsaturated to intermittently saturated zone between the ground surface and the water table.

1.4 State Survey Results

ITRC prepared a MAR survey and distributed the survey to points of contact in each state (see Appendix A. for MAR survey questionnaire). A total of 26 out of 50 states responded to the survey (Figure 1-2). ITRC gathered information on the 24 states that did not respond and supplemented the original database for those states that did respond.

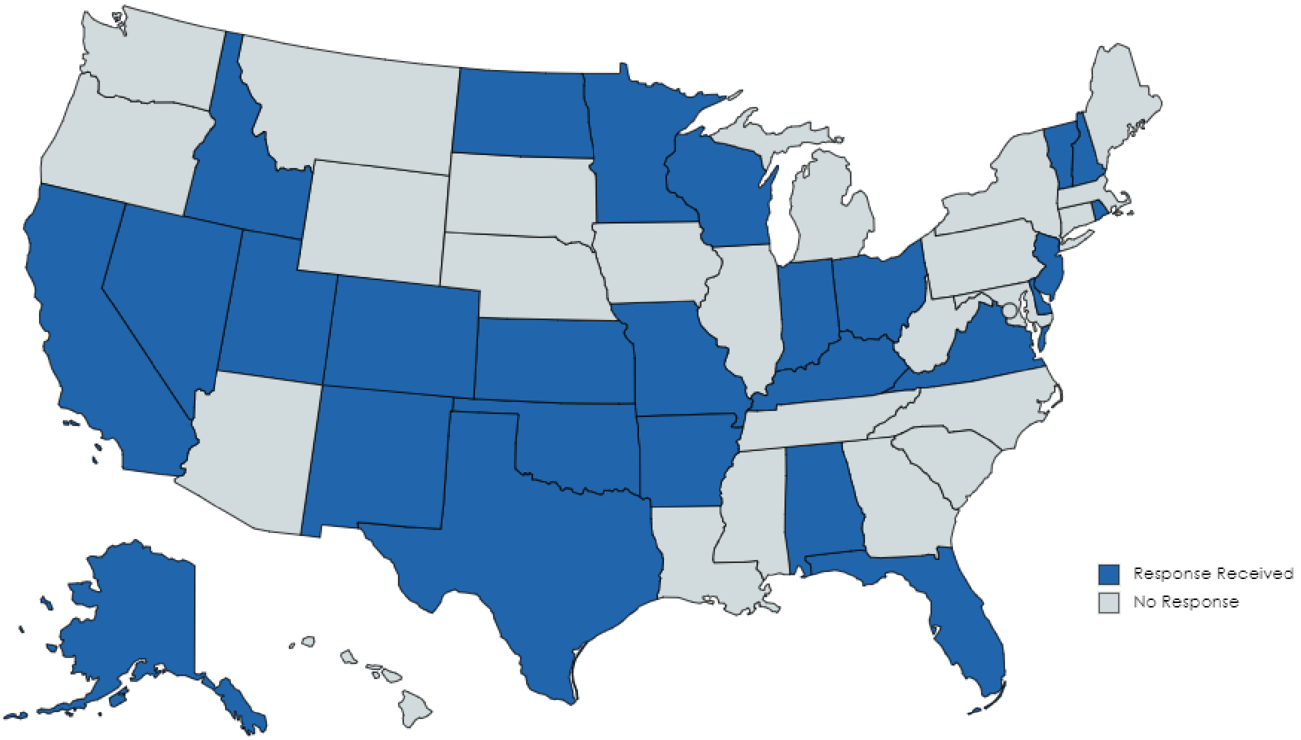

Figure 1-2. State Survey Respondents.

A discussion of the compiled information contained in the database is provided below.

1.4.1 MAR Is Widely Applied within the US

Based on the survey responses and our research, MAR projects were identified in all but 14 states. Figure 1-3 depicts the distribution of states with MAR projects versus states with no MAR projects or where MAR projects have not been confirmed.

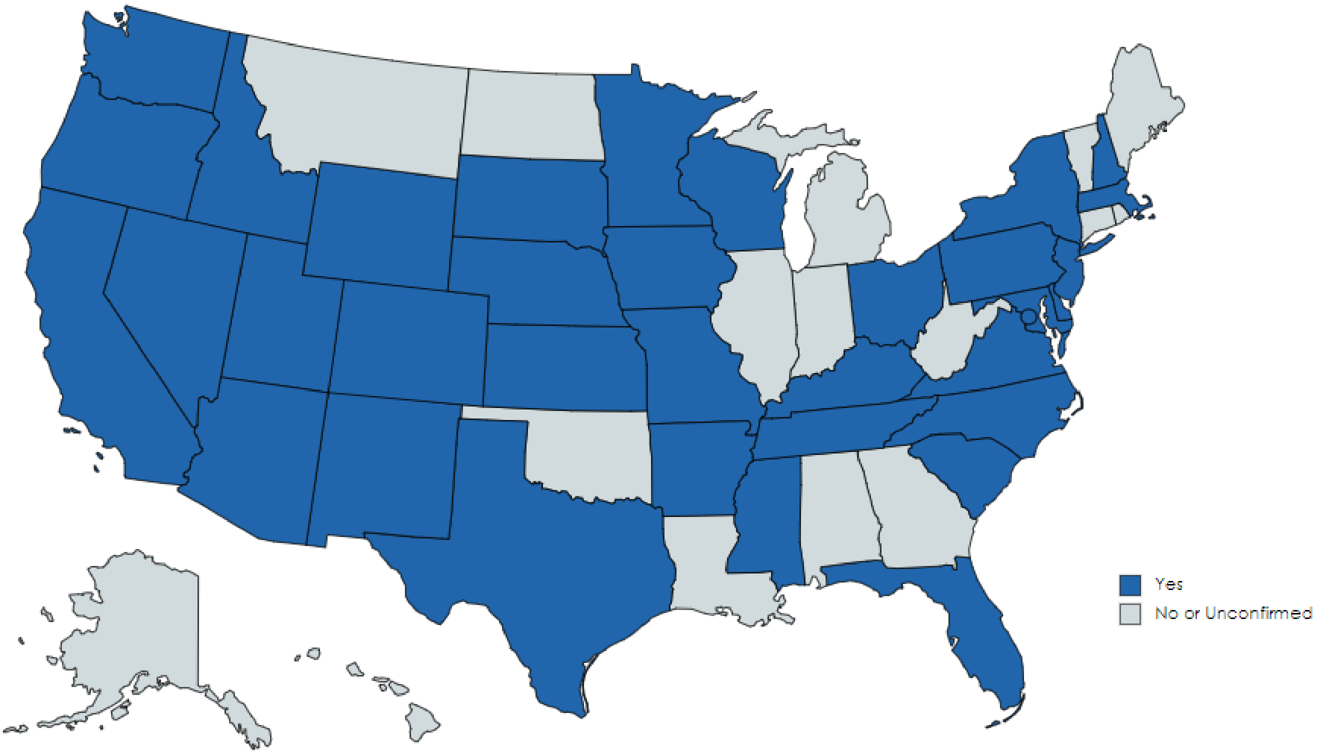

Figure 1-3. States with MAR experience.

The most common way to address fluctuating water demand is by implementation of MAR projects (50% of the respondents). This was followed by construction of surface water reservoirs and limited or restricted water use (38%), utilization of recycled water (36%), and utilization of alternative water sources (for example, desalinated inland- or seawater)

(32%).

The most common reason that MAR is implemented is for drinking water storage (46%), followed by stormwater management (32%), and drought mitigation (22%). Approximately 20% of the states used MAR for disposal and 14% for flood hazard mitigation (Figure 1-4). Eight coastal states responded that MAR is used to control saltwater intrusion, typically through arrays of injection wells placed along the coastline.

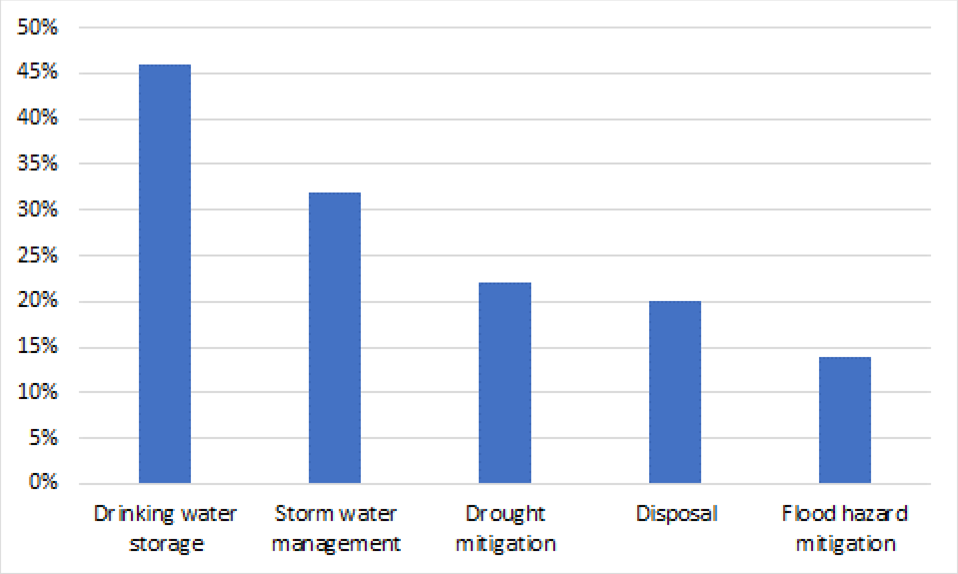

Figure 1-4. Reasons for MAR implementation.

1.4.2 Technical and Regulatory Barriers to Implementing MAR Are Wide-Ranging

The potential barriers to implementing MAR projects are wide-ranging and should be identified and accounted for early in the project planning and feasibility analysis. While there are common issues on all MAR projects, each usually has site-specific barriers that are often unique to that application. The most common barriers identified in the survey include water quality concerns (32%), statutory or regulatory restrictions (28%), water resources allocation (26%), prohibitive costs or lengthy time to implement (24%), water rights issues (22%), and stakeholder acceptance (18%). Less frequently cited barriers to MAR implementation include a lack of guidance (8%), lack of technical expertise (6%), and ineffective communications (6%) (Figure 1-5). Some states offer grants and other financial incentives to overcome economic impediments such as capital costs to build MAR infrastructure (property acquisition, pipelines, treatment facilities, and wells or basins).

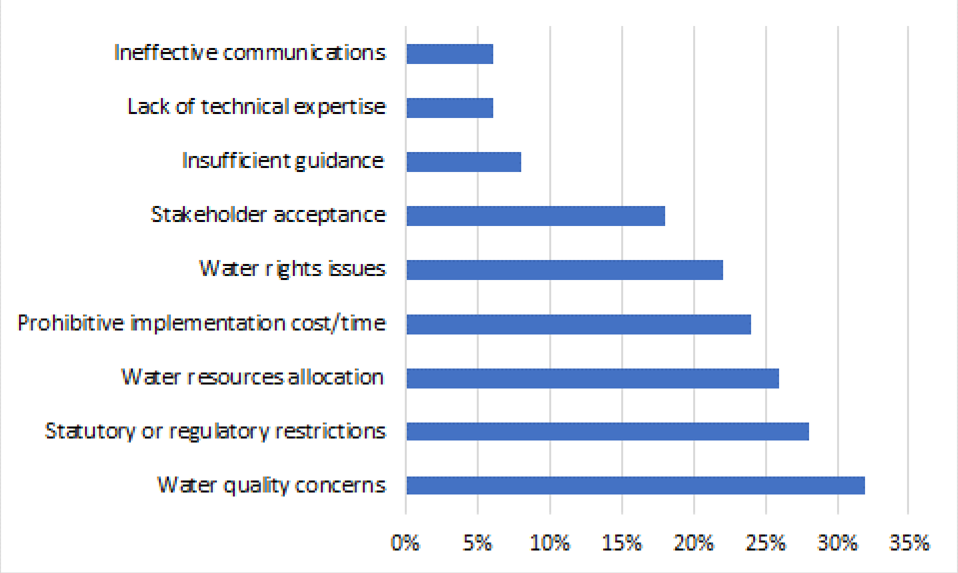

Figure 1-5. Technical and regulatory barriers to MAR implementation.

Contaminants of emerging concern (CEC), such as perfluoroalkyl and polyfluoroalkyl substances (PFAS), have had a significant impact on source water quality considerations and potential costs to treat source water prior to recharge, particularly in urban settings (Page et al. 2019; Cáñez et al. 2021). Similarly, ATW, due to its high purity, may require chemical adjustment or conditioning prior to application to avoid potential leaching of trace metals such as arsenic or other contaminants from sediments (Fakhreddine et al. 2015). Each MAR project will likely have site-specific water quality issues that will need to be considered early in the planning process, including the construction of expensive treatment plants. Thorough characterization of source water and receiving water chemistry and receiving aquifer matrix cannot be overemphasized. This is further addressed in Section 3.5.

Water rights are broadly defined as the right to use water from a stream, lake, irrigation canal, or aquifer. While water rights issues associated with MAR projects are specifically not addressed in this document, they can present a significant barrier to MAR implementation, particularly in groundwater basins where the water rights have not been determined or defined. For example, if a stakeholder group or utility desires to pay for and operate a MAR project where they have exclusive use of that additional groundwater, such a requirement could not be guaranteed in areas with unregulated withdrawals. It should be noted that water rights vary from state to state, complicating comparison of individual projects.

1.4.3 Water Chemistry Is a Major Concern

As anticipated, water chemistry is a concern among 34% of the states responding to the ITRC survey. These concerns were focused on source water that contains trace contaminants (30%), pathogens (24%), disinfection by-products (18%), and metals (14%) (Figure 1-6). Many states (30%) responded that they were also concerned with mobilizing aquifer matrix materials such as arsenic.

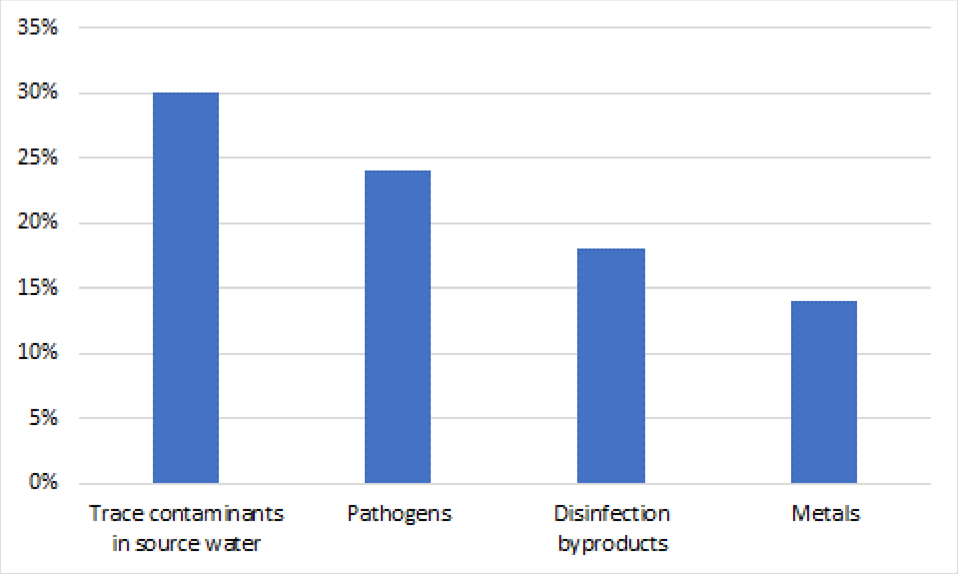

Figure 1-6. Water chemistry concerns.

1.4.4 Modeling Is an Important MAR Design Tool and Is Used by Most States

Groundwater and surface water modeling was identified as an important tool in the design, implementation, and permitting of MAR projects. Groundwater and/or surface water modeling is employed by 30% and 16% of the responding states, respectively. Only 10% of the states responded that models are not used on their MAR projects. Depending on the project characteristics and MAR project objectives, other types of modeling employed by states include water balance models (18%), watershed models (16%), surface water/groundwater interaction models (14%), solute transport models (14%), unsaturated flow models (10%), and reactive transport models (10%) (Figure 1-7). A total of 13 states responded that they run models in-house, while 16 may use outside contractors.

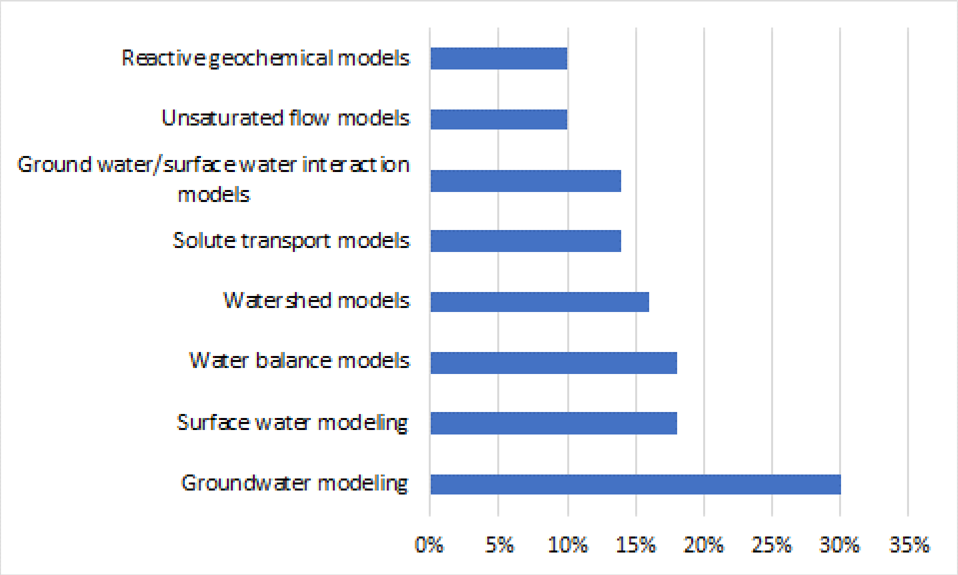

Figure 1-7. Modeling.

1.4.5 Many States Provide MAR Guidance Documents

Many of the responding states (92%) have existing guidance documents applicable to MAR projects, with the most common guidance documents regarding water infiltration technologies (16%), water allocation decision-making framework (16%), construction or design of recharge facilities (other than wells) (12%), and groundwater modeling (12%). Other types of guidance documents include water harvesting (10%), surface water modeling (8%), and risk management (8%) (Figure 1-8). Approximately 8% of the states indicated that they have no guidance documents for MAR-related projects.

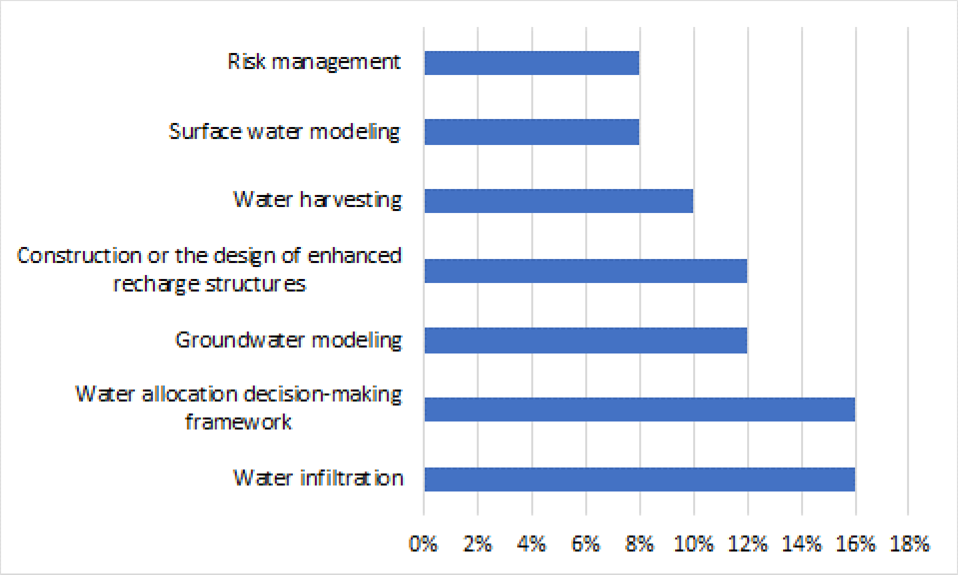

Figure 1-8. Guidance documents.

1.5 Document Organization

This document is organized as follows:

Section 1: Introduction — Introduces MAR, provides key definitions, discusses current approaches and stakeholders, document organization, and the MAR Process Model.

Section 2: Project Planning — Provides brief description of important aspects of planning a successful MAR project from a project management perspective.

Section 3: MAR Overview — Provides an overview of MAR and multiple forms of MAR, each requiring an understanding of the intended use, source water, receiving aquifer, and recharge mechanism.

Section 4: Recharge Technologies — Provides a series of fact sheets discussing recharge technologies applicable to MAR projects.

Section 5: Case Studies — Provides case study examples of MAR projects and a series of fact sheets regarding each case study.

Appendix A.: Managed Aquifer Recharge (MAR) State Survey

Appendix B.: Water Quality Parameters

Appendix C.: State, Territory, and Tribe Contacts for Managed Aquifer Recharge

Appendix D.: Team Contacts

Appendix E.: Glossary

Appendix F.: Acronyms

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2. Project Planning

Developing a MAR project requires an organized, comprehensive, and transparent approach. Although a detailed discussion of MAR project planning is beyond the scope of this guidance document, this section briefly describes the important aspects of planning a successful MAR project from a project management perspective.

2.1 Project Team

A successful MAR project will require the diverse skill sets of many people with training in different backgrounds, such as:

- science (geology, hydrology, chemistry, ecology, natural resources)
- engineering (civil, environmental, etc.)
- program management
- stakeholder and community engagement
- public policy
- water rights law
- federal, state, and local permitting/agencies

2.2 Feasibility

A feasibility study is one of the first steps in planning a MAR project. As part of a feasibility study, the advantages and disadvantages of potential recharge technologies are quantified and evaluated, including costs related to permitting; implementation; and operations, maintenance, and monitoring (OM&M). Developing a full-scale MAR project can be expensive and time-consuming. Feasibility studies can help determine where obstacles and limitations may exist as well as guide a decision of whether to move forward with the proposed project or make pertinent changes to the approach. Often the feasibility study is divided into an initial hydrogeologic feasibility study followed by an engineering feasibility study.

The hydrogeologic component of a feasibility study looks at water sources, recharge zones, surface vs. subsurface recharge, and characterization of the receiving aquifer and geologic zones to determine how practical a MAR project in the geologic setting will be. This evaluation may include a quantitative ranking analysis based on GIS and remote sensing data to determine suitable locations for MAR (Chowdhury, Jha, and Chowdary 2010; Aju et al. 2021). The engineering component of a feasibility study looks at costs and funding, infrastructure gaps and requirements, constructability, and limitations of the proposed design.

2.3 Economics

Successful MAR projects generally require funding in the millions of dollars. Designing and implementing a successful MAR project requires not only a capital investment but also funding for long-term OM&M costs, including costs for mitigation of any adverse outcomes. Sometimes the OM&M costs can exceed the initial capital costs. Therefore, project economics and cost-benefit analysis should be addressed during the beginning stages and feasibility studies of a MAR project. Funding sources should be identified and discussions with local, state, and federal agencies should begin. Seasonal variations in the cost of water may make the economics of a MAR project more attractive by providing a financial incentive to store water when its cost is low.

2.4 Stakeholder Engagement and Environmental Justice

During the planning process (and throughout the project) thoughtful discussions and involvement with the stakeholders will improve the chances of success. These outreach efforts should be specifically written into the planning and implementation phases.

Stakeholder considerations can vary depending on the type of MAR project and the location; urban stakeholders concerns will likely be different from rural ones. Each MAR project typically presents a unique set of stakeholders that need to be considered during the planning and communication process. Relevant stakeholders can include water purveyors, environmental government agencies, nongovernmental organizations such as environmental groups, and private well owners. These stakeholders can present interests that are in favor of or in opposition to the project. Understanding stakeholder interests, both positive and negative, will likely help streamline the permitting process and ensure that potential negative consequences are fully considered.

2.4.1 Potential Stakeholders

Stakeholders vary from government agencies to nongovernment organizations (NGOs) such as environmental organizations. Proper project planning, communication, design, and monitoring are effective in promoting the benefits of MAR and reducing unintended negative consequences. Example MAR stakeholders and their potential interests and concerns are presented below:

Federal, state, and local government — At the federal level, stakeholder agencies may include:

- USACE, where source water is derived from rivers and streams classified as waters of the United States or where flood control structures may be impacted
- USEPA for Safe Drinking Water Act (SDWA) considerations (for example, when recycled water is used for recharge)
- federal land management agencies such as the Bureau of Land Management (BLM) or U.S. Forest Service (USFS) if projects occur on federally administered lands
- National Oceanic and Atmospheric Administration (NOAA) or the U.S. Fish and Wildlife Service (USFWS) if biological resources are potentially impacted, such as anadromous fish in coastal applications or endangered species in or near project areas

State stakeholders often include state agencies that focus on surface water, groundwater, health, land management, and wildlife or natural resources. At the local level, government stakeholders typically include county flood control agencies, municipal water suppliers, and municipal building departments.

Native American tribes — Tribal governments are sovereign entities. In many parts of the U.S., native tribes have specific rights to both surface water and groundwater supplies. In the case of a MAR project on tribal land, the tribe may be the stakeholder. Tribal government and community interests in MAR projects may align with early project stakeholder engagement actions, particularly in consideration of Traditional Ecological Knowledge—spiritual and legal connections of Indigenous peoples to the ecosystem, waters, and land within MAR project regions. Historic issues surrounding tribal governance and rights may present environmental justice concerns where MAR projects are proposed on tribal land.

Water districts and utilities — Water districts and utilities often have jurisdictional control over recharge operations. Special utility districts are often established with the primary purpose of replenishing groundwater supplies and levy a fee on groundwater users to replenish local aquifers. Utilities are also an alternative source of water and include wastewater treatment plants and stormwater utilities.

Water right holders — All types of water rights holders in states with a prior appropriation water rights doctrine will likely be stakeholder in MAR proposals; they include senior hydroelectric power, industrial, municipal, agriculture, ecological, and domestic water rights holders. This includes any water rights holder if they believe the MAR project could change or impact their ability to exercise their right, whether it’s surface water, groundwater, or springs. Junior water rights holders may also try to take a position if they feel the proposed MAR project could impact their water use.

Agricultural — In general, agricultural stakeholders and interests are supportive of MAR projects, because they improve drought resilience. However, there can be negative consequences from MAR projects, including rising groundwater elevations resulting in impacts to crops and impacts on existing irrigation wells from MAR extraction wells, as well as possible soil and groundwater salinization. Costs to deal with infrastructure maintenance (for example, siltation, erosion), perceived risk to farmers’ land, and perceived risk of losing control of how they operate their property are negative incentives for agricultural stakeholders.

Commercial and industrial — Commercial and industrial stakeholders can have varied interests in a MAR project that range from positive impacts on water supply wells to negative impacts on groundwater contamination plumes. For example, if a MAR project changes or increases the extent of an existing groundwater plume, the costs to mitigate the plume may increase. Contamination liability may be a concern in some circumstances; therefore, due diligence in understanding potential pollutants mobilization and liability risks should be addressed in the MAR project process. MAR can also be an asset in helping to hydraulically control plume migration and dilute contaminant concentration.

Rural domestic and small water systems — MAR can have a positive impact on rural domestic users by stabilizing and increasing groundwater storage or raising groundwater level, therefore reducing cost for domestic well pumping and removing the need from well deepening. Negative impacts can include excessive increases in groundwater levels and ground saturation. MAR can also positively or negatively impact groundwater quality in private wells.

Nongovernmental organizations (NGOs) — Environmental NGOs may have interests in coastal water fishery enhancement, wetlands creation, resource conservation, or wildlife conservation, among others.

Environmental justice-impacted communities — MAR projects should be conscientious about environmental justice concerns when identifying and including environmental justice–impacted communities. Possible negative impacts of MAR projects should also be carefully evaluated. In recent years, awareness about the impact of infrastructure-related water projects on communities has been growing, though there is still more to understand. Changes to water management approaches, such as those that can occur with MAR, can sometimes benefit one community, while other communities may encounter negative, unintended effects such as water shortages, flooding, water contamination, or other consequences. Changes should be made only after thoughtful planning and engagement with affected communities.

2.4.2 Environmental Justice

Environmental justice (EJ) issues might arise from purposeful changes to groundwater management. While there are many definitions of EJ, one that has been used relative to MAR is:

Environmental justice is defined as the fair treatment and meaningful involvement of all people, regardless of race, color, national or ethnic origin, disability, gender identity or sexual orientation, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies, with no group bearing a disproportionate burden of environmental harms and risks (USACE 2023).

Fair treatment means that no population bears a disproportionate share of the negative environmental consequences resulting from, in this case, the implementation of a MAR program. Meaningful involvement requires effective access to decision makers for all, and the ability in all communities to participate in informed decisions and take positive actions that will be equitable for all involved. One example is when the Texas Commission on Environmental Quality (TCEQ) provided interpretation and translation services at public meetings to ensure better participation and understanding of the meeting content (TCEQ Environmental Law Division 2021). Additionally, recently issued rules and guidance in Texas require most permits (air, water, waste) to include alternative language translations for people who don't speak English. These examples illustrate ways to facilitate more engagement but are just first steps in interacting with a community.

2.5 Regulatory Considerations and Permitting

Implementing MAR projects requires permitting and compliance with various federal, state, and local regulations, depending on the nature of the project. These permits are varied and typically can range from broad federal environmental regulation and permitting—for example, National Environmental Policy Act, state water resources and health department permitting, local and county construction permits, Clean Water Act permitting through the USACE (for example, Section 404 and Section 10), and SDWA permitting through states with primacy and/or the USEPA (UIC permits, Groundwater Rule, drinking water minimum standards, state-specific rules). The USEPA developed regulations applicable to recharge wells and basins through its underground injection control (UIC) regulations. UIC rules are designed to ensure the safety of underground sources of drinking water (USDW). If a USDW is not impacted, recharge wells can be authorized by regulatory agencies without requiring a permit. Permits may be required to ensure that a USDW is not endangered by operations. More information can be found at the USEPA UIC website: Protecting Underground Sources of Drinking Water from Underground Injection (UIC) | USEPA (USEPA 2023d).

Currently, thirty-one states and three territories have primacy for multiple well classes under UIC. USEPA manages all well classes for seven states and the District of Columbia. Most MAR projects fall under Class V wells for UIC regulation. For a complete listing of states, tribes, and territories with primacy and which well classes are covered under the primacy, see the USEPA Primary Enforcement Authority for Underground Injection Control website: Primary Enforcement Authority for the Underground Injection Control Program | USEPA.

States and tribal governments with primacy may enact additional regulations for MAR projects. State/tribal regulations do not supersede federal regulations precluding USDW endangerment. Federal regulations state: "no owner or operator shall construct, operate, maintain, convert, plug, abandon, or conduct any other injection activity in a manner that allows the movement of fluid containing any contaminant into underground sources of drinking water, if the presence of that contaminant may cause a violation of any primary drinking water regulation under 40 CFR part 142 or may otherwise adversely affect the health of persons" (40 CFR 144.12L).

MAR permitting can range from relatively straightforward to complex depending on the project location, source water characteristics, target aquifer, water rights, and intended use of the recovered groundwater. Two hypothetical examples, one in a rural setting and the other in an urban setting, highlight this range of complexities that may be encountered in permitting a MAR project.

Flood-MAR — Flood-MAR has become an important method for recharging depleted aquifers, particularly in rural areas (KRCD 2021). This method involves flooding farm fields with excess surface water to promote recharge (also known as agricultural MAR). Permitting can include the Army Corps of Engineers to access river flows, environmental permitting, flood control districts, and local or state groundwater agencies. Typically, no pretreatment of the surface water is required.

Recharging public supply aquifer with ATW — MAR using ATW is often a complex permitting challenge. These MAR projects are typically used in urban settings where a source of treated wastewater is available. Often these projects involve multiple state and local agencies and require complex studies that include:

- detailed water chemistry studies
- evaluation of subsurface residence times for the treated wastewater using tracer studies and/or groundwater models
- public participation
- construction permits
- rights-of-way permits to construct pipelines and other infrastructure
- potential impact to existing groundwater plumes
- detailed monitoring systems
- pilot and demonstration studies

Regulatory considerations are project-dependent and will likely continue to evolve over time at the federal, state, and local level. More information on state regulations regarding the use of recycled water in MAR can be found in USEPA's Water Recycling for Climate Resilience through Enhanced Aquifer Recharge and Aquifer Storage and Recovery report.

2.6 Pilot Testing

It is always good practice to design and implement a pilot testing program, and it is important to check with state regulators about proposal and approval processes before beginning a pilot testing program. The purpose is to test the planned program along with alternatives at a smaller scale to evaluate both the effectiveness of the MAR program and any possible negative impacts on the environment, particularly the receiving aquifers. Careful monitoring and study during the pilot program will provide the necessary data and increase the likelihood that the final program will be successful. In some states, submitting results to state regulators will be required or encouraged.

Each state will have both local and state, and often federal, requirements to implement a pilot testing program, as well as a final program. One of the keys to success is to engage as early as possible the regulatory personnel so that the requirements and possible hurdles are understood and discussed in the beginning. Some of the agencies that will be involved in the permitting process include those that oversee the water rights in the state, the division of environmental quality or protection that oversees the protection of the groundwater resources, and the division of drinking water that oversees public drinking water supplies. There may be federal agencies involved, such as the USFS, USFWS, and USEPA.

2.7 Operations, Maintenance, and Monitoring (OM&M)

During the planning process and after the implementation of a final MAR program, the ongoing OM&M efforts will require planning and execution. Planning and budgeting will vary depending on the type of MAR implementation. For example, surface infiltration has a set of maintenance requirements that differs from those of direct injection to the aquifer.

An OM&M manual is needed in most cases, including simple and complex MAR projects. Below are some possible OM&M items that should be considered for ongoing effectiveness of the MAR project:

- well monitoring and maintenance (injection well fouling, redevelopment)
- infiltration basin clogging and cleaning
- system design and performance monitoring (infiltration rates)
- routine surface water and groundwater quality monitoring
- mitigation of water quality issues

Automated systems may be able to handle much of the monitoring and control, but oversight is still required. Periodic review and updating of the OM&M manual are also necessary to ensure that information is current and best practices are included.

3. Managed Aquifer Recharge Overview

The objective of this section is to provide an overview of all aspects of MAR projects. This section has been organized into the following subsections:

- Section 3.1 —Intended Use of MAR. The first step in any MAR project is to define the intended use (objective) that the project will be designed to accomplish. Section 3.1 includes a list of examples of MAR intended uses. A MAR project might, in some cases, have more than one use or objective.
- Section 3.2 —Source Water. All MAR projects must have a source of water that will be used to recharge the aquifer. Section 3.2 includes a list of potential sources of water and an overview of their advantages and disadvantages.
- Section 3.3 —Receiving Aquifer. Section 3.3 presents a list of considerations for evaluating the feasibility/suitability of a receiving aquifer for MAR and the potential concerns that could arise.
- Section 3.4 —Recharge Technologies. Section 3.4 contains short descriptions of several MAR technologies that are covered in greater detail on fact sheets in Section 4.
- Section 3.5 —Water Quality Considerations. Water quality considerations can have a substantial impact on the feasibility and/or success of a MAR project. In addition to the potential for introducing contamination to an aquifer, a MAR project could also result in undesirable geochemical reactions that can degrade the performance of the system. These issues are discussed in more detail in Section 3.5.
- Section 3.6 —Data and Modeling. Section 3.6 includes a discussion of data needs and modeling for MAR projects. Data needs may include review of existing data or acquisition of project-specific data. Important considerations for modeling include defining the model objectives; types of models; a summary of the approach, which includes the data used, the conceptual site model, and the numerical/analytical modeling; and modeling limitations.

3.1 Intended Use of MAR

MAR is being used in many novel and innovative ways to solve complex water supply problems and manage water resource challenges. In this section, real-world examples of how MAR has been applied to various intended uses are presented and discussed. More in-depth case studies can be found in Section 5. The MAR intended uses covered in this document include water supply resilience, improving groundwater quality, mitigation against saltwater intrusion, use of stormwater, use of floodwater, subsidence reduction, and protection of riparian ecosystems/maintenance of minimum streamflow.

3.1.1 Water Supply Resilience

Water supply resilience is the ability to recover from disruptive events such as droughts and floods and adapt to future uncertainty. MAR has significant potential to provide water supply resilience for the public, industrial, and agricultural use sectors in areas where the demand exceeds the available water supply due to overuse of groundwater resources and climate change. For some systems, MAR is the only means by which users will be allowed to withdraw additional water during peak demand periods. MAR is enhancing water supply resilience in many parts of the world (Dillon et al. 2021). The following provide some examples:

- California continues to plan and construct numerous regional-scale MAR projects to enhance water supply. These projects, in addition to those in existence for decades, are a response to a groundwater overdraft of approximately 81 million acre-feet that has been in the making since 1962 (Dahlke et al. 2018). Under the 2014 Sustainable Groundwater Management Act, new groundwater sustainability plans submitted to the state propose more than 2.5 million acre-feet of MAR annually, at a projected capital cost of $3 billion (Parker, Alley, and Job 2022). In addition to common MAR types such as injection wells and infiltration basins, the state is investigating an emerging MAR type known as Flood-managed aquifer recharge (Flood-MAR) (see Section 3.1.5) that involves the winter flooding of agricultural fields using existing irrigation infrastructure and available surface water resources (Dahlke et al. 2018). As recently as 2023, California used the abundant rainfall from winter storms to recharge aquifers through a flooding process by capturing water from the San Joaquin River and allowing it to soak into areas of the Central Valley. This will allow the water to be available for longer term use (James 2023).

- Wildwood, New Jersey, is a resort town on a barrier island that experiences a large influx of tourists in the summer. The water utility withdraws groundwater from wells located 5 miles inland of the island. Supplying the island's summer water demands from those wells would require a large pumping facility, a water treatment facility, and transmission lines that would be used to a much lesser degree during the offseason. To avoid the high costs of developing this system, groundwater pumped from the inland wells is injected via wells located on the island into saline aquifers beneath the island, where it forms a lens of good-quality water for later recovery from the same wells. The system has operated since 1967 (Lacombe 1996), making it one of the oldest aquifer storage and recovery (ASR) projects in the country.
- The Des Moines (Iowa) Water Works has implemented ASR to provide an additional source of water to (1) meet peak demands on its water system and (2) overcome challenges related to seasonally high nitrate concentrations in its surface water sources. Treated drinking water is injected into a deep bedrock aquifer for later recovery. Case Study 5.11 describes this system in more detail.
- In monsoonal northern India, recharge wells are being used at a pilot scale to inject water from village ponds to replenish alluvial aquifers in an intensively groundwater-irrigated, flood-prone area. In Ramganga Basin, adjacent to an irrigation canal, an unused village pond in clay soil was equipped with 10 recharge wells, and volumes and levels were measured over each wet season for 3 years. Recharge averaged nearly 14 million gallons per year at an average rate of 153,000 gallons per day over 3 months each year, enough to irrigate a 20–44 acre dry season crop (Alam et al. 2020). This was up to nine times the recharge without wells.

3.1.2 Improving Groundwater Quality

MAR can be used to improve groundwater quality. If the native groundwater in the receiving aquifer has exceedances of one or more drinking water MCLs, the concentrations of these contaminants could be diluted below the MCLs via the addition of cleaner source water. For a simple example, if fresh water with a chloride concentration of 50 mg/L is injected into a brackish aquifer with a chloride concentration of 400 mg/L, a blend of 43% injected water and 57% native groundwater would meet the 250 mg/L secondary MCL for chloride (Maliva and Missimer 2010). The advantage of mixing the two waters rather than simply using the fresh water directly is that the volume of recoverable blended water that meets the MCL may exceed the volume of injected fresh water, thereby increasing the available supply.

A word of caution, however, is needed. At times, geochemical incompatibility among water sources can result in unintended outcomes. For example, arsenic or manganese can be mobilized if the source waters are not compatible, resulting in degraded water quality. Careful consideration and planning are needed. See Section 3.5.1 for more discussion of geochemical compatibility. Case Study 5.2 describes a successful pilot project for a pretreatment system designed to reduce arsenic mobilization in ASR systems in Florida.

3.1.3 Mitigation Against Saltwater Intrusion

Groundwater withdrawals in coastal areas may induce the inland movement of saline water into freshwater aquifers, which results in a reduction in the usable volume of fresh water and the abandonment of wells due to saline water contamination. The use of MAR to mitigate saltwater intrusion involves the injection of freshwater landward of the saline water, which increases the freshwater head in the aquifer to the degree that saline water is prevented from moving inland. Injection recharge technologies have typically been used to address saltwater intrusion; however, unconfined aquifer recharge technologies may also be appropriate. Examples of large-scale saltwater intrusion barriers using MAR are listed below:

- The Los Angeles County Flood Control District constructed three seawater intrusion barriers to protect and replenish the groundwater supplies of a large coastal aquifer located in southern Los Angeles County, California. In total, the barriers are approximately 17 miles long and include hundreds of injection wells completed in multiple aquifers of the Central and West Coast Basins. Nearly 2 million acre-feet of water (both imported and advanced treated recycled water) have been injected into the barrier system to protect and replenish the inland aquifers since commencing operations in the early 1950s. This project is discussed in more detail as Case Study 5.3.
- The Floridan Aquifer in Hillsborough County, Florida, along the coast of the Gulf of Mexico, is the principal source of water in the region for agriculture, phosphate mining, and municipal supply. Historically, groundwater withdrawals to supply these uses have far exceeded the sustainable yield of the aquifer. This has resulted in saltwater intrusion from the Gulf of Mexico that has caused the abandonment of many coastal agricultural irrigation wells. In 2009, Hillsborough County Utilities began investigating the injection of highly treated reclaimed water to act as a barrier to saltwater intrusion and restore aquifer water levels. The county developed

two direct aquifer recharge pilot projects along the coast that pump reclaimed water into the saltwater zone that separates the saline water beneath the gulf from the fresh water in the aquifer. The recharged water creates a barrier that prevents saltwater intrusion into the aquifer and impounds fresh water in the aquifer several miles inland. This improves groundwater levels upstream of the area of reclaimed water recharge, which may allow for additional inland withdrawals of fresh groundwater. This project is discussed in more detail in Case Study 5.7.

3.1.4 Use of Stormwater

MAR can be used in certain situations to manage urban stormwater. As an alternative to constructing underground stormwater conveyance systems, a gravity drainage well system like most commercially manufactured stormwater devices can be developed to convey stormwater from collection areas on the surface into highly permeable aquifers. Gravity drainage wells are classified by the USEPA as Class V injection wells, which are wells used to inject nonhazardous fluidsinto or above a USDW. Because water is recharged to a USDW, water quality must generally meet or exceed the quality of the native groundwater in the aquifer. Stormwater treatment can be integrated into the design of the collection system to ensure suitable source water quality.

One of the most important aspects of stormwater systems in limestone aquifers is the safeguards put in place to ensure that sinkholes are not enlarged or created by the movement of stormwater into the aquifer. Sinkholes have occurred in stormwater systems overlying limestone where the infiltration of stormwater has caused soil within cavities in the limestone surface to erode out, resulting in destabilization and collapse of the overlying land surface. This problem can be avoided by casing the gravity wells through the sensitive soil/limestone interface, well into the limestone bedrock where erosion of soil cannot occur, and by monitoring water levels during storm events to ensure they do not rise into the soil/limestone interface where the soil in voids can be eroded. In certain cases, however, more or larger sinkholes may be desirable to infiltrate larger volumes.

Examples of MAR stormwater management systems include the following:

- The Los Angeles County Flood Control District operates 27 spreading grounds, which are large open areas that can be inundated (Los Angeles County Public Works 2023). The spreading grounds, which have been in use for stormwater conservation and flood control purposes since 1917, are generally located in areas containing predominately coarse-grained sediments that allow water to drain quickly into the subsurface, thereby replenishing groundwater supplies in multiple basins located in southern Los Angeles County. The amount of water conserved can be extremely beneficial to the local aquifers and is often a significant source of replenishment. This helps support local groundwater supplies for over 4 million people. The annual stormwater contribution to the spreading grounds (less imported and recycled water) is approximately 42% (Johnson 2007).
- A stormwater MAR system in the Philadelphia, Pennsylvania, area serves a mixed-use development of 130 acres (Lolcama et al. 2015). The system injects treated stormwater into limestone bedrock, while ensuring the stability of buildings, roads, and infrastructure is not compromised by sinkhole formation. The system has a disposal rate over 10,000 gallons per minute for the duration of a 2-year storm event and recovers quickly to allow the system to be reopened for injection of additional runoff. Stormwater gravity-flows into the bedrock through an interconnected piping network that recharges 19, 12-inch diameter Class V injection wells, drilled to depths of up to 135 feet and spaced within a 3-acre footprint. The water table throughout the well field is monitored automatically, and the level is manipulated by small adjustments to the recharge rate.
- Another example is approximately 150 drainage wells in Orlando, Florida, that are used to help manage stormwater. While this adds water to the Floridan Aquifer, water quality concerns, including infiltration of pollutants, need to be considered and managed. In some cases, natural filtration through the soil or through wetlands helps to improve water quality (City of Orlando 1991).

3.1.5 Use of Floodwater

Flood-managed aquifer recharge, or Flood-MAR, can help reduce flood risk and boost groundwater supplies on a regional scale. The Flood-MAR concept involves the collection of high-flow floodwaters and their conveyance downstream where they are spread across the land to create bird and terrestrial habitat, support agricultural activities, recharge depleted aquifers, and increase flows into adjacent streams or rivers. The recharge process also enhances water supply resilience, reduces flood risk, and increases drought preparedness. In California, aquifer recharge through Flood-MAR helps offset overdevelopment of groundwater, which provides 40% of the state’s water supply in a typical year (and up to 60% in a dry year), while acting as an important buffer against drought, the effects of climate change, and land subsidence. In contrast to the spreading grounds mentioned in the previous section, which are lands set aside specifically for groundwater recharge, Flood-MAR typically uses fallow agricultural fields or other working landscapes that are not dedicated recharge locations.

The potential for Flood-MAR in California is very significant in the Central Valley, which has high flood risks and is experiencing severe groundwater depletion and reduced water supplies as a result of the recent historic drought. Increasingly, dry wells are being used in conjunction with the traditional practice of flooding agricultural land (also known as agricultural MAR). The Mustang Creek Case Study 5.8 highlights this concept.

In addition, Westlands Water District, a very large agricultural operation in the Central Valley, is in the process of converting 400 agricultural production wells to ASR wells so that when excess water is available it can be stored deep underground and then recovered from the same wells during dry periods and droughts (Westlands Water District 2019). Flood flows from the Kings River make up a portion of the source water for this project.

3.1.6 Subsidence Reduction

Land subsidence often results from compaction of compressible confined aquifer systems (both aquifers and confining units) resulting from over pumping of groundwater and the accompanying reduction of artesian pressure. MAR has been used with significant success to slow or stop land subsidence in many areas. MAR can mitigate land subsidence through injection wells, which normally require a supply of high-quality surface water. The water can be used to offset the groundwater withdrawals that are producing the subsidence, which contributes to water resilience. As the water supply is recharged to the aquifer, the aquifer acts as the distribution system while also providing significant treatment of the recharged water through natural microbial, geochemical, and physical processes that occur underground.

An important example of subsidence control by injection of water through wells is the Wilmington oil field in Southern California. Repressuring of the oil zones to increase oil production and to control subsidence in the Wilmington field began on a major scale in 1958. By 1969, when 46 million gallons of water per day were being injected into the oil zones, the subsiding area had been reduced from 22 to 3 square miles, and locally the land surface had rebounded by as much as 1 foot (Mayuga, M. N. and Allen, D. R. 1969).

3.1.7 Protection of Riparian Ecosystems/Maintenance of Minimum Streamflow

MAR is being used at several locations in the United States for ecosystem protection and streamflow maintenance. Examples include these projects:

- A study was conducted on the Henry’s Fork of Idaho’s Snake River (Kirk et al. 2020) to evaluate the effectiveness of MAR on maintaining summer streamflow and temperatures for cold-water fish. The Snake River is a highly regulated system that supports agriculture worth $10 billion and recreational trout fisheries worth $100 million. Henry’s Fork receives groundwater from infiltrating agricultural irrigation and MAR operations located approximately 5 miles from the river. Estimates derived from an aquifer model showed a long-term 4%–7% increase in summertime streamflow from annual MAR. Water temperature observations confirmed that recharge increased streamflow via aquifer discharge rather than reduction in river losses to the aquifer. In addition, groundwater seeps created summer thermal refuges. Measured summer stream temperature at seeps was within the optimal temperature range for brown trout, averaging 58°F, whereas ambient stream temperature exceeded 66°F, the stress threshold for brown trout (Kirk et al. 2020). This project is described in more detail in Case Study 5.6.
- Large-scale ASR systems are being developed as a major water storage and management component of the Comprehensive Everglades Restoration Plan in South Florida. The concept is to capture and store large volumes of wet-season inflows into Lake Okeechobee in a series of ASR wells. Water will be recovered from the wells when needed to provide adequate flow for the Everglades ecosystem during drought periods (Mirecki 2022). A decade-long regional study of the concept concluded that a phased implementation of a regional-scale ASR system is feasible and can provide beneficial water storage and availability for Everglades restoration efforts.

3.2 Source Water

Many sources of water are available to use in MAR projects, each with varying advantages and constraints that need to be considered in the context of specific projects. MAR projects can utilize multiple source waters to achieve project goals (for example, the Pure Water Monterey project in California). As depicted on the MAR Process Model, common factors when considering the suitability of source water for MAR projects include the source water origin and availability, source water quality, geochemical compatibility with the receiving aquifer, and regulatory requirements. Water rights considerations can also be important.

Source water quality is a major component of evaluating the feasibility of a MAR project and will limit the methodologies applicable to a project site. Surface infiltration, known as soil aquifer treatment, may be adequate to filter and degrade contaminants under some circumstances, yet local soil, vadose zone, and aquifer properties will affect the suitability and limitations of some potential source waters. As with any application of water to soil, the filtering of contaminants by the soil media can lead to an accumulation of contaminants over time. The sustainability of contaminant loading to soils for a MAR project must be evaluated on a case-by-case basis, as is done in agriculture with metals in biosolids, salts in irrigation water, and other leachable contaminants of concern, such as pesticides or nutrients. Any constituent of concern in the MAR recharge waters or present in the soil must be considered.

Source water quality must also be evaluated in the context of the receiving aquifer, where the mixing of different waters and resulting geochemical interactions can have unintended negative impacts on the aquifer water quality and reservoir characteristics, such as mobilizing in situ contaminants or facilitating various forms of clogging within the aquifer (LRE Water 2021; Martin 2013). Source water quality considerations are discussed in detail in Section 3.5.

A primary consideration when evaluating the feasibility of a MAR project is the proximity or location of source waters in relation to a MAR project area. If sufficient conveyance infrastructure exists between the MAR project and a proposed water source, the timing and volume of water deliveries will need to be negotiated with owners and operators of the existing conveyance infrastructure to ensure project feasibility. In some instances, the new construction of conveyance infrastructure may be economically feasible for long-term or high-value projects. Permanent underground or temporary aboveground pipelines, ditches, and aqueducts are all potential conveyance methods, each with variable capital costs, operational and maintenance costs, lifespans, and permitting and legal considerations. In some instances, water transfers within or between basins may be negotiated, but these complex agreements are made under state-specific legal frameworks, involve significant regulatory and legal oversight, and are often negotiated on an annual basis, which introduces uncertainty to the reliability of available water.

An overview of potential source waters for MAR projects is detailed in the following sections.

3.2.1 Treated Drinking Water

Treated drinking water is a common source of water for ASR projects, a specific type of MAR in which water is banked in an aquifer for later extraction. Excess drinking water can be stored for later use, or high-quality water can be introduced to an aquifer to improve groundwater quality. Treated drinking water must meet all federal MCLs and any applicable state MCLs or other water quality standards. Though the water has been treated, geochemical compatibility is still a necessary component of a feasibility evaluation and a monitoring program. Even when all these requirements are met, the water may also contain emerging contaminants that are not yet regulated. Case Study 5.11, the Des Moines Water Works Army Post Road ASR Well, uses treated drinking water as source water.

3.2.2 Surface Water

Surface water, such as rivers, streams, lakes, or reservoirs, is one of the main water sources for use in MAR projects (Luxem 2017). Case Study 5.9, the Walla Walla Basin Watershed, is one of several case studies that use surface water as the source water. Surface water has highly variable chemistries and can contain a wide array of regulated and unregulated drinking water contaminants, such as various classes of synthetic and natural organic compounds, metals, agrochemicals, pharmaceuticals, industrial chemicals or waste products, halogenated compounds, cyanotoxins, and microbial contaminants, in addition to many other substances.

Some recharge technologies can address or mitigate these water quality challenges, such as surface infiltration methods that take advantage of the filtering properties of soils to reliably remove some of the above listed contaminants. Particulate matter or other physical and chemical properties could impact the feasibility of projects by affecting the porosity of the receiving aquifer under various recharge technologies, such as pore clogging from sediments, pore sealing resulting from high sodium levels in recharge waters interacting with clays in the receiving aquifer, or precipitation reactions from geochemical changes in the receiving aquifer.

Water rights may be a barrier to MAR implementation when utilizing surface waters in overallocated basins, basins with interstate compacts that constrain use or have specialized accounting systems, or priority (prior appropriation) water rights governance systems (see Case Study 5.10). The seasonal and annual variability of surface water availability can also place constraints on MAR projects.

3.2.3 Treated Municipal Wastewater

Treated municipal wastewater can be used as MAR source water. Case Study 5.1, the SWIFT program, uses treated wastewater for source water. Treated wastewater can provide a steady supply of source water, often with less concern from other water users (Luxem 2017), although water rights considerations are still necessary as the legal status of used water can vary between and even within states (Coleman and Education 2014). The degree of wastewater treatment needed for use in MAR projects will depend on the specific MAR application technology (USEPA 2023a). Soil or surface application technologies can take advantage of soil filtration and aerobic microbial activity, while direct injection projects may require treatment beyond Clean Water Act or SDWA standards to remove pathogens and unregulated or emerging contaminants. Microbial pathogens, such as bacteria, viruses, and protozoa, are a primary acute risk to public health in MAR projects, and must be considered and addressed (USEPA 2023a).

Advanced wastewater treatment, such as reverse osmosis, might generate water that exceeds water quality standards, yet require additional considerations. At times, this water might require conditioning before drinking or introduction to the environment or aquifers. Water recycling and direct potable reuse are becoming more common as water scarcity increases, and these more immediate uses may compete with MAR projects for utilization of this water source. Some states, such as Colorado, may limit the number of times water can be reused.

3.2.4 Captured Water

Captured water for MAR is a broad category that can include a variety of water sources, including wet weather flows such as stormwater, floodwater, and snowmelt capture, or other transient waters such as leaking wastewater collection systems, residential or urban irrigation runoff, or other sources. These sources can be rerouted and applied to MAR projects. Stormwater, despite its sporadic and seasonal availability, has become a popular source of water for aquifer recharge because stormwater MAR projects decrease flooding and capture water that is otherwise lost as runoff (Luxem 2017). Case Study 5.8, the Mustang Creek Watershed Dry Well Pilot Study, is an example of a MAR project that uses captured water.

Stormwater quality can be highly variable and dependent upon the origin or delivery method of source waters, in addition to storage and conveyance factors. High total suspended solids (TSS) can result in significant risk of clogging with some MAR application technologies, posing a barrier to implementation with increased costs and infrastructure requirements and treatment requirements, such as settling ponds or other engineered solutions. Additional water quality issues from pollutants picked up by stormwater can pose challenges to using stormwater for MAR. Sufficient storage or conveyance infrastructure may be required to capture and use these short-duration transient water sources.

3.2.5 Industrial Process Water

Water from industrial processes might be useful for MAR projects, depending on the quality and quantity available and reliability of the supply. Many industrial waters are discharged into sanitary sewers, while other facilities treat water onsite to be discharged under the requirements of relevant state and/or federal discharge permits. Utilizing a waste stream as source water may introduce significant risk to the project. Industrial processes are difficult to define and sample, and unregulated or emerging contaminants not currently known to state or federal health agencies could be present in the waste stream. Often, monitoring for harmful contaminants is not done in industrial process water, meaning that the composition of the water’s contaminants might not be fully characterized by standard sampling and reporting requirements. Expensive or cost-prohibitive treatment may be needed to fully address risks. A detailed suitability and risk evaluation should inform the utilization of this water source.

3.2.6 Agricultural Return Flows

Agricultural return flows may be a suitable source of water for certain MAR projects, depending on the water quality. Agricultural nonpoint source pollution, such as runoff from farms, is the leading source of impairments to surveyed rivers and lakes (USEPA 2005). Irrigated lands may produce surface and subsurface agricultural return flows with degraded water quality from suspended solids and other contaminants, which creates an opportunity to repurpose this water in MAR projects in a way that can benefit aquifer recharge while improving surface water quality. States manage and account for agricultural return flows differently, and there may be legal challenges with the utilization of this water source. Agricultural return flows often contain high amounts of nutrients, sediment, microorganisms, and potentially pesticides and herbicides. The water quality considerations would likely make certain MAR technologies, such as direct injection, inadequate for this source of water if the water cannot be treated adequately in a manner that is acceptable and cost-efficient. Case Study 5.10, the Clark Fork River Basin MAR Modeling, is an example of a MAR project that uses agricultural return flows.

3.2.7 Produced Water

Oil and gas produced watersare a substantial waste stream requiring management and disposal, which creates potential economic opportunities to use produced water beneficially. Produced water commonly contains high concentrations of salts, metals, radionuclides, and hydrocarbons (Allison and Mandler 2018). Produced water quality can vary greatly between wells, even across relatively short distances or similar locations within an oil- or gas-bearing formation, and the utilization of this water source requires constant water quality assessment and monitoring to detect changes in water quality and to ensure suitability within specified project parameters. Even so, this water source could be used beneficially in aquifer storage if appropriate water quality criteria are met (Katie Guerra, Katharine Dahm, and Steve Dundorf 2011). For example, treatment allows for beneficial use in Wellington, Colorado, where treated produced water is used in an ASR project (National Research Council 2010, Allison and Mandler 2018).

3.2.8 Dewatering

Dewatering projects could be a source of high-quality water to support MAR projects under certain circumstances. Dewatering can occur in support of construction activities, foundation dewatering, and mining, among others. Some sites require dewatering for extended periods of time (or in perpetuity with certain foundations, remedial controls, or facilities), and the length of time of expected dewatering and volume of water produced will affect the feasibility of this water source for MAR projects. Opportunities for transient, periodic, or seasonal augmentation to existing MAR projects might be feasible from dewatering projects. Site-specific conditions and comprehensive dewatering plans coupled with predictive modeling may be needed to assess long-term impacts to water resources. Detailed characterization of water quality originating from dewatered sites is necessary, as with any MAR source water.

3.2.9 Desalinated Water

Desalinated seawater and brackish groundwater are becoming more feasible as sources of water in MAR projects as water scarcity increases, specifically in ASR applications. Water quality following reverse osmosis and conditioning is suitable for introduction to many drinking water aquifers, although geochemical considerations of the source and receiving waters still require evaluation. Seawater supply is essentially endless in coastal regions and has little if any legal stipulations concerning use, although high-salt waste streams and estuary impacts are a consideration in coastal areas, and in noncoastal areas the disposal of waste streams from reverse osmosis (RO) treatments can increase project costs. Brackish aquifers are somewhat common and are not often used, so legal stipulations concerning water use or rights are rare. The withdrawals of water from any aquifer could have impacts on adjacent aquifers that affect water quality, physical stability, and other considerations; therefore, substantial hydrogeologic investigation into the feasibility and potential impact of utilizing brackish water aquifers may be necessary to investigate a potential MAR project. The removal of brackish or saline groundwater could also create opportunities for ASR projects within the same aquifer, creating more feasible and sustainable projects.

3.2.10 Environmental Remediation Sites

Remediation sites may offer opportunities to source water for MAR projects. Many sites require control of overland flow via stormwater routing or capture, and many sites require groundwater pumping to capture or manage flow rates and directions of contaminant plumes or prevent uncontaminated groundwater from migrating into cleanup areas.

Some remedial sites have onsite treatment in place where regulated effluents are of sufficient quality to allow for discharge to sanitary sewers or under a National Pollutant Discharge Elimination System (NPDES) permit, and in such cases the effluent may require little additional treatment for use in MAR projects. The feasibility of sourcing water from remedial sites will be site-specific and will likely require significant efforts to coordinate and evaluate the suitability, liabilities, and risks for use in MAR projects. State and federal agencies that operate or oversee these sites would be the primary stakeholder and could be engaged on the feasibility on a case-by-case basis.

3.2.11 Groundwater Transfers

Transferring water from underused aquifers to MAR project sites may be feasible in some instances. Typically, groundwater-to-groundwater transfers are not practical because the withdrawal and conveyance of waters from one aquifer is expensive and can be directly used, but special circumstances and project goals may warrant groundwater-to-groundwater transfers. Case Study 5.4, the San Antonio H2Oaks ASR Project, is an example of a groundwater-to-groundwater transfer, as is the Wildwood, New Jersey, example described in Section 3.1.1. Another example is Colorado’s Augmentation Plans (Colorado DWR 2023), which are a broad category of water operations designed to increase supplies of water for beneficial use. Augmentation Plans allow junior (out of priority) water rights holders in over appropriated basins to divert water if they can provide a replacement water supply to senior water rights holders. The replacement water supply could involve moving water from one aquifer to another, and in this case the groundwater from the first aquifer would be the source water for a MAR project that recharges the second aquifer.

3.3 Receiving Aquifer

There are many considerations that are important to the evaluation of the receiving aquifer and the selection of MAR technology to accomplish the intended use. The parameters described in the following subsections should be considered.

3.3.1 Aquifer Classification

The choice of MAR technology may depend on the type of aquifer available. Aquifers are broadly classified into two categories: unconfined and confined (Freeze and Cherry 1979). Figure 3-1 is a conceptual illustration of unconfined and confined aquifers.

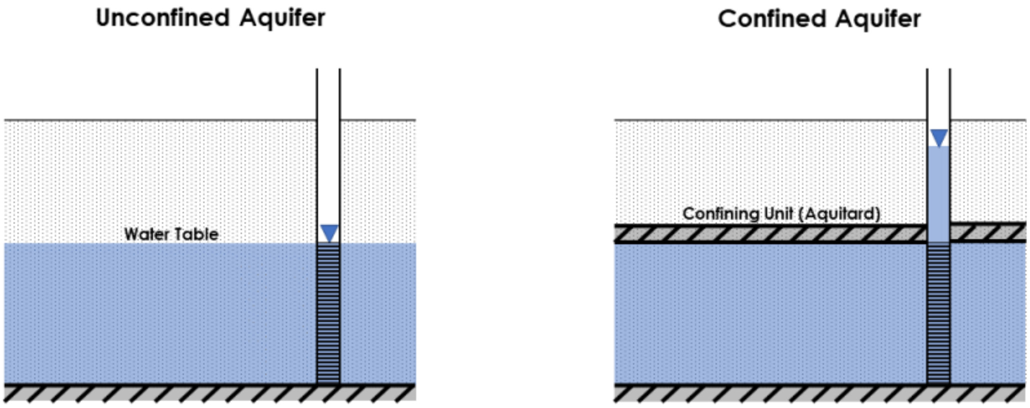


Figure 3-1. Conceptual illustration of unconfined and confined aquifers.

The top of an unconfined aquifer is the water table. MAR technologies that involve the percolation of source water through the vadose zone, such as infiltration basins, can only be used with unconfined aquifers. Lenses of low-permeability materials located in the vadose zone can impede recharge from the land surface to unconfined aquifers. In this situation, dry wells can be used to penetrate the low-permeability lenses and facilitate percolation below them.

Confined aquifers are bounded above and below by low permeability confining units. The water in confined aquifers is pressurized, as illustrated on Figure 3-1 by the water level in the well rising above the top of the aquifer. Because the aquifer is pressurized and the overlying confining unit impedes recharge via percolation, MAR projects that utilize confined aquifers must inject the source water directly into the aquifer.

3.3.2 Aquifer Lithology and Structure

The aquifer matrix can be composed of unconsolidated deposits, such as sand and gravel, or bedrock formations, such as sandstones or limestones. Unconsolidated deposits and clastic sedimentary rocks (for example, sandstones) are typically porous media aquifers, meaning that groundwater flows through the pore spaces between individual grains of the aquifer matrix. Due to the tortuous paths the water must take around individual grains, groundwater flow velocities in porous media aquifers are slow, on the order of feet per year (Alley, Reilly, and Franke 1999). Carbonate rocks (for example, limestones) and crystalline rocks (for example, granite) typically have very low primary porosity and can only function as aquifers if they are sufficiently fractured. Groundwater flow velocities can be much higher in fractured rock aquifers than porous media aquifers because the flow channels are much larger in diameter and the flow paths are more linear. Preferential flow paths along fractures could be beneficial to a MAR project by allowing more rapid infiltration, but the complexity of fractured rock systems may result in unexpected flow directions or detrimental impacts (Nicolas et al. 2019).

Karst aquifers are a special case of fractured rock aquifer in which dissolution of a carbonate rock matrix has opened large voids and caverns, sometimes resulting in the formation of sinkholes. MAR has the potential to enhance dissolution of carbonate rocks; chemical interactions between source water and rock are discussed in more detail in Section 3.5.

3.3.3 Storage Potential

The receiving aquifer must have sufficient storage potential (available volume) to accommodate the proposed project. Groundwater modeling, discussed in more detail in Section 3.6, is a useful tool for evaluating receiving aquifer storage potential for both unconfined and confined aquifers. Storage potential is mostly a function of the physical properties of the aquifer. Poor native groundwater quality does not automatically render an aquifer unsuitable for MAR. For example, many ASR projects utilize brackish or saline aquifers. The development of a “buffer zone” in the aquifer maintains separation between the stored fresh water and the native saline water.

Important aquifer properties that affect the storage potential are:

- thickness and areal extent
- depth to water table (for unconfined aquifers)
- specific yield (for unconfined aquifers)
- specific storage
- hydraulic conductivity (in both the horizontal and vertical directions)
- Pressure head (for confined aquifers)
- Water budget (especially existing discharges to wells, surface water, and phreatophytes)

3.3.3.1 *Unconfined Storage Potential*

When water is recharged to an unconfined aquifer, the water table rises and moves into pore space that was previously occupied by air. The locally higher water table near a recharge area is referred to as a groundwater mound, and the height of the mound is a function of the recharge rate, the specific yield, and the hydraulic conductivity of the aquifer (Carleton 2010). If the hydraulic conductivity and specific yield are low compared to the recharge rate, water mounds up at the recharge site because it is being added to the aquifer faster than it can flow away and only a small volume of pore space is available. Conversely, when the hydraulic conductivity and specific yield are high compared to the recharge rate, reduced mounding occurs because water can quickly flow away from the recharge site and ample pore volume is available for storage. Excessive mounding may result in undesirable outcomes, such as basement flooding or damage to existing subsurface infrastructure from uplift pressure, so it is critical to understand how much mounding will occur at a recharge site. Seasonal water table fluctuations must also be considered when estimating an acceptable level of mounding.

3.3.3.2 *Confined Storage Potential*

Storage for injected water in confined aquifers is created by a combination of displacing existing water in the aquifer, expansion of the aquifer pore space due to increased pore pressure, and compression of the water, also due to increased pressure. The aquifer hydraulic conductivity is the primary control on how high the injection pressure needs to be in order to force the source water into the aquifer. Highly compressible aquifers (large specific storage) may experience heaving due to the increased aquifer pressure near the injection site. The confining units that bound a confined aquifer, though much lower permeability than the aquifer, are sometimes permeable enough to transmit appreciable quantities of water; therefore, the increased pressure in the receiving aquifer due to injection can cause the migration of water from the receiving aquifer into adjacent aquifers.

When injecting into bedrock aquifers, excessive injection pressure may induce seismicity (see Section 3.3.4) or cause fracturing that can compromise adjacent confining units and lead to migration of water into other aquifers. UIC regulations prohibit injection pressures that would exceed the pressure level that could cause fracturing at a given depth (the fracture gradient). The potential for this should be evaluated when considering MAR options.

3.3.4 Impacts to Existing Conditions/Uses

Effects on existing groundwater users—Existing groundwater users located near a MAR project could experience positive or negative effects. For example, enhanced water quantity from MAR may benefit existing groundwater users, but new pumping wells installed to recover the recharged water could adversely affect existing wells. Changes to aquifer water quality resulting from MAR could be beneficial or detrimental. Modeling, discussed in Section 3.6, is commonly used to evaluate potential effects from a proposed MAR project on existing groundwater users.

Effects on surface water features—Surface water features such as rivers/streams, springs, and wetlands are often hydraulically connected to aquifers, and therefore the use of these aquifers as receiving aquifers for MAR may result in impacts to surface water. These impacts may be positive, such as increased streamflow or spring discharge, or negative, such as degraded water quality at springs. In some cases, impacts to surface water may be the MAR intended use. Case Study 5.9, the Walla Walla Basin Watershed, is an example of a project where MAR is used to augment streamflow.

Existing aquifer restrictions—Aquifers may have existing restrictions intended to preserve water quantity and/or quality; for example, the USEPA’s Sole Source Aquifer program exists to prevent contamination of aquifers that supply at least 50%

of the drinking water of their service area (USEPA 2022c). In such situations, MAR projects may explicitly be prohibited or would be subject to additional review and requirements.

Proximity to known contamination—Changes to groundwater flow and direction resulting from a MAR project could impact the size and shape of an existing contamination plume and potentially affect the performance of an existing remediation system. If a MAR project enlarges an existing plume, the MAR project owner could potentially be held liable for increased cleanup costs under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) or be subject to other legal action. Groundwater modeling can be used to evaluate potential impacts to existing plumes and remediation systems from a proposed MAR project. As noted in Section 3.2.10, there may also be potential to incorporate MAR into a pump-and-treat remediation system by using the effluent as a MAR source water.

3.3.5 Geotechnical Considerations

Slope stability—Upland regions are often natural recharge areas for aquifers and may be promising locations for MAR projects to augment the natural recharge. However, enhanced recharge in proximity to steep slopes in upland areas could cause slope failures due to the changing position of the water table. For this reason, screening analyses for MAR projects (for example, Aju et al. 2021) have included slope stability in their criteria for identifying suitable recharge sites.

Heaving/subsidence—As mentioned in Section 3.1.6, MAR is a strategy for mitigating subsidence caused by compression of confining units and confined aquifers in response to pumping. Heaving is the opposite of subsidence, and heaving could be desirable when the intended use of MAR is subsidence mitigation. Heaving could also be an undesirable side effect of a MAR system that involves injection into confined aquifers, though it is not likely due to the low injection pressures typically associated with MAR projects. New pumping wells installed as part of a MAR project could also cause subsidence if located in a susceptible area.

Seismicity—Injection wells, particularly those used for hazardous waste disposal (UIC Class I) and in oil and gas operations (UIC Class II), have been implicated as the cause of numerous earthquakes (Nicholson and Wesson, 1990; Douglas and Baddour 2022). The increased fluid pressure from injection (typically hundreds of pounds per square inch) may cause faults or fractures to slip. Compared to Class I and Class II wells, which must be very deep to be located below the deepest USDW, MAR injection wells typically target shallower, more permeable receiving aquifers and can therefore operate at lower pressures, which reduces the risk of triggering seismic activity. While no MAR project has yet been linked to injection-induced seismicity (Conley et al. 2022), the potential for seismicity should be evaluated nonetheless, especially if known faults exist near a proposed MAR injection site.

Liquefaction—Mounding due to MAR may increase the risk of liquefaction in seismically active regions. The potential for liquefaction is a function of the water table depth and the subsurface material composition. The liquefaction risk increases as the water table approaches the land surface (Chung and Rogers 2013) and saturates sandy soils.

3.4 Recharge Technologies

Multiple technologies are available to recharge the receiving aquifer with the source water. This section includes conceptual schematics and brief descriptions of five of the most common recharge technologies. More detailed fact sheets for each of these five technologies are included in Section 4. Selection of the most appropriate recharge technology for a MAR project is typically a component of the project’s feasibility study (see Section 2.2).

3.4.1 Infiltration Basin

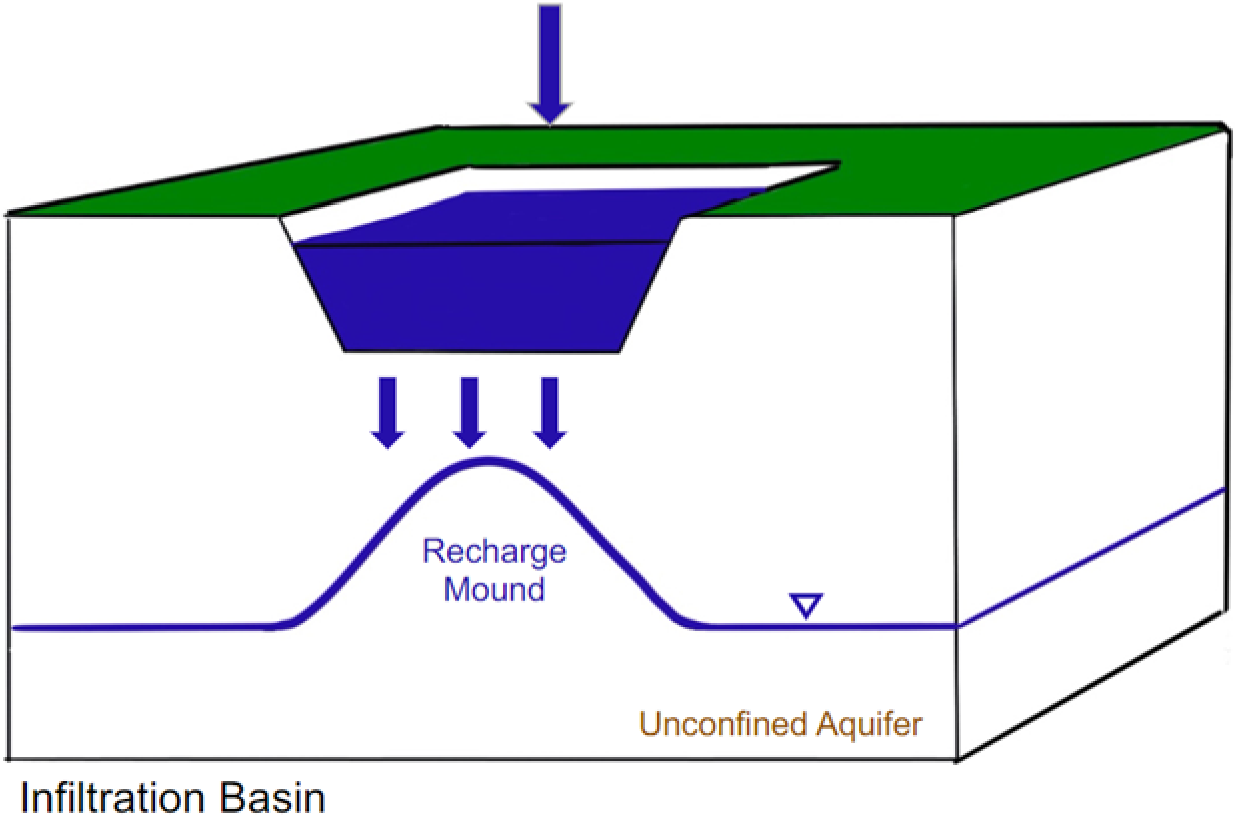


Figure 3-2. Infiltration Basin

Infiltration basins are surficial ponds that are used for percolating water into unconfined aquifers. These basins are typically excavated or bounded by earthen berms and can receive water that can vary in quality and quantity over time, such as stormwater. The size of the basin and the permeability of the underlying soil are key controls on the infiltration capacity. Infiltration basins can be cost-effective when compared to other recharge technologies, though they must be sized adequately and can be prone to clogging and water table mounding. An advantage of infiltration basins is that they can provide secondary benefits such as addressing stormwater management requirements and serving as aquatic habitat for migratory birds.

3.4.2 Retention and Diversion Structures

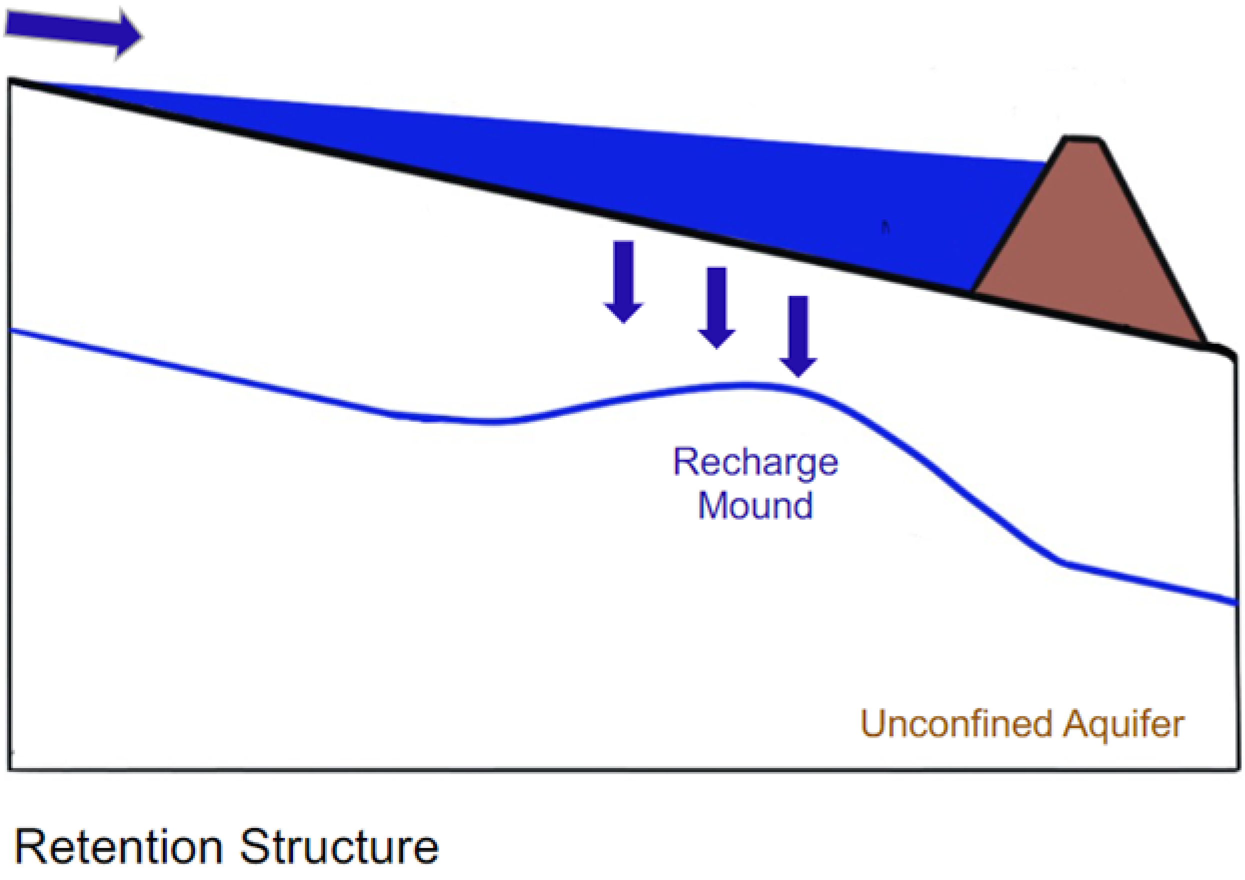


Figure 3-3. Retention Structure

In addition to constructed infiltration basins, it is also possible to use native features such as sinkholes, fractures/faults, losing reaches of streams, seasonal wetlands, or highly permeable soil systems as infiltration locations to recharge unconfined aquifers. Retention and diversion structures are used to integrate native features into MAR systems. Retention structures are constructed within existing channels and are designed to capture available runoff behind a dam or weir so that water can infiltrate through the streambed into an unconfined aquifer. Diversion structures are built to direct MAR source waters to native features for infiltration. Retention and diversion structures can be very cost-effective because they use existing native features instead of completely new construction; however, the reliance on native features and environmental permitting requirements can limit where they can be used.

3.4.3 Injection Well

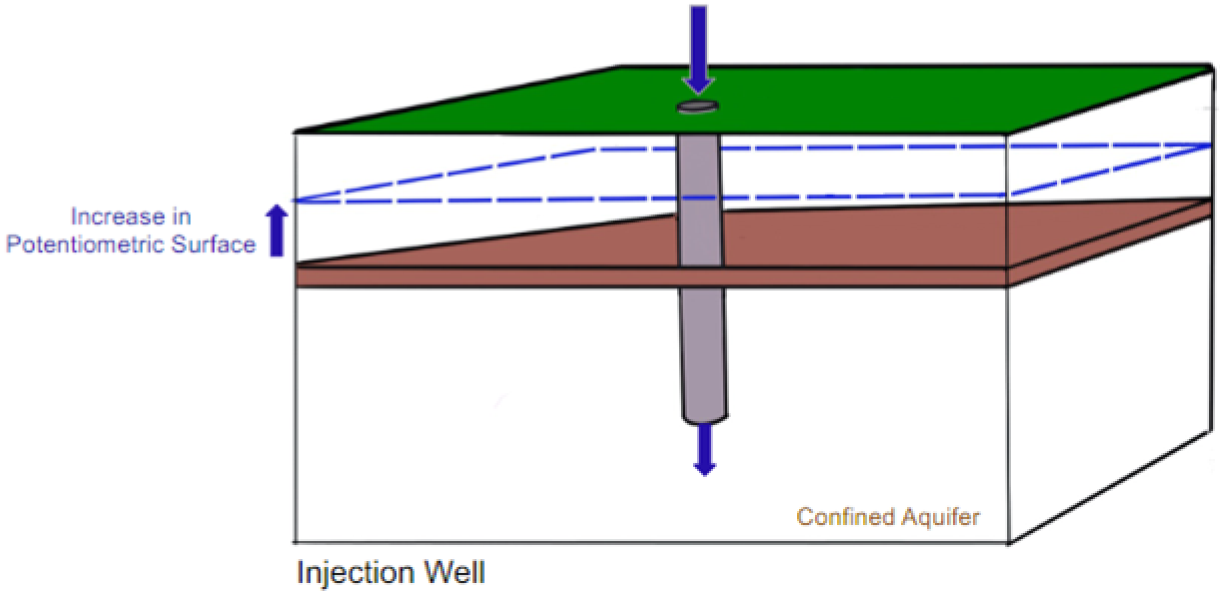


Figure 3-4. Injection Well

Injection wells are used to inject water directly into aquifers when the presence of confining layers prohibits recharge via percolation or when available surface area limits other options. Injection wells are necessary for MAR in confined aquifers but may also be required for unconfined aquifers if there are low-permeability layers present in the vadose zone. Injection wells are typically constructed in a vertical orientation as depicted in the schematic but can also be constructed in a horizontal orientation. The source water must be pressurized above the aquifer pressure to inject the water into the aquifer and pretreated to minimize clogging and meet water quality requirements. Compared to surface recharge technologies like infiltration basins, injection wells allow greater flexibility as to the choice of receiving aquifer and typically require less land. However, injection wells can be expensive to construct, operate, and maintain. MAR injection wells are regulated as UIC Class V wells.

3.4.4 Dry Well

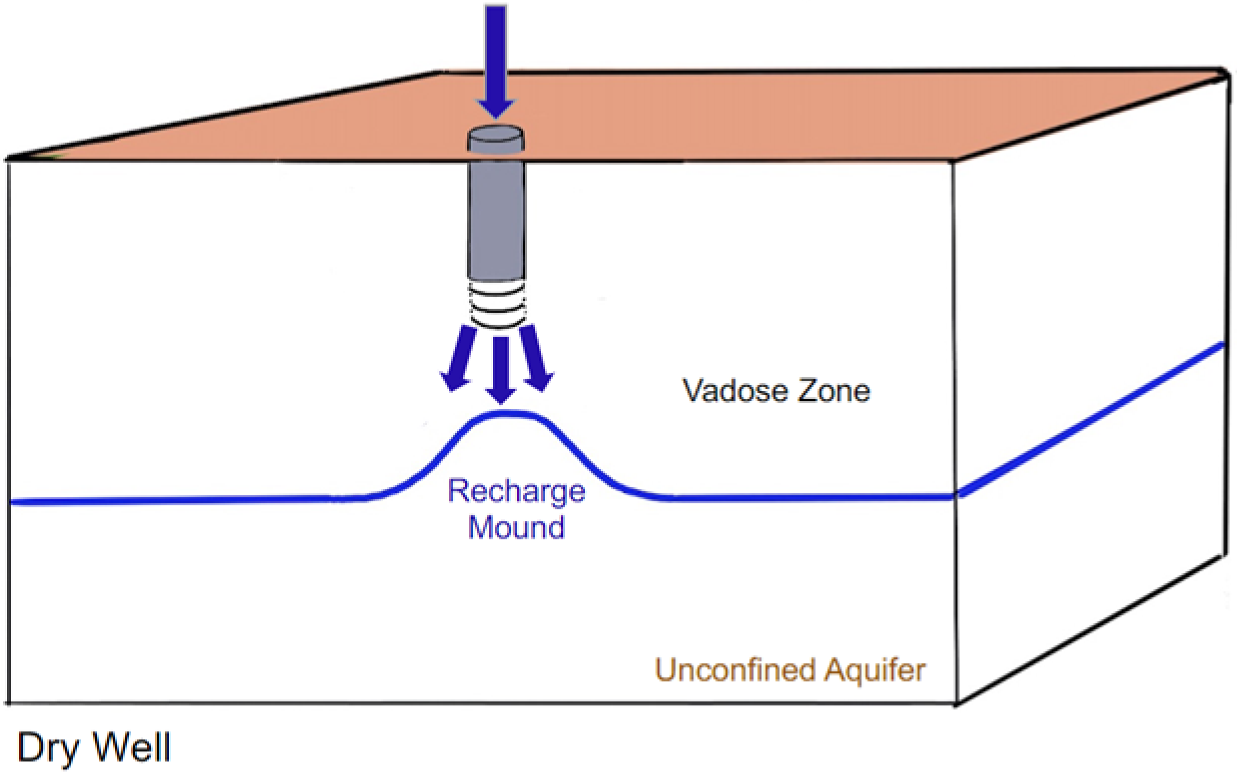


Figure 3–5. Dry Well

Dry wells (or “drywells”) are gravity-fed wells that are used to recharge the vadose zone above an unconfined aquifer. Common source waters for dry wells are stormwater and treated wastewater. They are typically constructed as boreholes lined with perforated casing, and the casing may also be filled with permeable fill material (for example, gravel). Dry wells operate similarly to infiltration basins and galleries but, because they are oriented vertically with a greater depth than width, they require a much smaller footprint and can be constructed to penetrate low-permeability layers above the water table. However, unlike an injection well, the capacity of a dry well is principally controlled by the hydraulic conductivity of the surrounding soils. Dry wells are regulated as UIC Class V wells.

3.4.5 Infiltration Gallery

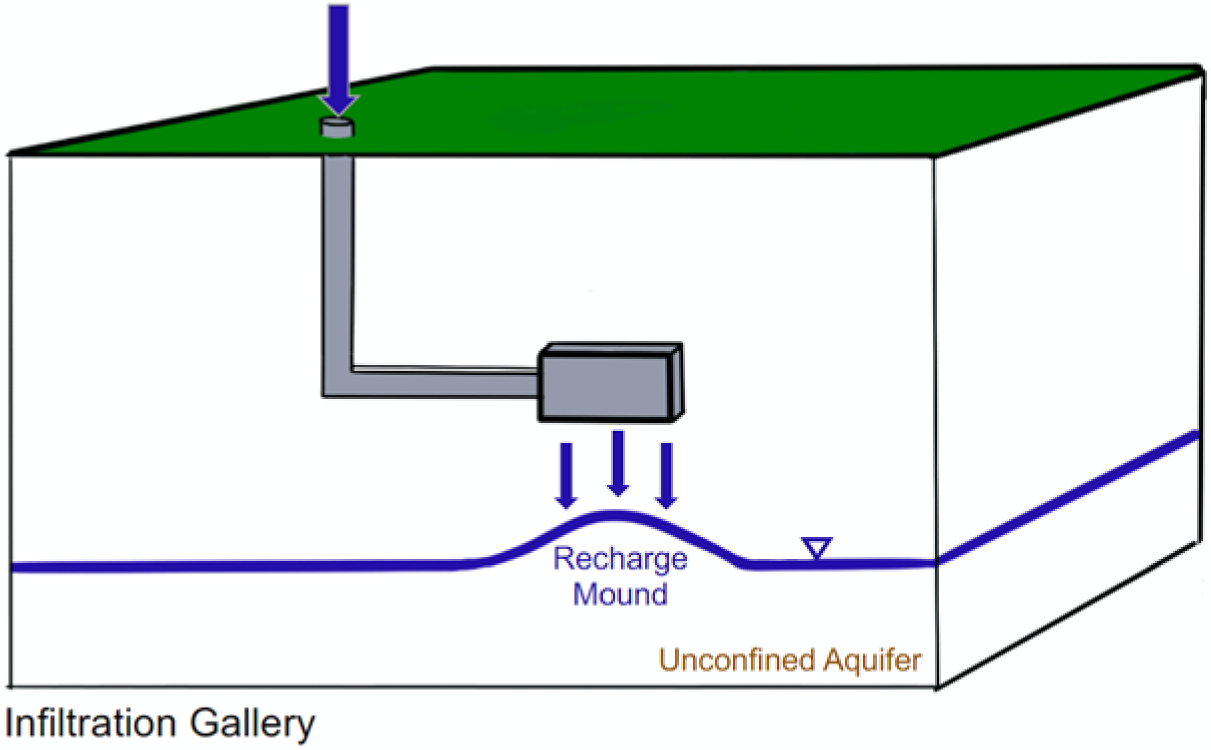


Figure 3-6. Infiltration Gallery

Infiltration galleries are belowground structures that allow for rapid infiltration of water through the vadose zone into an unconfined aquifer, generally over a greater area than dry wells, that can be comparable to infiltration basins. A gallery typically consists of individual, horizontally laid, perforated pipes or individual trenches backfilled with porous media. In the subsurface, infiltration galleries can be placed at near-surface shallow depths or deeper within the bedrock. Like infiltration basins, infiltration galleries can be susceptible to clogging and are also vulnerable to intrusion of plant roots. An advantage of infiltration galleries over other recharge technologies is that the land above these structures can be developed for other beneficial uses. Infiltration galleries are regulated as UIC Class V wells.

3.5 **Water Quality Considerations**

Depending on the goals and geography of a MAR project, the source water chemistry (see Section 3.2), the characteristics of the receiving aquifer/vadose zone matrix (see Section 3.3), the receiving groundwater chemistry, and the applied recharge technology (see Section 3.4) can vary substantially between projects and result in unique water quality issues and outcomes. MAR has been shown to degrade or improve water quality (for example, Fakhreddine et al. 2015; Drewes 2009). MAR projects must also meet federal and state-specific water quality standards (discussed in Section 3.5.1). Thus, water quality should be considered at every stage of a MAR project, from source water capture to recharge and subsurface storage to recovery and end use (Dillon et al. 2022, Table 7).

3.5.1 Water Quality Standards

Water quality should be considered in the context of geochemical compatibility and regulatory frameworks, such as clean water and safe drinking water regulations. Some parameters that are not governed by regulations or human health concerns may have implications for project feasibility, and vice versa. For example, the dissolved oxygen, pH, and oxidation-reduction potential can control many different geochemical reactions that could occur in the receiving aquifer and should be monitored throughout a MAR project. A list of physical, chemical, biological, and radiological parameters to be considered in the source water and/or receiving groundwater for a MAR project are provided in Table 3-1. Additional information on these parameters is provided in Appendix B.

Table 3-1. Example physical, chemical, biological, and radiological parameters

Parameter Class	**Example Parameters**

Physical	Temperature
	Turbidity
	Total suspended solids (TSS)
Chemical	Alkalinity
	Biological oxygen demand (BOD)
	Disinfection by-products
	Dissolved oxygen
	Emerging contaminants (PFAS, pharmaceuticals, microplastics)
	Inorganic chemicals (metals, for example, arsenic, iron, vanadium) Major anions (sulfate, chloride, nitrate)
	Nutrients Oxidation-reduction potential
	Pesticides
	pH
	Salinity
	Sodicity
	Total dissolved solids (TDS)
	Total organic carbon (TOC)
	Volatile organic compounds
Biological	Algae/cyanobacteria
	Bacteria
	Protozoa
	Viruses
Radiological	Naturally occurring radioactive materials (NORM)

Water quality standards can vary from one state to another. Some states use the federal Maximum Contaminant Levels (MCL) to determine acceptable water quality for MAR, while other states have laws that specify their own requirements. Below are a few examples:

- In 2014, California updated their indirect potable reuse regulations and associated water quality parameter requirements for groundwater replenishment reuse projects (GRRP). These updated regulations and requirements specifically apply to the reuse of recycled water (for example, treated municipal wastewater). Analytical testing is required for numerous contaminants, including pathogens (viruses, *Giardia,* and *Cryptosporidium*), nitrogen compounds, and various regulated contaminants (inorganic, organic, radionuclide, disinfection products, lead, and copper). These water quality parameters must meet or exceed regulatory limits such as notification levels (NL), secondary MCLs, and/or primary MCLs. Surface spreading applications also require TOC testing to demonstrate the effectiveness of soil aquifer treatment. California also specifies a “response retention time” where recycled water applied must be retained underground for a period necessary to provide sufficient response time to identify treatment failures and implement actions and shall be no less than 2 months (CCR §60320.124). To demonstrate compliance with the underground retention times, a tracer test is required using an added tracer (or in some cases an intrinsic tracer) under hydraulic conditions representative of the GRRP.
- Unlike California, Texas has taken a case-by-case approach and usually has not defined any statewide water quality parameters, other than the federal MCL. In general, the water quality of the source water must be consistent or compatible with the quality of the receiving aquifer (Texas Water Code Title 2, Subchapter D, Chapter 27 Subchapter G and Subchapter H). Any mobilization of arsenic that occurs must be addressed. In some areas of Texas, buffer zones have been created around wells to prevent the release of naturally occurring arsenic from the aquifer matrix.
- Washington State has developed Table 1 in Chapter 173-200 of the Washington Administrative Code to establish chemical parameters for groundwater quality. Chapter 173-200 also establishes that these values must be used for aquifer recharge in addition to assessing ambient groundwater.
- In 2022, New Jersey updated their MAR procedures to protect groundwater quality by requiring a water quality assessment prior to injection and ensuring compliance with the ground water quality standards (NJAC-7:9C). Groundwater quality standards are established for 232 chemical constituents in New Jersey. Of these, 133 constituents have New Jersey groundwater quality standards but do not have a promulgated federal drinking water MCL. Further, there are 36 constituents for which the state groundwater quality standards are more stringent than the associated federal drinking water MCL.

To ensure water quality standards are met, check on your state’s applicable requirements, including appropriate laboratory analytical methods. Some states may require laboratory certification, such as the National Environmental Laboratories Accreditation Conference Institute, to improve data quality. See Appendix C for state, territory, and tribe contacts for MAR.

3.5.2 Geochemical Compatibility: Source Water–Receiving Aquifer Interactions

Geochemical reactions between the source water, groundwater, and aquifer matrix can occur during MAR infiltration or injection and before recovery. The following geochemical compatibility topics relevant to MAR are discussed further in this section:

- The types of geochemical reactions that may occur during MAR are discussed in Section 3.5.2.1. These geochemical reactions may include processes such as biodegradation, ion exchange, formation of complex ions, redox reactions, acid-base reactions, sorption, and/or mineral precipitation and dissolution (Appelo and Postma 2005; Maliva 2020; Pyne 2005).
- Potential challenges that may arise during MAR as a result of geochemical incompatibility between the source water and receiving aquifer, such as well clogging and mobilization of contaminants, are discussed in Section 3.5.2.2.
- Mitigation strategies for geochemical compatibility issues are discussed further in Section 3.5.2.2. Conventional treatment technologies can be implemented to remove contaminants from the source water and enhance the performance of MAR. Treatment technologies can also be implemented to prevent well clogging and maximize recharge capacity during infiltration or injection.
- Chemical characterization of source water is essential to prevent introduction of contaminants into aquifers and to meet regulatory standards. Geochemical characterization methods are discussed further in Section 3.5.2.3.

3.5.2.1 Geochemical Processes during MAR

During MAR, many geochemical processes may occur as source water, aquifer materials, and native groundwater interact in the subsurface. These processes are affected by physical mixing in the subsurface and can result in either improved or degraded water quality of the recovered water. In the case of MAR, geochemical compatibility refers to the source water, aquifer matrix, and native groundwater chemical characteristics that will minimize adverse chemical reactions that could degrade water quality or impact recharge rates.

Chemical reactions often occur at the recharge front for both infiltration and injection MAR methods (Figure 3-7). For direct injection methods such as ASR or ASTR, mixing between recharge water and the native groundwater can occur via advection and dispersion around the injection well and as recharge water moves away from the injection well (Pyne 1995). The degree of mixing depends on hydrogeologic characteristics such as porosity, hydraulic conductivity, anisotropy, hydraulic gradients, and aquifer thickness (see Section 3.3.1). The degree of mixing also depends on how the wellfield is designed. In cases where the receiving aquifer is brackish or of poor quality, an ASR or ASTR project can be designed to minimize mixing between the recharged water and the aquifer. Several techniques can be employed to minimize mixing, including injection of recharge water into a thin, confined aquifer, or operating ASR wells to initially form and then maintain an adequate buffer zone around the well that is never to be recovered (Pyne 1995). This buffer zone serves to separate the subsequently stored water from the surrounding, sometimes brackish, groundwater.

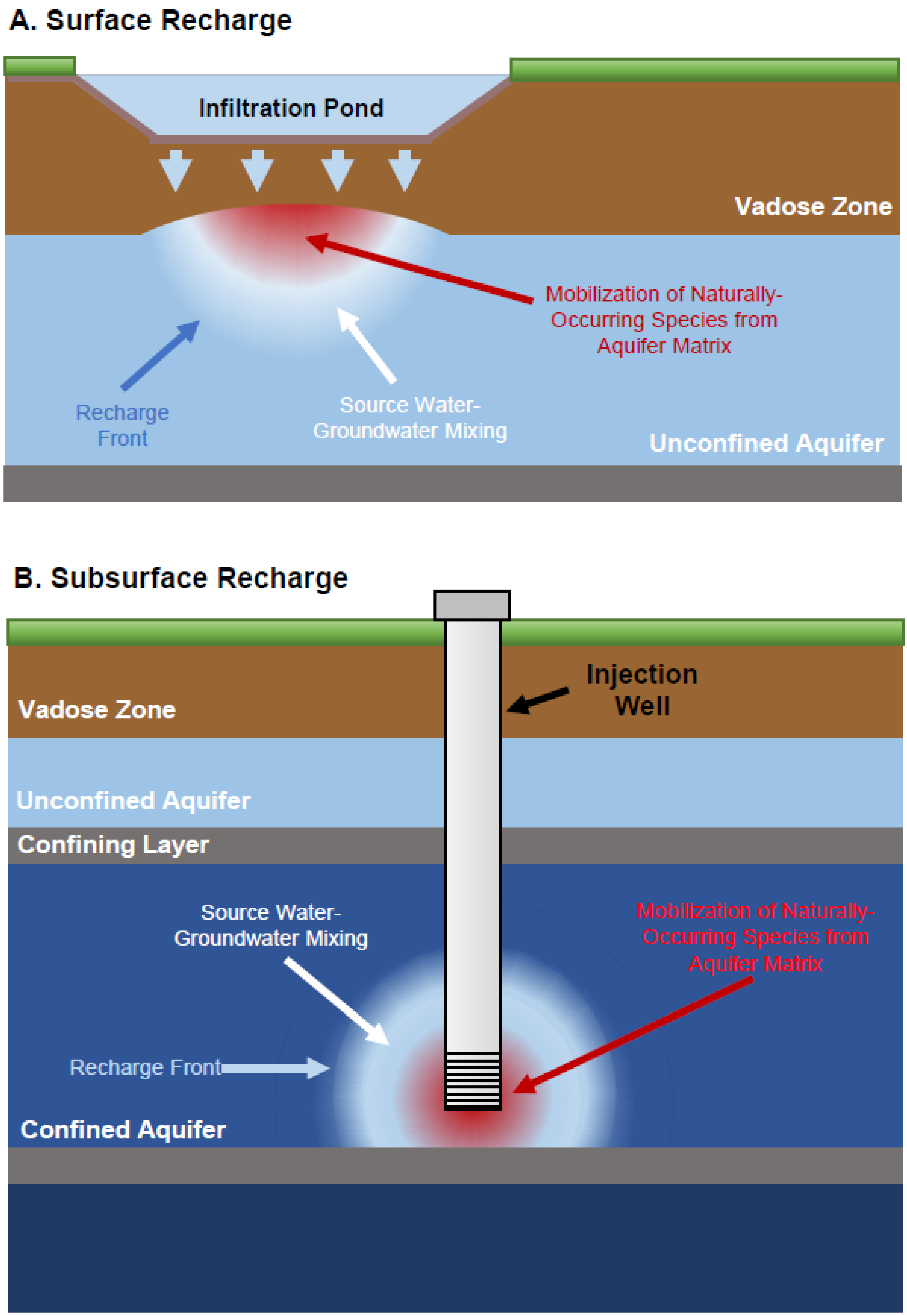


Figure 3-7. Geochemical reactions and recharge fronts.

Source: Beth Hoagland, SSPA. Used with Permission

Geochemical reactions from mixing of recharge water and groundwater that occur at the recharge front are often spatially limited and do not have a significant impact on overall water (Fakhreddine et al. 2021). Instead, interactions between the source water and aquifer matrix often have a more notable effect on the quality of recovered groundwater. Sites where source water and the aquifer are geochemically incompatible can result in degradation of groundwater quality. Negative consequences of geochemical incompatibility include (a) changes in water quality that increase concentrations of regulated contaminants, and (b) biofouling or mineral precipitation that occludes pore spaces or clogs well screens. In some states, the quality of native groundwater is protected by regulating geochemical incompatibility. For example, the Antidegradation Policy in California requires best practicable treatment or control of discharges to high-quality receiving waters to prevent pollution and maintain the quality of existing water resources (SWRCB 1968). This means that source water cannot introduce contaminants to groundwater or cause contaminants to be released from the aquifer matrix.

Interactions between the aquifer matrix and groundwater are likely to occur along the flow paths between the location of the source water injection and the location of the extraction well if the extraction well is at some distance from the injection well. Water-rock interactions that potentially affect MAR include oxidation/reduction (redox) reactions, mineral precipitation/dissolution, ion exchange, or adsorption/desorption (Figure 3-8).

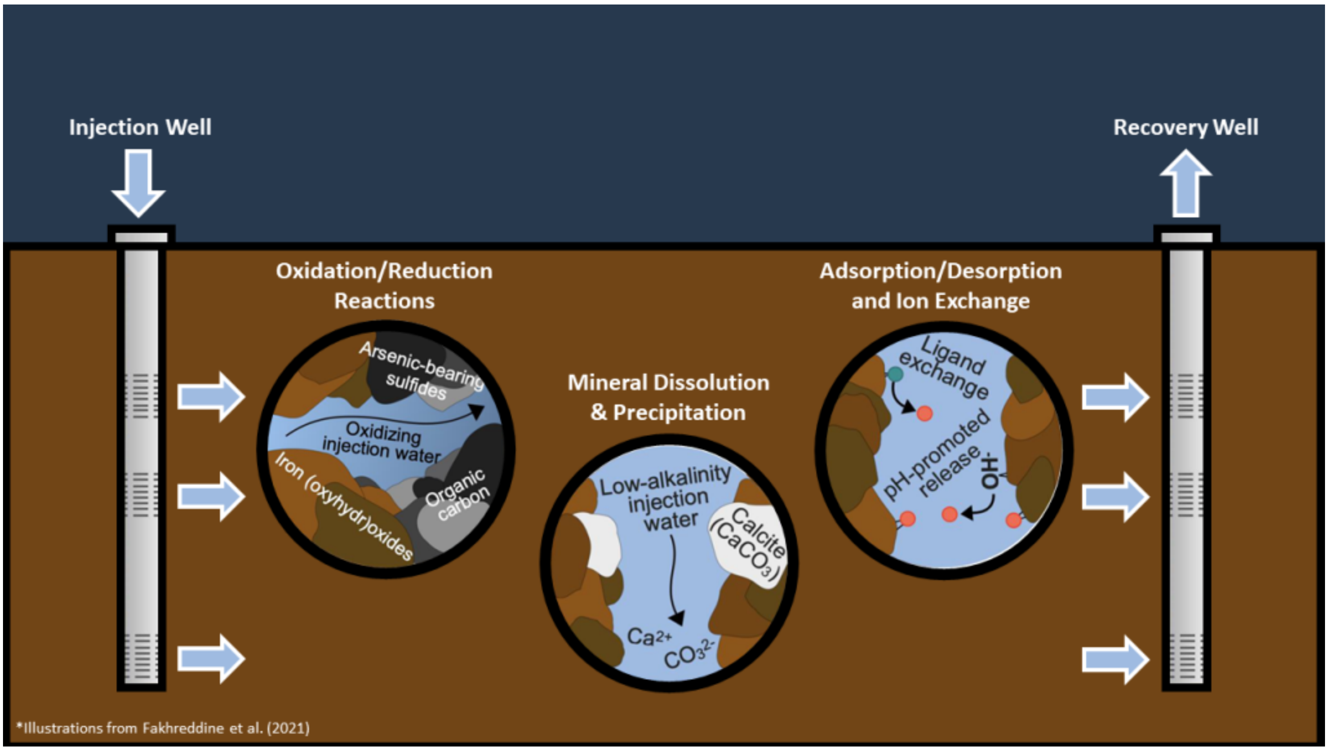


Figure 3-8. Geochemical reactions that may occur during MAR.

Source: Adapted with permission from Fakhreddine, Sarah, Henning Prommer, Bridget Scanlon, Samantha Ying, and Jean-Philippe Nicot. 2021. "Mobilization of Arsenic and Other Naturally Occurring Contaminants during Managed Aquifer Recharge: A Critical Review." Environmental Science & Technology 55 (January). https://doi.org/10.1021/acs.est.0c07492*., Copyright 2021,American Chemical Society.*

Redox reactions will occur during MAR as source water rich in dissolved oxygen and/or nitrate mixes with oxygen-poor groundwater containing sediment-bound organics or sulfide minerals (Fakhreddine et al. 2021). Typically, the difference in redox potential between source water and groundwater is greater with subsurface technologies, such as ASR or ASTR, compared to surface technologies, such as infiltration basins or galleries. This is because subsurface technologies often involve injection into deep, anoxic aquifers, whereas surface technologies involve infiltration of source water into shallow vadose zones. Changes in redox conditions may degrade recovered water quality by triggering the release of metals around ASR injection/extraction wells. In other cases, redox reactions may improve water quality. For example, Maeng et al. (2011) found that pharmaceutical products degraded at the reaction front of infiltrating water where oxic conditions changed to anoxic during bank filtration projects.

Mineral dissolution and precipitation reactions represent the processes by which minerals dissolve or precipitate as water interacts with the surrounding aquifer matrix. These reactions are determined by how close a water is to equilibrium with the host rock, which can be predicted using the saturation index. Minerals will neither dissolve nor precipitate if the water is in equilibrium with respect to minerals in the aquifer matrix. The rate of mineral dissolution or precipitation is influenced by pH and other chemical characteristics of the water. For subsurface technologies, source water is injected into deep aquifers where native groundwater is presumed to be in equilibrium with the aquifer matrix. Dilute, low-alkalinity source water is often not in equilibrium with the aquifer matrix, which may cause the dissolution or precipitation of minerals during injection.

Significant differences in dissolved carbon dioxide gas between the source water and deep aquifers may also lead to degassing of carbon dioxide within the area of injected water. This may cause a change in pH, mineral dissolution reactions at the recharge front, and result in the release of carbon dioxide to the atmosphere during pumping of groundwater.

The receiving aquifer lithology and mineralogy will also affect water quality during MAR. In a carbonate aquifer, for example, calcite minerals dissolved during injection of urban stormwater because the stormwater was undersaturated with respect to calcite (Vanderzalm et al. 2010). Dissolution of redox-sensitive minerals such as iron oxides and sulfides during MAR may release trace metals such as arsenic, selenium, cadmium, chromium, and uranium to groundwater (Fischler, Hansard, and Ladle 2015). For example, injection of source water with high amounts of organic carbon can encourage microbial activity that can result in the release of arsenic into groundwater (Vanderzalm et al. 2010).

Additional water-rock interactions that commonly occur during MAR include solute adsorption onto or desorption from mineral surfaces or ion exchange reactions. Source waters with low levels of calcium and magnesium can lead to arsenic desorption from sediments into the receiving aquifer (Fakhreddine et al. 2015). Source waters with high concentrations of cations such as calcium can displace other cations such as magnesium from sediments in the receiving aquifer, and release these cations into groundwater (Ganot et al. 2018). Ion exchange can also result in the destabilization of clay minerals and lead to clogging of pore spaces in the aquifer matrix.

3.5.2.2 *Geochemical Compatibility Issues and Mitigation*

Contaminant Introduction—MAR projects may unintentionally introduce contaminants to the receiving aquifer. Further, there are contaminants of emerging concern (Table 3-1, Appendix B) for which no state standards exist, and may possibly be introduced to groundwater during MAR. For example, treated wastewater can pose a potential risk of introducing emerging contaminants such as pharmaceuticals, antibiotic-resistant bacteria, viruses, and disinfection by-products to receiving aquifers if the wastewater is not sufficiently treated for these constituents prior to recharge (Casanova, Devau, and Pettenati 2016). It is suggested that monitoring for such parameters occur to understand the level and presence of these contaminants in the injectate and/or in the underlying aquifer.

The choice of recharge technology can mitigate the introduction of emerging contaminants to receiving aquifers. If emerging contaminants for which no state standards exist are present in the source water, the use of infiltration technologies rather than direct injection may be considered so that emerging contaminants are not introduced into confined aquifers. The use of infiltration basins may reduce concentrations of contaminants in treated wastewaters via adsorption or biodegradation as the source water infiltrates through the unsaturated zone. Optimizing the source water retention time in the subsurface has also been found to enhance the attenuation of chemical and microbial contaminants (for example, Regnery et al. 2017). In contrast, PFAS are a class of emerging contaminants that are ubiquitous and persistent and could be transported long distances if present in the source water used for MAR projects. MAR projects can be designed to prevent contaminant introduction into an aquifer. Technologies such as granulated activated carbon or ion exchange may need to be implemented to remove PFAS or other emerging contaminants from source water (Page et al. 2019). Direct injection wells have been used to create barriers and prevent seawater intrusion (Russo, Fisher, and Lockwood 2014). Another example for surface MAR methods includes the installation of reactive barriers at the bottom of infiltration basins to remove organic pollutants (Valhondo et al. 2020).

Contaminant Mobilization—Mobilization or formation of contaminants such as trace metals or disinfection by-products may occur during MAR. For example, the change in aquifer redox chemistry or pH during ASR injection can cause naturally occurring minerals with trace amounts of toxic metals to become unstable and dissolve (Table 3-2). Chemical analyses of the source water and receiving water can help project managers anticipate and prevent contaminant mobilization. Mitigation options may include treatment of source water before recharge and/or post-treatment of recovered water. The standards to which recovered water is treated will depend on the anticipated end use.

One well-known case of metal mobilization caused by MAR is arsenic release to the Floridan aquifer of Florida (see Case Study 5.2). The injection of oxygenated water into the oxygen-poor, reducing groundwater of the Floridan aquifer has led to the oxidation of naturally occurring pyrite minerals and the release of arsenic associated with these minerals (Mirecki, Bennett, and López-Baláez 2013). To eliminate arsenic leaching, sodium hydrosulfide was added to remove free oxygen from the source water and maintain the low-oxygen conditions of the aquifer (see Case Study 5.2). Another technique used to mitigate arsenic concentrations in recovered water is to operate ASR wells to create a buffer zone that separates the recharged source water from the surrounding groundwater (Pyne 1995). It is hypothesized that by creating a buffer zone, arsenic in contact with oxygenated recharge water close to the well is rapidly mobilized and then transported away from the well, typically a distance of a few tens to hundreds of feet. Another example of contaminant mobilization during MAR is the formation and introduction of disinfection by-products to aquifers, particularly for projects using recycled water. Disinfection by-products form in treated water because of reactions between organic matter and water treatment chemicals such as chlorine. Treatment of source water before recharge in ASR or injection wells may include chlorination for disinfection or to help control biofouling around the injection well; however, this may result in the formation of disinfection by-products such as trihalomethanes and haloacetic acids (Pavelic et al. 2005). Hyun-Chul Kim et al. 2017 found that treatment with ozone removed organic acids from source water, decreased the potential for disinfection by-product formation, and improved the performance of the artificial aquifer recharge system. Investigations at five ASR sites found that disinfection by-product concentrations in chlorinated drinking water decreased over several weeks during storage under both anoxic and aerobic conditions, likely due to biological activity (Pyne, R. David, Singer, Philip C, and Miller, Cass T 1996).

Table 3-2. Chemical conditions of receiving aquifer and contaminant mobility

Contaminant	**Impact of Aquifer Conditions on Contaminant Mobility**				**Additional Aquifer Conditions to Avoid**
	pH		**Redox**		
	Low	**High**	**Reducing/ Low Oxygen**	**Oxidizing/ High Oxygen**	
Iron (Fe)	**Increase**	**Decrease**	**Increase**	**Decrease**	
Manganese (Mn)	**Increase**	**Decrease**	**Increase**	**Decrease**	
Arsenic (As)	**Decrease**	**Increase**	**Increase**	**Decrease**	High phosphate, compaction of aquifer matrix from over pumping
Chromium (Cr)	**Decrease**	**Increase**	**Decrease**	**Increase**	Fluctuating water table (caused by surface recharge technologies)
Uranium (U)	**Decrease**	**Increase**	**Decrease**	**Increase**	High bicarbonate, high nitrate
Vanadium (V)	**Decrease**	**Increase**	**Decrease**	**Increase**	
Selenium (Se)	**Decrease**	**Increase**	**Decrease**	**Increase**	

Aquifer and Well Clogging—Clogging of well screens and aquifer pore spaces is one of the main challenges facing sustainable operation of MAR and has the potential to affect any MAR project regardless of the recharge technology (Figure 3-9). Aquifer and well clogging can occur as a result of physical, mechanical, or biogeochemical processes. Physical clogging of injection well screens or spreading basins may occur if suspended sediments are present in the source water or if injection or infiltration causes the migration of fine-grained sediments in the aquifer. Mobilization of clays is particularly common in sandstone aquifers. Physical clogging of screens may also occur due to clay swelling, particularly when fresh source water is recharged to a saline receiving aquifer (Martin 2013), or when the aquifer contains sodium montmorillonite clays. Mechanical clogging processes may include the entrainment of air/gas (Martin 2013). Biogeochemical reactions can also lead to clogging during MAR projects.

Biogeochemical reactions may include precipitation or dissolution of minerals, colloid formation, or biofouling. Precipitation of minerals or formation of biofilms during MAR is often a result of redox reactions, where source waters rich in oxygen and other oxidants such as nitrate are injected into the aquifer. Iron is one of the main inorganic species that causes chemical clogging or biofouling during MAR. The presence of oxygen or nitrate in recharged water can trigger iron-oxidizing bacteria to precipitate iron hydroxides and excrete biofilms that clog well screens or pore spaces (Martin 2013). Recent research found that iron concentrations in recharge water for MAR should remain below 0.3 mg/L to inhibit clogging (Cui et al. 2023).

Microbial growth represents a significant clogging issue for MAR projects. The amount of microbial growth, and biofouling, is directly related to the total organic carbon and nitrogen concentration, carbon to nitrogen ratio, pH, and temperature in the source and receiving waters (Cui, Ye, and Du 2021). Bacteria may form biofilms that can adhere to the injection well screen or the aquifer matrix. In fact, managed aquifer recharge has been found to alter the diversity and composition of microbial communities during infiltration or injection, and in some cases, MAR favors the growth of certain microbial populations that may assist in the biodegradation of pollutants (Barba et al. 2019).

Indications that clogging is occurring in an ASR well include observations that the rates of injection decrease independent of water levels in the injection well, or if observed water levels in the injection well rise independent of injection rate. A general guidance is that if the injection capacity has declined by approximately 25%, then rehabilitation of the well should begin (Martin 2013).

For surface infiltration systems, such as spreading basins, clogging typically occurs at the soil-water interface and consists of a thin layer of suspended solids, microbes, algae, dust, and/or salts. The clogging layer has been found to reduce hydraulic conductivity by as much as five orders of magnitude (Hutchinson, A., Banerjee, M, and Milczarek, M 2013).

Clogging can be mitigated by treating source water before injection. Treatment options include nutrient reduction, chemical dosing to inhibit microbial growth, or filtration and/or chemical treatment to remove suspended sediments. For example, the Orange County Water District in California has been testing the use of riverbank filtration to reduce suspended solids concentrations in captured storm flow prior to recharging the water in a spreading basin (Hutchinson et al. 2017). Other operations and maintenance options for MAR injection wells may include periodic chemical dosing to prevent microbial growth and buildup of scale or periodic backwashing of the recharge wells (Martin 2013). A recommended practice is to maintain a disinfectant residual in the well, not only during recharge but also during storage periods exceeding about 2 weeks, thereby controlling downhole microbial growth that can rapidly clog a well.

Backflushing of injection or ASR wells is another option to mitigate the effects of clogging. For ASR wells, backflushing is typically required every few weeks to every few months and involves pumping the well at a high flow rate that exceeds the recharge flow rate. Backflushing typically lasts from 30 minutes to an hour or more. Initial monitoring of water quality during backflushing by collecting jar samples every 5 minutes will indicate the pumping duration needed to purge particulates from the well. Many different well rehabilitation methods are available, ranging from simple to complex and aggressive.

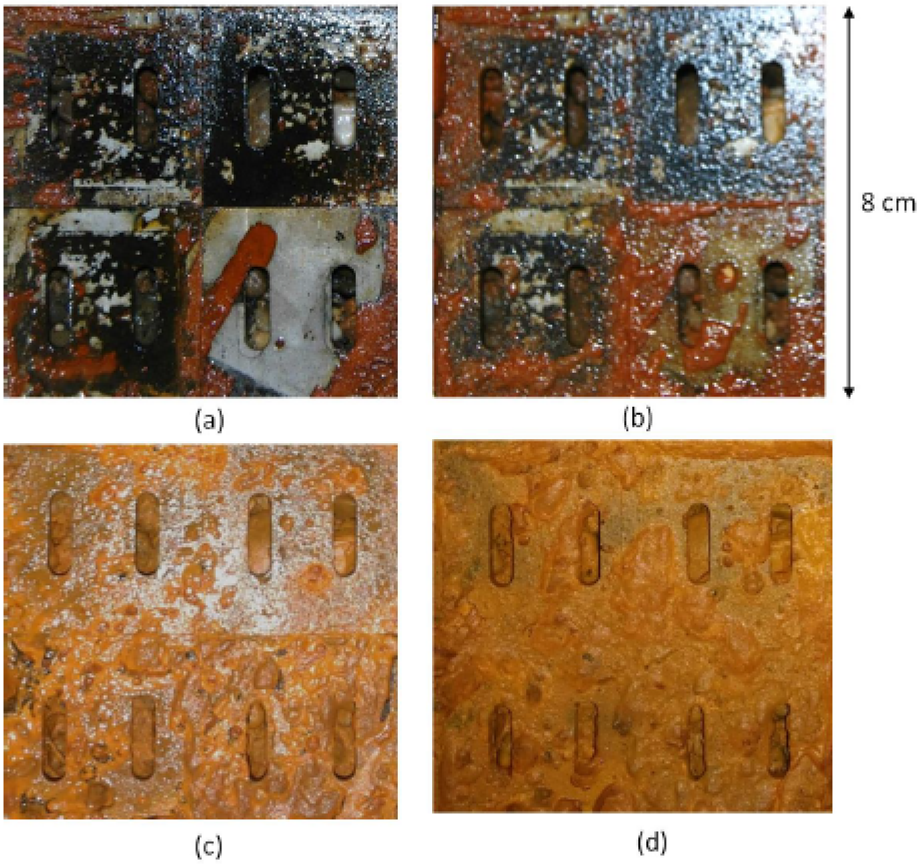


Figure 3-9. Example of well screen clogging after (a) 1, (b) 20, (c) 29, and (d) 73 days.

Source: Camprovin et al. (2017)

3.5.2.3 *Geochemical Characterization Methods*

Before implementing MAR, geochemical characterization of source water may be required by regulatory agencies. A hydrogeologic conceptual model that includes information on the chemical and physical attributes of the aquifer system will inform pre-injection and post-recovery water treatment strategies that may be necessary to meet regulatory standards (see Section 2 on Project Planning). Further, the full range of chemical variability in the source water should be characterized to understand the possible chemical reactions that could occur during recharge at various times of the year and over the projected life of the project (McCurry and Pyne 2022). To understand the potential for nutrient leaching to groundwater in Flood-MAR projects, additional factors such as nitrogen management practices, soil permeability, and the history of land use should be considered (Waterhouse et al. 2020).

Source water and receiving groundwater characterization typically includes monitoring of physicochemical parameters such as pH, dissolved oxygen, conductivity, and temperature. Additionally, water samples may be analyzed for major ions, metals, or organics using techniques such as chromatography or spectrometry. The geochemistry of source waters, such as urban stormwater, can be highly variable, and thus source water sampling should occur frequently enough to capture the full range of geochemical variability. Ongoing regulatory required monitoring can also be a useful source of information on water composition.

The geochemistry of the receiving aquifer matrix may also be characterized to predict what water-rock interactions may occur during MAR. For recharge sites where the geochemistry is uncertain and/or for locations that have known or suspected problematic geochemical issues, collecting core samples is recommended (see Section 3.5.2). Sediment/rock mineralogy can be characterized using methods such as scanning electron microscopy/energy dispersive X-ray spectroscopy SEM/EDS or X-ray fluorescence (XRF). Cation exchange and adsorption capacity of the aquifer matrix can be characterized using lab-based experiments, including batch reactions and column studies. Contaminant concentrations and speciation in the sediment/rock matrix can be quantified using sequential extraction methods. Rock/sediment samples can be prepared using lithium metaborate fusions or acid digestions and analyzed for bulk oxide chemistry using spectrometry.

In combination with the site hydrogeology, the analytical data for the source water, receiving water, and receiving aquifer matrix can be used to constrain computational models of geochemical compatibility. See Section 3.6 for descriptions of computational models used to evaluate geochemical compatibility for MAR projects, including mixing and reactive transport models.

3.6 **Data and Modeling**

Collecting data before, during, and after implementation of the pilot study and the main project is important for the overall success of a MAR project. The first part of this section briefly discusses the typical data needs of MAR projects. MAR projects frequently use some of this data to construct models that are used to assess the feasibility of the project, inform the design, and fine-tune the operations. The second part of this section discusses modeling as it relates to MAR projects.

3.6.1 Data Recommendations and Acquisition

The data requirements for a MAR project are a function of the size and complexity of the project. At a minimum, the storage potential of the receiving aquifer and the geochemical compatibility of the source water and the native receiving aquifer water must be characterized. For screening-level analysis, some aquifer information may already be publicly available in state and/or federal databases and reports; however, detailed analysis for feasibility and design requires site-specific data collection. Table 3-3 provides a summary of common data requirements for MAR projects and possible sources of this information.

Table 3-3. Data recommendations and acquisition summary

Data Category	**Examples**	**Sources**
Geologic	Stratigraphic contacts Aquifer minerology	State/federal databases Site borings
Hydrogeologic	Hydraulic heads Gradients Aquifer properties	State/federal monitoring well networks Site-specific aquifer testing

Hydrologic	Streamflow measurements Seepage estimates Reach condition (wet/dry) observations	State/federal stream gage network Remote sensing/satellite data Site-specific studies
Chemical/Biological	Source water chemistry Receiving aquifer chemistry Pretreatment evaluation	Site-specific sampling
System Design	Basins/well locations Access to wells and equipment Other engineering details	Site-specific feasibility study
Other	Cultural resources Land use/suitability/availability Climatological	Site-specific survey

3.6.2 Modeling

Successful operation and maintenance of MAR projects requires understanding dynamic physical and chemical processes that may be occurring within complex subsurface environments. Reasonable estimates of the stability of, or changes in, these processes under future (postconstruction) conditions are likely to be important design considerations. A variety of modeling techniques, ranging from simple conceptual demonstrations to complex numerical simulations of physical/geochemical processes, are frequently used for these purposes in supporting MAR projects. The following sections provide an overview of common modeling techniques and examples of important considerations relative to MAR projects.

3.6.2.1 *Modeling Objectives*

The purposes or intended use(s) of the information produced by models are key considerations when selecting appropriate modeling techniques. For example, if a MAR project is intended to assist in mitigating saltwater intrusion potential and modeling is being performed to estimate future changes in the local position of the saline/freshwater interface, either a density-dependent flow model or a sharp interface model should be used, depending on the modeling needs and available resources. Therefore, objectives should be carefully considered and clearly stated prior to selecting a modeling approach. Modeling objectives for MAR projects can be generalized into the following categories:

- **Predictive**—using a model to assess responses to a MAR project and support design and operation of the system. Examples include groundwater flow modeling to estimate future hydraulic responses within the aquifer caused by infiltrated and/or injected groundwater and reactive solute transport modeling to estimate potential geochemical reactions occurring under injection scenarios.
- **Interpretive**—using a model to evaluate hypotheses pertaining to observed conditions (for example, water quality and/or performance changes). Examples include geochemical modeling to assess processes responsible for observed conditions such as biofouling and solute transport modeling to assess potential groundwater flow paths suggested by measured thermal responses.
- **Regulatory**—using a model to support UIC permit applications and/or inform data collection strategies to address regulatory requirements. Examples include performing analytical and/or numerical groundwater modeling to estimate groundwater mounding potential caused by a proposed infiltration structure, and numerical groundwater flow modeling being used to assess timing of hydraulic responses in receiving waters intended to be receiving supplemental baseflow.
- **Communicative**—using a model to develop graphical representations of projected outcomes for stakeholder and public meetings. Examples include conceptual animations of intended MAR project outcomes and graphical summaries of anticipated future conditions derived from analytical and/or numerical modeling studies. It is also important to communicate the limitations of the model and the data used in developing the model.

3.6.2.2 *Types of Models*

Conceptual Models are primarily qualitative tools that use text and/or graphics to synthesize available information, both known and hypothesized, for a given site. Conceptual models are often used to define the framework of computational models. Here are some types of conceptual models relevant to MAR projects:

- **Conceptual geologic models** provide an understanding of the soil, stratigraphy, and lithology within the basin.

They will help determine the most appropriate MAR process for the site and the potential size and viability of the MAR project, and can serve as the basis for a more comprehensive conceptual site model.

- **Conceptual hydrogeologic models** are also typical components of more comprehensive conceptual site models and provide an understanding of the groundwater flow system to which MAR water is delivered—including water volumes, storage volumes, and flows within a basin. Aquifer properties are established, water levels are assimilated, potentiometric surfaces are developed, groundwater/surface water interactions are evaluated, and aquifer flow conditions (inflow, outflow, inter-aquifer flow, intra-aquifer flow) are estimated. Basin wide quantities, such as hydrogeologic properties, boundary conditions, and long-term (typically annual) water budgets, are also estimated.
- **Conceptual water quality/geochemical models** may also be parts of more comprehensive conceptual site models and provide an assimilation of available water quality data that may impact groundwater quality, such as contaminant sources, total dissolved solids (TDS), salinity, and pH of source and receiving water. These models also provide a preliminary understanding of the potential vulnerabilities of a MAR project to water quality or to the aquifer matrix.

Computational Models are quantitative tools routinely used by engineers and scientists to simulate various aspects of a MAR project and to provide visualization of those simulated results. A wide range of these models is available—from simple analytical solutions to more complex numerical models. Some common examples of each type of model are included below; for a more comprehensive list of modeling tools, refer to (Ringleb, Sallwey, and Stefan 2016).

- **Geologic block models** are 3-D representations of subsurface geology that are typically generated by interpolating boring logs and/or geophysical data. These models are often used to make subsurface visualizations (for example, cross sections), as well as to define inputs to groundwater flow models. Earth Volumetric Studio (C Tech 2023) and Leapfrog Geo (Seequent 2022) are two examples of software packages that are commonly used to create geologic block models.
- **Groundwater flow models** use analytical or numerical methods to solve the governing equations of groundwater flow in the saturated and/or vadose zones. Analytical models rely on a variety of simplifying assumptions, the validity of which must be carefully considered in evaluating the reliability of model estimates against modeling objectives. An example of an analytical groundwater flow model commonly used in support of MAR projects is the solution to the groundwater flow equation proposed by (Hantush 1967) that estimates, under a variety of simplifying assumptions, the deflection in water table elevation generated under localized infiltration (mounding) or extraction (drawdown). Some MAR applications may require surface water/groundwater interaction modeling to meet objectives. Models that exist in the Alluvial Water Accounting System (AWAS) (Schroeder 1987) are common analytical tools used for this purpose. Compared to analytical models, numerical models, such as MODFLOW 6 (Langevin et al. 2017), generally rely on fewer simplifying assumptions and therefore provide greater flexibility for representing site-specific complexity, though they are more complex and require significantly more training and expertise to use than analytical models. Numerical groundwater flow simulations may also be extended to assess the fate and transport of solutes using auxiliary modeling codes, such as those discussed below. McCray, Thyne, and Siegrist (2005) compared and contrasted analytical and numerical modeling approaches and noted that analytical models are likely to be most useful as screening-level assessments that may indicate the need for more robust numerical modeling. The analytic element method (Analytic element method—Wikipedia) has potential to contribute to MAR applications and is under investigation (USEPA 2022h).
- **Fate and transport models**, like groundwater flow models, may be analytical or numerical in form. Analytical methods are based on simplifying assumptions and may be applied in cases where these approximations are generally acceptable. The simplest numerical transport models are called particle tracking models, which may solely simulate advection or may also estimate the effects of hydrodynamic dispersion and/or decay. MODPATH (Pollock 1989), most recently issued as version 7 of the code (Pollock 2016), is a common particle tracking model. More complex numerical solute transport models provide greater flexibility to account for transport processes more specifically, such as advection, dispersion, and/or molecular diffusion, while simultaneously accounting for solute fate, meaning mass gains and losses, via representations of in situ reactions and/or decay. Examples of numerical fate and transport models include USG-Transport (Sorab Panday 2023, Panday et al. 2013), MT3D (Zheng 1990), MT3D-USGS (Bedekar et al. 2016), RT3D (Clement 1997), SEAM3D (Widdowson et al. 2002), and the Groundwater Transport Model present within the MODFLOW 6 framework (Langevin et al. 2017). For saltwater intrusion problems, MODFLOW 6 or SEAWAT (Guo and Langevin 2002), a combination of MODFLOW

and MT3D, can be used to simulate density-dependent flow. Saltwater intrusion may also be simulated using sharp interface models such as the SWI2 package of MODFLOW.

- **Geochemical models** are used in a water quality assessment to simulate the reactions that may occur when the source water and native receiving aquifer water are mixed. Common geochemical models are PHREEQC (Parkhurst and Appelo 2013) and Geochemist's Workbench (Aqueous Solutions LLC 2023).
- **Inverse models** are used in groundwater and/or solute fate and transport modeling to support calibration, which typically involves approximate "history matching" using data representative of historical site conditions. In effect, certain components of the inverse version of a given model, such as parameter values, are varied within user-defined limits to minimize the value of an objective function, the magnitude of which is generally indicative of the degree of agreement with considered measurements, including groundwater level, groundwater flow, and solute concentration. Depending on the objectives and extent of modeling, numerical models may require a considerable amount of data to calibrate. In addition to supporting calibration of a given model, inverse modeling may also provide the necessary tools to assess the significance of available or proposed data (data worth assessment) and/or quantify model sensitivity and predictive uncertainty. Examples of software utilities that support inverse modeling include UCODE (E. E. Poeter et al. 2005) and PEST (Doherty 2015).
- **Optimization models** are used to fine-tune the operations of a project to maximize potential benefits under physical, climatic, or anthropogenic constraints. Management decisions made by optimization models may include minimization of cost for construction and operation, alternatives analysis, maximizing capacity of a project, or minimizing the risk of failure of a project, among others. GWM: Groundwater Management Process for MODFLOW (Ahlfeld, Barlow, and Mulligan 2005) is an example of a software utility that can be used to conduct optimization modeling.

- **Data models** are increasingly being used to understand and manage groundwater basins. Data models may use multivariate statistics, machine learning, or other methods to evaluate complex trends in available data or correlations within multiple sets of information. Data models may be used in conjunction with other computational models to analyze site conditions and associated impacts of a MAR project. GoldSim (GoldSim Technology Group 2023) is one example of a data modeling framework that supports predictive data modeling.

Complex modeling that may include geochemical reactions, inverse modeling, and/or optimization would require the regulatory community reviewing the results to properly understand the information. Useful guidance on best practices in groundwater flow modeling is provided by Anderson, Woessner, and Hunt 2015; Barnett et al. 2012; Bredehoeft 2003; Bredehoeft 2005; via the National Groundwater Association (NGWA) website; and in various ASTM International documents. Common modeling errors are summarized at the conclusion of each chapter of (Anderson, Woessner, and Hunt 2015) and are useful to ensure data quality objectives are met for the modeling effort. The principle of simplicity presented by (Barnett et al. 2012) is useful to develop practical modeling results.

3.6.2.3 *Modeling Scope*

The modeling effort depends on the scope of the MAR project, the complexity of site hydraulics and/or hydrogeology, the potential risk of negative impacts, and potential external means of mitigating adverse outcomes—all of which should be used to develop clearly stated modeling objectives. A large MAR project with higher potential for impacts (positive and negative) may require a more rigorous evaluation when compared to a smaller project with less associated risk. Beyond directing the modeling approach, the objectives of the modeling effort will influence the following:

- data and information requirements (noting data availability may also influence the modeling approach)
- assumptions
- calibration and adequacy of history matching
- consideration and handling of predictive uncertainty
- limitations

The appropriate modeling approach(es) for a given set of objectives will yield reliable results while avoiding unnecessary complexity and effort. A hydrogeologic conceptual model with analysis of water levels and basin wide water budgets may be adequate for certain scenarios. A conceptual water quality/geochemical model may determine no cause for further concern. Data models or computational models may be required to better quantify impacts of MAR operations as may be governed by site/project conditions. Screening-level calculations can be performed using analytical solutions, semi analytical models, or simple box models constructed using a numerical simulator. Site-specific models may need to be developed if screening level models are inadequate or if screening level models determine potential risk. Inverse modeling may be used to calibrate complex models and provide information on sensitivity and predictive uncertainty where risks of violating hydrogeologic, environmental, or water quality constraints may be high. Optimization models may be used to design high value projects. Complexity to the modeling studies should only be to the level necessary for the project, as it can add exponential burden on time and effort.

The availability of specific guidance on modeling approaches that are appropriate for MAR-related objectives has been limited to date, particularly in terms of meeting local and/or state regulatory requirements. In the northeast region of the U.S., certain states require groundwater modeling to demonstrate that proposed stormwater infiltration designs will comply with design/performance standards and/or laws intended to prevent adverse effects to natural habitats such as wetlands (for example, NJDEP 2021). Thus, in these areas, similar modeling requirements may apply to MAR projects involving surface or shallow belowground infiltration. In western states, analytical or numerical groundwater modeling may be required under court decrees dictating practices intended to replace out-of-priority uses of groundwater (for example, Brown and Caldwell 2017).

General guidance on best practices in certain modeling disciplines (for example, numerical groundwater flow modeling) is more widely available (for example, guidance authored by the U.S. Geological Survey (Reilly and Harbaugh 2004), ASTM, and NGWA for various aspects of groundwater modeling and reporting). The textbook by Anderson, Woessner, and Hunt 2015 is an excellent reference.

4. Recharge Technologies

The Recharge Technologies section consists of five fact sheets. Each fact sheet will describe a method of recharge with multiple technology options. The technologies within a method will have many common features; however, where the technology details vary, the specific differences will be discussed in more detail at the end of the fact sheet. This approach was taken to reduce the amount of repeated material presented.

MAR technologies are divided into two categories, surface recharge and subsurface recharge. As a group of technologies, surface recharge systems (Fact Sheet FS-1 and Fact Sheet FS-2) are generally preferred for MAR because it is easier to control clogging of the aquifer and have the ability for contaminants to be attenuated in vadose zone processes that improve the water quality of recharge source water (Maliva 2020). Surface recharge technologies are also designed to passively recharge the aquifer (Herman Bouwer 2002), and sometimes natural features are used instead of engineered structures for surface recharge technologies.

Subsurface technologies involve recharge of the saturated zone of confined and unconfined aquifers and are covered in Fact Sheet FS-3, Fact Sheet FS-4, and Fact Sheet FS-5. Because the horizontal hydraulic conductivity of a given formation can be orders of magnitude higher than the vertical hydraulic conductivity, greater aquifer recharge rates can, in some instances, be obtained by recharging directly into an aquifer or vadose zone rather than by surface spreading (Maliva 2020). The subsurface recharge technology fact sheets provide information on technologies that recharge groundwater with wells and/or underground structures. Many of these technologies are well defined in other areas, such as stormwater control, but have been adapted to MAR by changing things such as scale and site selection.

Recharge technologies are often complemented by aquifer recovery technologies (for example, production wells; aquifer storage and recovery (ASR) wells; aquifer storage, transfer, and recovery (ASTR) wells) to more sustainably manage groundwater supplies and demands, spatially and temporally. Selecting the appropriate technology depends on many site-specific factors, including the target aquifer type, source water type, available land, overall project cost, and permitting and regulatory requirements. The costs of each of these technologies are highly site-specific and cannot be generalized. Some of the case studies provided include cost information, but these costs will not be relevant for all intended use cases. Surface recharge technologies typically are the most cost-effective method for recharging unconfined aquifers, while direct injection technologies provide a means for replenishing water into confined aquifers or aquifer zones located below low-permeability geologic material that would otherwise impede groundwater recharge. Table 4-1 shows which recharge technologies are applicable for various intended uses.

Table 4-1. Applicability of recharge technologies for intended uses

Intended Use	Surface Recharge Technology		Subsurface Recharge Technology		
	Fact Sheet FS-1: Infiltration Basin	Fact Sheet: FS-2: Diversion and Retention Structures	Fact Sheet FS-3: Injection Well	Fact Sheet FS-4: Dry Well	Fact Sheet FS-5: Infiltration Gallery
Water Supply Resilience	Yes	Yes	Yes	Yes	Yes
Subsidence Reduction			Yes		
Use of Floodwater	Yes	Yes			
Use of Stormwater	Yes	Ye		Yes	Yes
Mitigation against Saltwater Intrusion	Yes	Yes	Yes	Yes	Yes

Improving Groundwater Quality	Yes	Yes	Yes	Yes	Yes

Factors that distinguish surface and subsurface recharge technologies include:

- In general, better-quality, and higher compatibility source water is required for subsurface recharge technologies than for surface technologies because surface technologies typically provide an initial passive level of treatment (soil aquifer treatment) that occurs while water is being transported through the vadose zone and aquifer prior to and during recharging the saturated aquifer material.
- Factors that need to be considered when selecting, designing, and operating any of these recharge technologies include the potential impacts of the source water type(s) on the receiving aquifer and ambient groundwater quality. Impacts to the aquifer can be mitigated with careful planning, monitoring, and maintenance of facilities. Consideration should be given to assessing the variable frequency and duration of hydraulic loading to maintain optimal performance.

4.1 **Surface Recharge Technologies Overview**

The surface recharge technologies fact sheets provide information on infiltration basins and diversion and retention structures. Surface recharge technologies are conducted at or near ground level, designed to passively recharge the aquifer, and allow water to percolate into unconfined aquifers after the water has passed through the underlying sediments. This form of MAR technology typically filters the water prior to it reaching the aquifer. Streams, canals, or other surface water features are used for MAR, often in combination with reservoir releases in a measured, managed way. Also, extraction wells can be pumped to induce infiltration through the streambed and pretreat recharged surface water, resulting in a water supply from a process commonly referred to as riverbank filtration.

Infiltration basins (Fact Sheet FS-1) are typically shallow excavated impoundments with earthen walls that are used to pond water and can receive water of varying quality (for example, levels of pretreatment), intermittently or continuously, depending upon the source water type and availability, size of the basin, and the permeability (recharge capacity) of the underlying sediments and aquifer system. Retention structures (Fact Sheet FS-2) are other surface recharge technologies that are used to retain and divert available surface water into various natural geologic features (for example, ephemeral stream channels and sinkholes) by restricting surface water movement, which induces percolation of surface water through the subsurface. The water is retained behind the structure then percolates into the aquifer.

4.2 **Subsurface Recharge Technologies Overview**

The horizontal hydraulic conductivity of a given hydrogeologic material is often orders of magnitude higher than the vertical hydraulic conductivity of the same material, hence greater aquifer recharge rates can, in some instances, be obtained by recharging directly into an aquifer or vadose zone rather than by surface spreading (Maliva 2020). The subsurface recharge technology fact sheets provide information on technologies that recharge groundwater with wells and/or underground structures. The subsurface recharge technologies include injection wells (including ASR wells), dry wells, and infiltration trenches/galleries/pits.

4.2.1 Saturated Zone Technologies

Injection wells (Fact Sheet FS-3) are used to inject water directly into aquifers when the presence of confining layers prohibits recharge via percolation or unconfined aquifers when site-specific project conditions warrant their use. Injection wells penetrate the saturated zone and are used to directly recharge the aquifer. Injection wells, which are designed to recover water later (for example, during summer and/or droughts) from the same well, are defined as aquifer storage and recovery (ASR). An aquifer storage, transfer, and recovery (ASTR) project is similar in concept; however, injection and recovery occur at separate locations, with extraction or “capture” of water taking place downgradient of the injection well. Recharging directly into the saturated zone using injection wells is an attractive option where storage capacity has been enhanced by historical pumping, and the aquifer has sufficiently high transmissivity to accommodate target flow rates.

4.2.2 Vadose Zone (Variably Saturated) Technologies

Dry wells (Fact Sheet FS-4) are gravity-fed wells located within the vadose zone and operate similar to surface infiltration technologies, as they passively recharge an aquifer using boreholes filled with perforated casing and permeable fill (gravel) material. Water introduced into the dry well infiltrates through the vadose zone and is filtered to improve water quality. Dry wells can help recharge groundwater below low permeability layers that would make infiltration basins impractical. Dry wells are often used in stormwater management applications and in urban locations where infiltration basins are impractical. Dry wells, however, have some limitations. If improperly designed, they can be challenging to maintain and keep clear of sediments. Also, depending on the infiltration capacity of the soils at the site, multiple dry wells may be necessary for the requisite volume of water to be recharged.

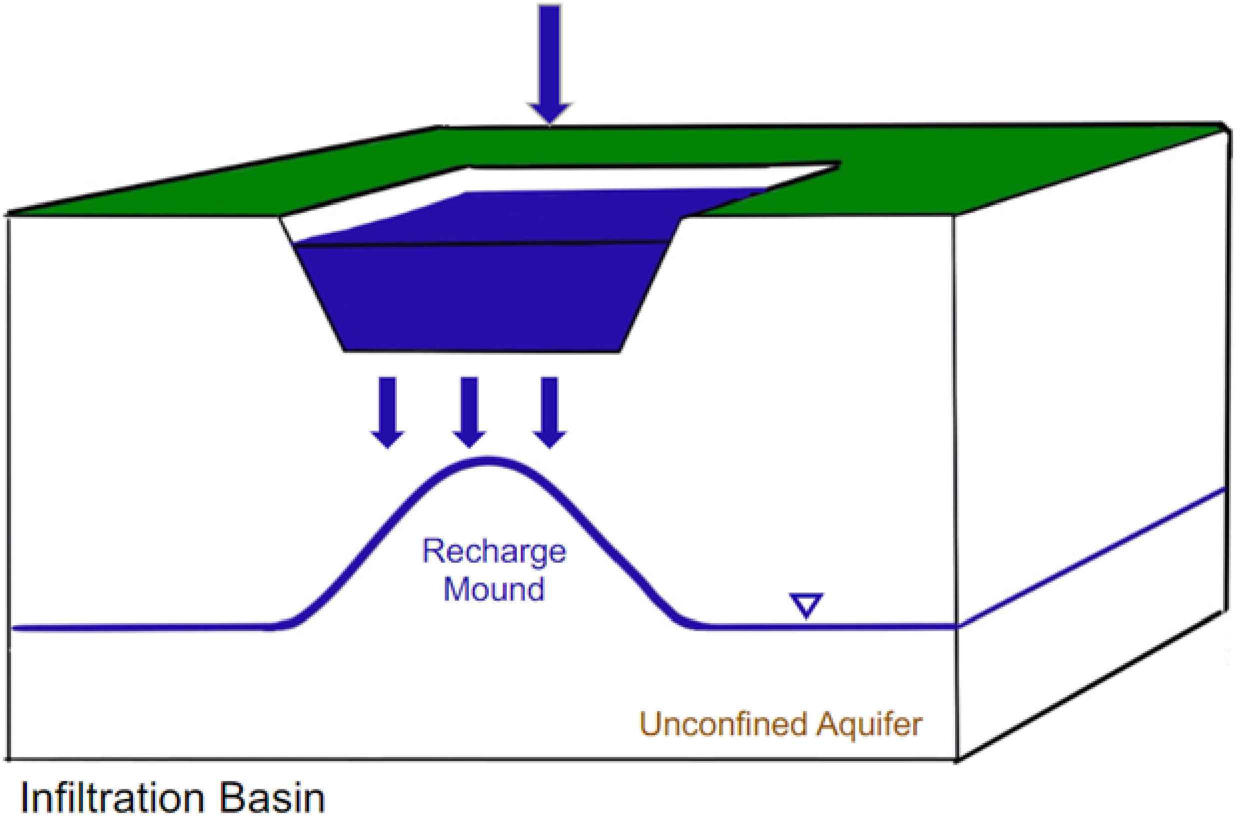
Infiltration galleries, trenches (French drains), and shafts (Fact Sheet FS-5) are subsurface structures that allow for rapid infiltration of water to the unsaturated zone. Infiltration galleries can be placed at near-surface shallow depths or deeper within the bedrock and can be engineered using simple designs, such as gravel channels and French drains, or more complex subsurface structures. Infiltration galleries have similar limitations resulting from clogging due to TSS content in source water, which can be mitigated with adequate planning and maintenance.

Infiltration Basin Fact Sheet (FS-1)

ITRC Managed Aquifer Recharge Team
December 2023

Introduction

Infiltration basins (see figure below), including recharge basins, percolation ponds, rapid infiltration basins, and spreading basins, are types of managed aquifer recharge (MAR) used to passively recharge unconfined aquifers through infiltration and percolation from the ground surface. Infiltration basins are designed to add water to the aquifer throughout the year or over intermittent periods of time and are used to augment water supply, enhance declining water tables, or increase streamflows for environmental purposes, such as wetland rehabilitation and habitat protection. According to the (National Research Council 2008), surface spreading generally requires a diversion and retention structure, and an unconfined aquifer with infiltration capacity or storage capacity that can accommodate the required recharge scheme. Infiltration basins can vary in size from many acres of land to small ponds, pits, trenches, and channels. In parts of Arizona dry washes are used for enhanced recharge by placing source water into a normally dry river channel and letting the water percolate into the vadose zone.



Applicability

Infiltration basins are constructed when impermeable layers are not present below the intended recharge area. The construction of a basin requires a retention structure, such as an earthen bank surrounding the site, or by excavating into the ground. Basins can operate with minimal maintenance when high-quality water is the intended recharge source; however, compaction of the surface must be kept to a minimum to maintain the permeability of the unsaturated zone. Recharge water with high loads of suspended solids commonly requires maintenance to remove the clogging layer and restore infiltration rates.

Advantages

Infiltration basins are generally cost-effective when compared to other forms of MAR, such as injection wells (including aquifer storage and recovery (ASR wells) and aquifer storage, transfer, and recovery (ASTR wells), since infiltration basins recharge the aquifer by percolating water through the vadose zone (soil aquifer treatment). Soil aquifer treatment improves water quality through many physical and biological processes and generally helps minimize the need for pretreatment. Treatment (and recharge) of treated wastewater can be maximized as a result of soil aquifer treatment in infiltration basins by installing a layer of soil in the infiltration basin (Maliva 2020). Research has shown that certain organic materials are effective in reducing high nitrate concentrations in source water (for example, agricultural runoff) (for example, Schmidt et al. 2011; Gorski et al. 2020).

The main advantages of infiltration basins are:

- They are robust and usually fail safe.
- Less operator technical expertise is required for their operation.
- They provide some underground storage to absorb seasonal or other differences in supply and demand.
- They enhance the public acceptance of reuse by breaking the pipe-to-pipe connection between the treatment plant and reuse activity (the water loses its identity as sewage water) ((H. Bouwer, Rice, R. C., and Bouwer, E. J. 1983); Herman Bouwer 1991).
- They are usually less costly than injection well systems.
- Operation and maintenance are easy.

Limitations

Utilizing infiltration basins to recharge an aquifer is a passive approach that requires minimal utility cost compared to other MAR methods. However, project objectives often depend on proper site-specific characterizations because the size of the infiltration basin will vary based on subsurface material properties, which can be challenging to predict since subsurface characterization is often unknown or expensive to investigate. The most important characterizations include determining correct infiltration rates of soils, the unsaturated zone, and the aquifer. Other aquifer characteristics and hydrogeologic investigations include determining the aquifer thickness, specific yield, hydraulic conductivity, heterogeneity, depth of the water table, and the timing of recharge. Each of these factors plays a role in determining a site plan and infiltration basin size. Basins that are improperly sized (too small) or have limited infiltration capacity can cause flooding. While large basins may be costly due to land acquisition, they may be cheaper to operate in the long term (Ross and Hasnain 2018). It is also important to make sure the vadose zone does not contain undesirable chemicals or contaminants that could leach into the receiving aquifer.

Clogging is also a limitation associated with infiltration basins because the performance of a basin deteriorates when clogging of the recharge areas increases. Clogging of basin sediments can occur due to settling of suspended solids and growth of algal biofilms (especially in the summer). Managing operational costs can be problematic when extensive clogging occurs but can be reduced through maintenance of the basin, such as drying and scraping the clogged layers from the surface. The scraped layers can be used to build the bank of the basin or may need to be hauled away from the site. Clogging layer removal and mitigation of excessive mounding of groundwater levels often require intermittent periods of dry basin conditions (no recharge occurring).

Disadvantages of infiltration basins include:

- They require large land areas, which can be a major constraint in already developed (for example, suburban and urban) areas.

- Soil aquifer treatment does not remove all organic contaminants.
- Soil aquifer treatment does not remove salts, and a modest salinity increase can occur due to evaporation, leaching of salts in the soil, and the atmospheric deposition of salt as dust and aerosols.
- There’s a potential for insect production (midges, mosquitos) and odors.

Performance

Infiltration basin performance is often monitored using the following metrics:

- cumulative recharge volume (for example, total recharge in acre-feet)
- volumetric recharge rate (for example, acre-feet per year, millions of gallons per day, and cubic feet per second)
- infiltration (percolation) rate (for example, feet per day)

Each performance metric has advantages and limitations. Cumulative and annual recharge volumes are useful for big-picture performance tracking and planning fiscal year budgets by determining what the marginal cost of water per acre-foot ($/acre-foot) for ratepayers should be to evaluate the cost/benefit for developing, operating, and maintaining MAR projects, programs, and portfolios. In California, some water agencies must prepare and defend their capital improvement program budgets with the California Public Utilities Commission. Daily volumetric and infiltration rates are useful for understanding current and recent trends in basin performance.

Typical recharge rates of infiltration basins vary in the range of 20–300 acre-feet/year (USEPA 2003). Recharge performance can be impacted by clogging layer development, seasonal temperature, and development (mounding) of shallow water tables. Bouwer (2002) described a conceptual model that supports the idea that excessively deep ponded water can compress the clogging layers and further reduce infiltration rates. Academic research projects have used various combinations of site-specific data (for example, sediment cores and grain size distribution analysis, infiltrometer tests, chemical tracers such as SF6 (Gerenday et al. 2020), temperature as tracers (Racz et al. 2011; Becker, Bauer, and Hutchinson 2012; Mawer et al. 2016; O'Connell, Patrick James 2019; Medina et al. 2020), water level data, and inflow rates) and modeling (Frei et al. 2009; Yonatan Ganot et al. 2016) to better understand the dynamics that impact infiltration basin performance. Research has shown that there is a benefit to measuring and monitoring infiltration rates (for example, using temperature as a tracer) with water level data (for example, surface water stage and groundwater levels) to track changes in hydraulic conductivity (Lamontagne et al. 2014).

The performance of infiltration systems depends on a variety of factors, including areal extent, source water quality, and hydrogeologic setting. Table 1 of Orange County Water District (OCWD) Surface Recharge System Operations Manual (OCWD 2021) shows that maximum recharge rates range from 3 to 120 cubic feet per second (cfs) among their 22 recharge basins. One of the highest performing recharge basins is the La Palma recharge basin, largely due to using almost entirely highly treated recycled water from the OCWD Groundwater Replenishment System (GWRS) with essentially no total suspended solids (TSS) content (minimal clogging potential). In the Kings Subbasin of the San Joaquin (Central) Valley of California, the 15 recharge basins covering 600 acres exhibit recharge performance varying between 360 and 2,200 acre-feet per year (KRCD 2021).

Regulatory Considerations

Regulatory considerations vary by state but may require a water right or permit to divert and/or recharge water, in addition to possible regulatory oversight to recover recharged water. Because recharge is conducted through infiltration, rather than injection, the U.S. Environmental Protection Agency (USEPA) does not regulate infiltration basins as they do with ASR wells; however, some states have requirements for groundwater level depths beneath basins.

Some examples of state requirements for minimum vadose zone thickness between the basin land surface; travel times; and water table to be considered adequate for nitrogen and contaminant removal of source water that consists of recycled wastewater (Maliva 2020) include:

- **Delaware**—At least a 2-foot thickness between the basin surface and mounded water table (Turkmen et al. 2008).
- **Nevada—**At least 10-foot-thick vadose zone, and at least 40 feet depth to an impermeable layer (BWPC 2017).
- **Florida**—Demonstrate that the mounded water table will not intercept the ground surface or interfere with reasonable uses of nearby properties.
- **California**—The permitting of a recharge basin (a discretionary project) that is not exempt from the California Environmental Quality Act requires the lead agency to prepare an initial study to determine whether the project may have a significant adverse impact on the environment. Typically, this results in a Mitigated Negative Declaration or requires an Environmental Impact Report; however, due to the extreme drought conditions exhibited in the greater southwest U.S., the California governor issued an executive order on March 10, 2023, to temporarily bypass these environmental regulations to make it easier to capture floodwater associated with rainfall and anticipated snowmelt from above-average winter snowpack to recharge groundwater (Governor Newsom Issues Executive Order to Use Floodwater to Recharge and Store Groundwater | California Governor).

If recycled water is used in the infiltration basin, the siting must be provided for a 6-month travel time to the nearest drinking water well as required by California Code of Regulations Title 22 Groundwater Replenishment Reuse Project Regulations. Because of the long travel times to drinking water well receptors, California allows a default credit of 1-log virus reduction for every month of retention time. The travel time estimated can be modeled initially; however, after the project is constructed, the travel time is required to be verified with a tracer study.

Riverbank filtration can be used to help utilities meet the USEPA Long-Term 2 Enhanced Surface Water Treatment Rule to protect against the health effects associated with *Cryptosporidium* in surface water used as a drinking water supply (USEPA 2022a).

Stakeholder Considerations

Infiltration basins generally require a large footprint of land to recharge high volumes of water for subsequent recovery. Stakeholders can take a position of opinion on many aspects of a MAR project, such as concerns with surface water diversions, land acquisition, and groundwater quality. Points of contention can also arise anytime throughout the duration of a project. Research suggests stakeholders, including the public, require project transparency. This includes consideration of communicating technical knowledge in a manner that is accessible to those without technical backgrounds and consideration to those whose cultural heritage is tied to land (Kurki and Katko 2015).

Lessons Learned

MAR involving passive infiltration is a common approach to recharging unconfined aquifers; however, site-specific characterization of the aquifer and the unsaturated zone is important to estimating an infiltration basin size with respect to the desired recharge volume. Although infiltration basins are less expensive to operate than injection wells, soil compaction and clogging will reduce infiltration capacity. Regular maintenance to retain infiltration and percolation rates is common and routine. This usually consists of scraping the biofilm/fine layer that accumulates on the bottom of the basin.

When it comes to using advanced treated wastewater (ATW), the OCWD learned after the first couple years of operation of their La Palma recharge basin that the ATW delivered 14 miles inland from the advanced groundwater Treatment Facility, via the groundwater replenishment system, contains such low levels of impurities (for example, TDS) that it leaches mineral content from the concrete distribution line. The lesson learned is that it is important to consider investing in epoxy lining for concrete distribution lines that use ATW (for example, reverse-osmosis-level treated wastewater or desalinated seawater). While mineral leaching is not unique to MAR, it is an important consideration for any project dealing with very low TDS waters.

Case Studies (FS-1)

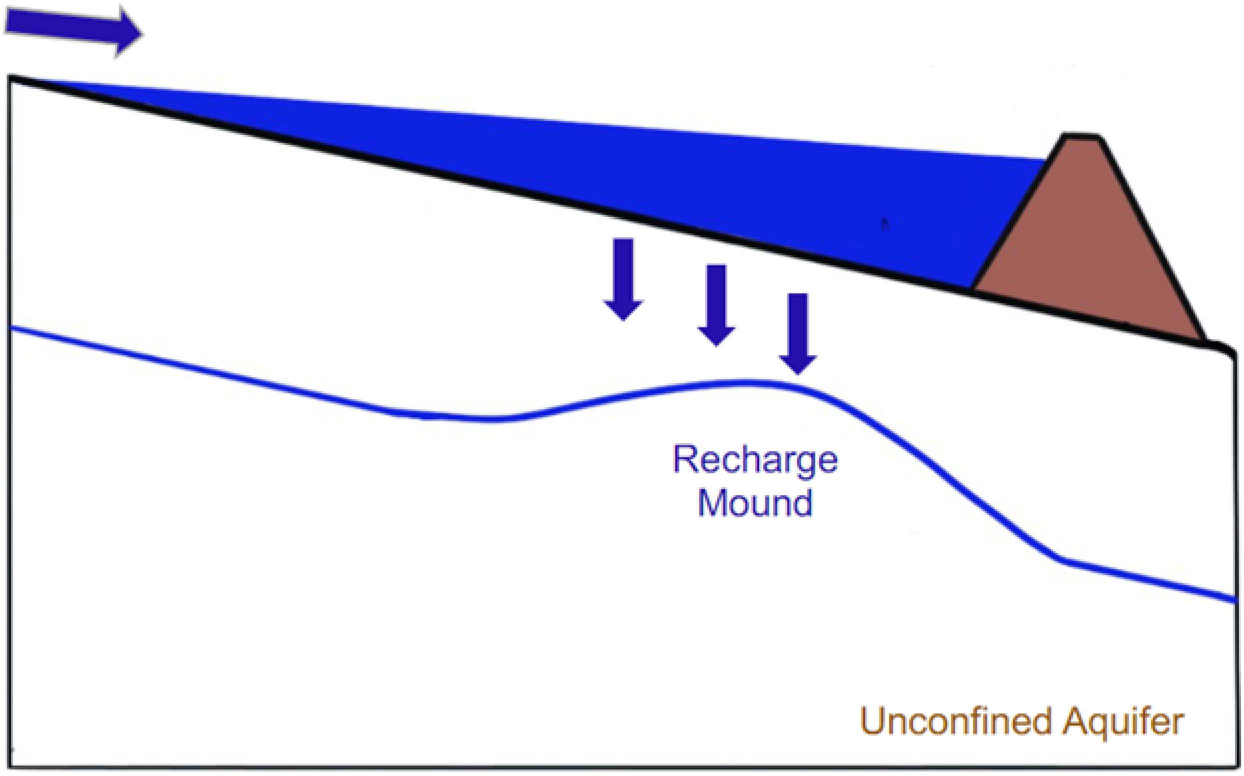
- Orange County, California—Maximizing Infiltration Rates by Removing Suspended Solids: Results of Demonstration Testing of Riverbed Filtration in Orange County, California
- Central Arizona—Central Arizona Project (CAP) Recharge Program—Increasing the reliability of water supplies
- Walla Walla, Oregon—The Walla Walla Basin Watershed Council (WWBWC) managed aquifer recharge program (see also Walla Walla Water Basin Case Study 5.9).

Retention Structures Fact Sheet (FS-2)

Introduction

Retention structures are often critical components for development of a managed aquifer recharge (MAR) program or portfolio that relies on several MAR projects and technologies. Aquifer recharge retention structures (see figure below) are typically impoundments, built along natural runoff channels or, in some cases, in the form of channel structures, which are designed to percolate water to recharge the aquifer. The goal of such structures is to route surface water to where recharge is needed most and slow the flow of surface water to maximize capture of source water for recharge within watersheds (for example, to augment baseflow in stream channels for ecosystem resilience).

A retention structure is usually a dam (dike, levee, embankment) that captures surface water (stream) flow or storm runoff to maximize the amount of water that is recharged (at the expense of less surface water flow downstream). Rubber inflatable dams can also be used as retention structures. Weirs can be a component of such retention structures and can be constructed upstream of the dam and at the spillway to measure inflow and outflows. Retention ponds are typically small (usually less than 5 acres) but may be placed in series to increase system capacity.



Retention Structure

Figure 1 provides an example of a retention structure MAR program for the Orange County Water District's (OCWD) Surface Recharge system.

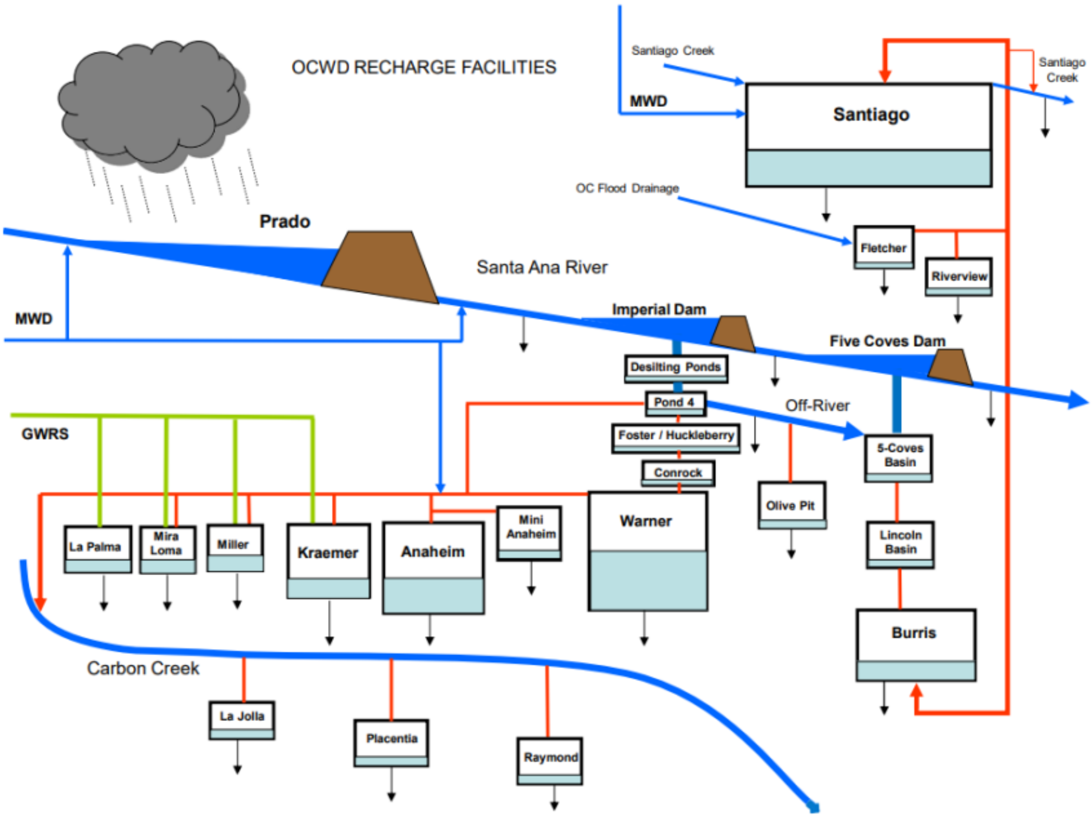


Figure 1. Schematic of diversion (shown by arrows) and retention structures in MAR program for Orange County Water District's Surface Recharge system.

Source: OCWD (2021)

Other examples of emerging diversion and retention structure surface recharge technologies include the following pilot programs in California:

- Agricultural Flood-MAR is a recent development that is being pilot-tested in California. It involves flooding farmland to replenish aquifers—for example, Merced Irrigation District's Mariposa Creek Flood-MAR pilot project. The geochemical processes and potential water quality benefits and concerns are being studied (Levintal et al. 2023).
- The Recharge Net Metering (ReNeM) concept (Kiparsky, M. et al. 2018) to incentivize groundwater recharge is being tested with a pilot program initiated in Pajaro Valley, Santa Cruz County (Miller, Fisher, and Kiparsky 2021). The goal of ReNeM is to give farmers monetary incentives to augment stormwater capture for recharge in return for receiving pumping credits against their groundwater pumping fees balance. In an abstract sense, this concept is similar to issuing carbon storage credits for CO_2 emitters that practice carbon sequestration (injection).

Applicability

Retention structures used in recharging aquifers have the following objectives:

- maintain or augment groundwater levels in the aquifer
- conserve available surface water (storm flow) by transferring it to subsurface storage
- reduce the impact of downstream flooding by altering the storm flow-base flow balance within a watershed
- augment spring flow, which also enhances flow in spring-fed streams
- enhance streamflow during seasonal dry periods or in response to drought or climate alterations
- maintain minimal in-stream flows to protect endangered aquatic species and/or riparian ecosystems

- combat saltwater intrusion by using recharge to create and maintain a flow boundary, or hydraulic barrier, between the intruding saltwater and the freshwater aquifer

Recharge structures should be planned after proper hydrogeologic investigations are carried out for selection of the recharge site and design of the structure. These investigations should include:

- characterize subsurface geology
- determine the presence or absence of impermeable layers that may impede infiltration
- determine the amount of drainage area that will flow into the structure and calculate storage
- determine the depth to the water table and groundwater flow direction
- calculate the maximum rate of recharge that can be achieved at the site
- evaluate water quality to ensure groundwater geochemical compatibility
- evaluate benefit/cost considerations

Advantages

Advantages of retention structure MAR technologies include:

- reducing the peak flow rate and cumulative volume of flood flows to retain more surface water for recharge, while reducing the risk of flooding and/or amount of water lost downstream (for example, to an ocean)
- allowing suspended solids to settle out, improving water quality, and reducing the clogging potential before conveyance to a recharge facility
- lower capital costs to build temporary retention structures (for example, rubber dams) than permanent retention structures (for example, earth/concrete dams or infiltration basins)

Limitations

Limitations of diversion and retention structure MAR technologies include:

- The aquifer needs to be unconfined and without significant impermeable layers so that surface water can infiltrate into the subsurface.
- Not every unconfined aquifer is conducive to the use of retention structures (for example, shallow aquifers with high water tables do not have much recharge capacity).
- Retention structures need to be located at strategic locations along channels, depending on the local physiography.
- In the case of agricultural Flood-MAR, the land may be unsuitable for desired infiltration rates (resulting in excessive ponded conditions that may damage crops) and/or the land may be impacted with salts, pesticides, and/or herbicides that could leach and contaminate the target aquifer.

- Placing a retention structure in an existing stream/river channel may present a constraint for flood control. The project may need to work with local flood control districts and potentially the U.S. Army Corps of Engineers (USACE). In coastal streams, there could be issues with the U.S. Fish and Wildlife Service (USFWS) and National Marine Fisheries Service (NMFS).

Performance

It is important that MAR projects are evaluated with objective and quantitative metrics to minimize ambiguity in how success is defined and evaluated (Maliva 2020; Maliva and Missimer 2010). Like other recharge technologies, the performance of diversion and retention structures is typically measured and monitored using volumetric measures (for example, recharge and recovery rates and volumes) and evaluated with economic metrics (for example, cost/volume and benefit/cost ratio).

Examples of volumetric performance metrics include recharge rates associated with diversion and retention structures used by OCWD along the water district's 6-mile portion of the Santa Ana River, which is at the core of the water district's MAR program and can recharge up to 65 mgd of water (OCWD 2021). When it comes to a comparison of recharge and recovery volumes, Figure 2 shows an example comparison of cumulative recharge volumes associated with a retention structure (for example, an infiltration basin) (Pajaro Valley Water Management Agency 2018).

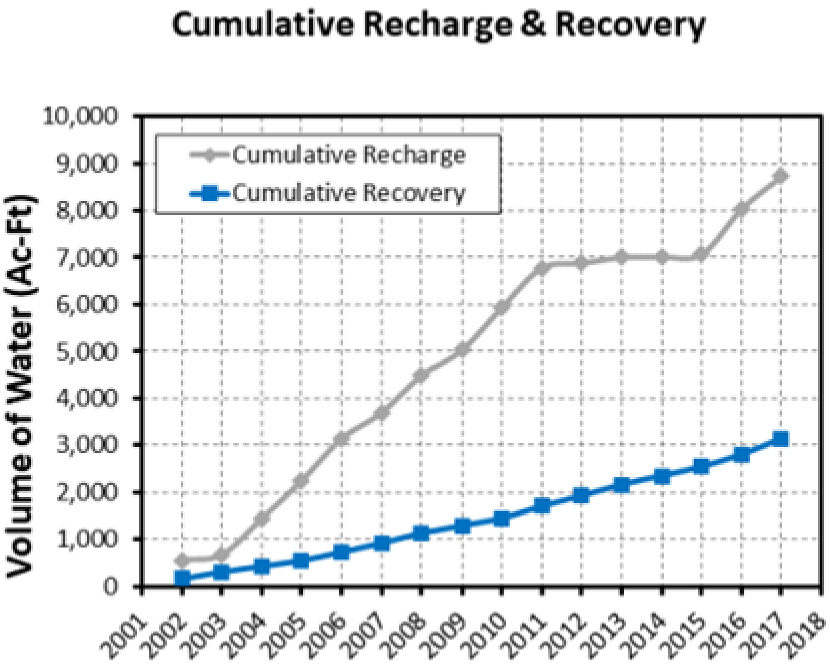


Figure 2. Example comparison of cumulative recharge and recovery volumes over time.

Source: Modified from Figure 15 of Pajaro Valley Water Management Agency (2018)

Examples of economic performance metrics in Ross (2022) show the advantages of MAR based on the benefit/cost ratio of several MAR programs across the globe. The Idaho Eastern Snake Plain aquifer has demonstrated low costs since 2014, accounting for capital cost; conveyance fees; and operation, maintenance, and monitoring costs (Hipke, Thomas, and Stewart-Maddox 2022).

Regulatory Considerations

Retention structures, especially if streamflows or streambeds are modified, typically require some type of permitting through state and federal regulatory agencies including:

- federal agencies with oversight of dams and flood control infrastructure (for example, Federal Emergency Management Agency (FEMA), Federal Energy Regulatory Commission (FERC), USACE, U.S. Bureau of Reclamation (USBR)) and/or environmental (for example, USEPA, USFWS, and NMFS) regulations
- state agencies with oversight of water rights and quality (for example, the California State Water Resources Control Boards (SWRCB), or New Jersey, which requires several permits, such as flood hazard area and wetland permits for dam diversion structures)
- local governments (for example, an adjudicated basin watermaster or special district)

Stakeholder Considerations

Various types of stakeholders that are typically involved with MAR projects span the private and public sectors, namely owners, operators, regulators, ratepayers, consultants, academics, and environmental agencies. Stakeholders that provide financial support for retention and diversion technology expect to get cost-effective benefits from MAR programs. Ideally, retention and diversion structures result in stable water supplies and project costs, especially in the face of climate uncertainty. Collaboration among the various types of stakeholders is ideal for addressing complex water resource management issues.

Regulatory stakeholders are primarily concerned with public safety. Examples include the USACE's role in ensuring flood control, and federal and state agencies' roles in regulating water quality for the protection of human consumption and ecological habitat. When it comes to diverting and retaining water, it is important for MAR program sponsors to be mindful of environmental stakeholders regarding ecologically sensitive habitat (for example, flora and fauna) that are subject to the Endangered Species Act. Adverse impacts to aquatic habitat and fish are often mitigated by installing fish screens and ladders, as well as substantial permit fees.

Collaboration among stakeholders on MAR programs can be critical for achieving sustainable water supplies. For example, projects sponsored by the Los Angeles Department of Water and Power (LADWP) and the Water Replenishment District (WRD) in Los Angeles County, California, are investing in recharge and recovery technologies to improve water supply resilience by reducing reliance on imported surface water supplies (from hundreds of miles away in Northern California and the Colorado River) and impacts to stakeholders in regard to uncertainty of future climate conditions.

Lessons Learned

Examples of lessons learned regarding retention and diversion recharge technologies, include:

- It is important for buyers and sellers of retention and diversion infrastructure, spanning private and public sectors, to participate in water banking projects as part of water markets (Ayers et al. 2021).

- There are potential impacts to environmental stakeholders due to diversion of surface water flows from navigable waters of the United States (for example, the interpretation of the Public Trust Doctrine by the NMFS).
- Collaboration among stakeholders helps realize mutual benefits. For example, federal agencies (for example, USACE and USBR) have been partnering with academic institutions (for example, the Scripps Institute of Oceanography) and water agencies (for example, OCWD and Sonoma Water) to develop Forecast Informed Reservoir Operations programs to optimize groundwater recharge, flood control, and protection of ecologically sensitive habitat.
- Pilot programs help stakeholders understand the advantages and limitations of emerging recharge technologies (for example, water markets, on-farm recharge, and ReNeM).

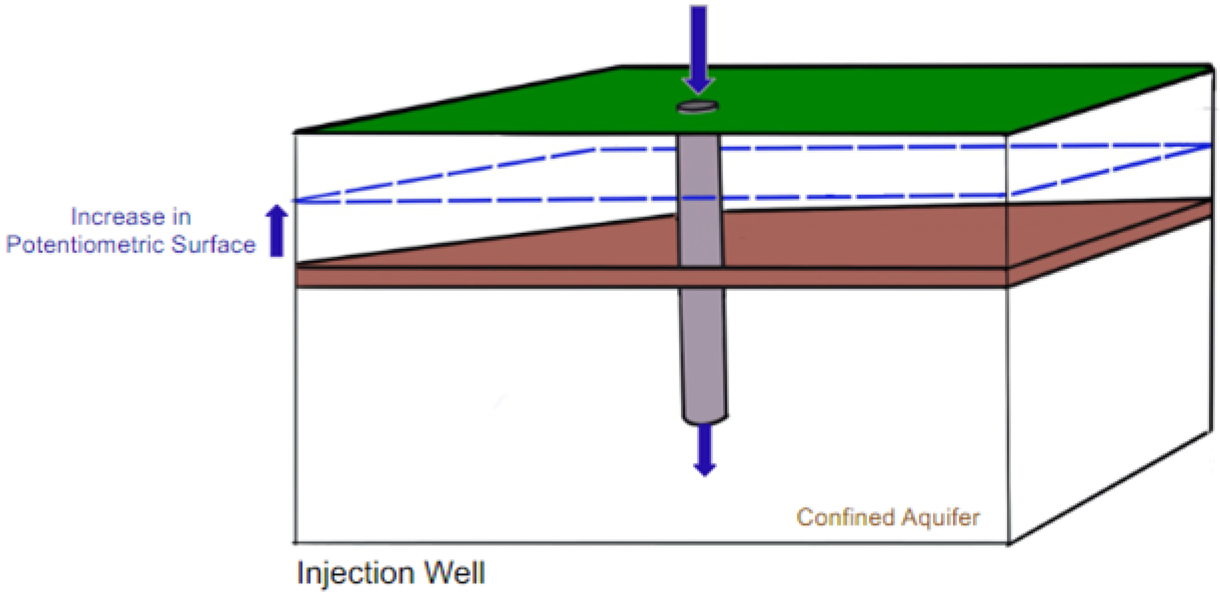
Case Studies (FS-2)

- Southern Idaho—Eastern Snake Plain Aquifer Recharge Program (see Case Study 5.6)
- Orange County, California—Orange County Water District's (OCWD) Groundwater Replenishment System—Groundwater Recharge to Address Seawater Intrusion and Supply in an Urban Coastal Aquifer | Case Studies in the Environment | University of California Press (ucpress.edu)
- Santa Cruz County, California—Pajaro Valley Water's Watsonville Slough System Managed Aquifer Recharge and Recovery Projects (https://www.pvwater.org/wss-marr) in the Pajaro Valley of Santa Cruz County, California
- Santa Cruz County, California—Pajaro Valley Water's Coastal Distribution System (https://www.pvwater.org/the-coastal-distribution-system)
- Santa Cruz County, California—Pajaro Valley Water's Recharge Net Metering (ReNeM) pilot program (Incentivizing Groundwater Recharge in the Pajaro Valley Through Recharge Net Metering (ReNeM) | Case Studies in the Environment | University of California Press (ucpress.edu))
- Merced, California—Merced Irrigation District's Mariposa Creek Flood-MAR pilot project State Agencies Fast-track Groundwater Recharge Pilot Project to Capture California Flood Waters for Underground Storage—Multiple Landowners Can Divert Excess Flows from Mariposa Creek Near the City of Merced to Recharge a Key Groundwater Basin (goldrushcam.com)

Injection Well Fact Sheet (FS-3)

Introduction

Injection well usage as part of a managed aquifer recharge (MAR) program (typically an aquifer storage and recovery (ASR) well) became widespread in the 1990s. Injection wells (see figure below) developed as part of a MAR project are used to directly recharge water into deep porous or fractured geologic formations. Typically, the injected water serves to provide a future source for supply; however, the water may be injected to halt saltwater intrusion or alleviate subsidence issues. Injection wells are used for additional purposes that are not associated with water, such as carbon sequestration; injection of hazardous, radioactive, and nonhazardous wastes; injection of fluids for mineral solution mining and oil recovery (fracking); and injection of media for remedial action. However, for the purposes of this fact sheet, injection wells discussed will be limited to the three aquifer recharge purposes mentioned above (storage, saltwater intrusion, and subsidence control). As with the uses of injection wells, installation (various drilling methods), construction (various completion methods), permitting, operation, and closure of injection wells are important considerations and are regulated through the U.S. Environmental Protection Agency (USEPA) Underground Injection Control (UIC) program as required by the Safe Drinking Water Act (SDWA) (Clark, Bonura, and Van Voorhees 2005) or states with primacy.



Compared with typical recharge technologies that use surface infiltration as the recharge mechanism, injection wells require a significantly smaller footprint and can be advantageous in areas where land is scarce. A relatively high rate of recharge can be attained via injection wells.

Injection well depths can range widely depending on the target aquifer being recharged. Sources of water can vary (river, stormwater, mountain runoff, groundwater) and need to be analyzed for geochemical compatibility with the aquifer groundwater prior to injection. Because injection wells can be hundreds to thousands of feet deep and water is injected under pressure, their construction is important so that the well can be maintained throughout a long service life. In addition, ASR wells used for both injection and extraction may be subject to a high potential for corrosion and clogging. The operation and maintenance of an injection/extraction well, typically consisting of backwash cycling at a frequency determined by individual well performance and plugging rates, is crucial to sustain successful operational ability.

Applicability

Injection wells can be applied in any situation where it is desirable to introduce source water into an underlying shallow or deep aquifer; however, injection wells provide the greatest advantage where:

- the target aquifer is confined or beneath low-permeability deposits that impede surficial recharge
- real estate costs are prohibitive for surface recharge facilities
- there is a lack of groundwater availability

Replenishing groundwater supplies by artificial recharge through wells has been practiced in many areas, including many sites in California and more than a thousand recharge wells on Long Island, New York (Todd 1959; Signor, Growitz, and Kam 1970).

Aquifer Storage and Recovery (ASR)

As the benefits of employing MAR techniques continue to be developed and documented, wells are being used more often for aquifer recharge. ASR programs consist of dual-purpose wells that are used for both injection and extraction of water. ASR wells are designed and operated to store surface water supplies underground with the intention of later recovery during times of less surface water or groundwater availability (for example, dry seasons and drought periods as shown on Figure 1 and Figure 2). Conceptually, ASR well programs are developed where groundwater level gradients are relatively flat to allow for the formation of a “bubble” of stored water that can be captured with an acceptable percentage recovery. Pyne (2005) provided a thorough reference for the full life cycle process of developing ASR wells and programs.

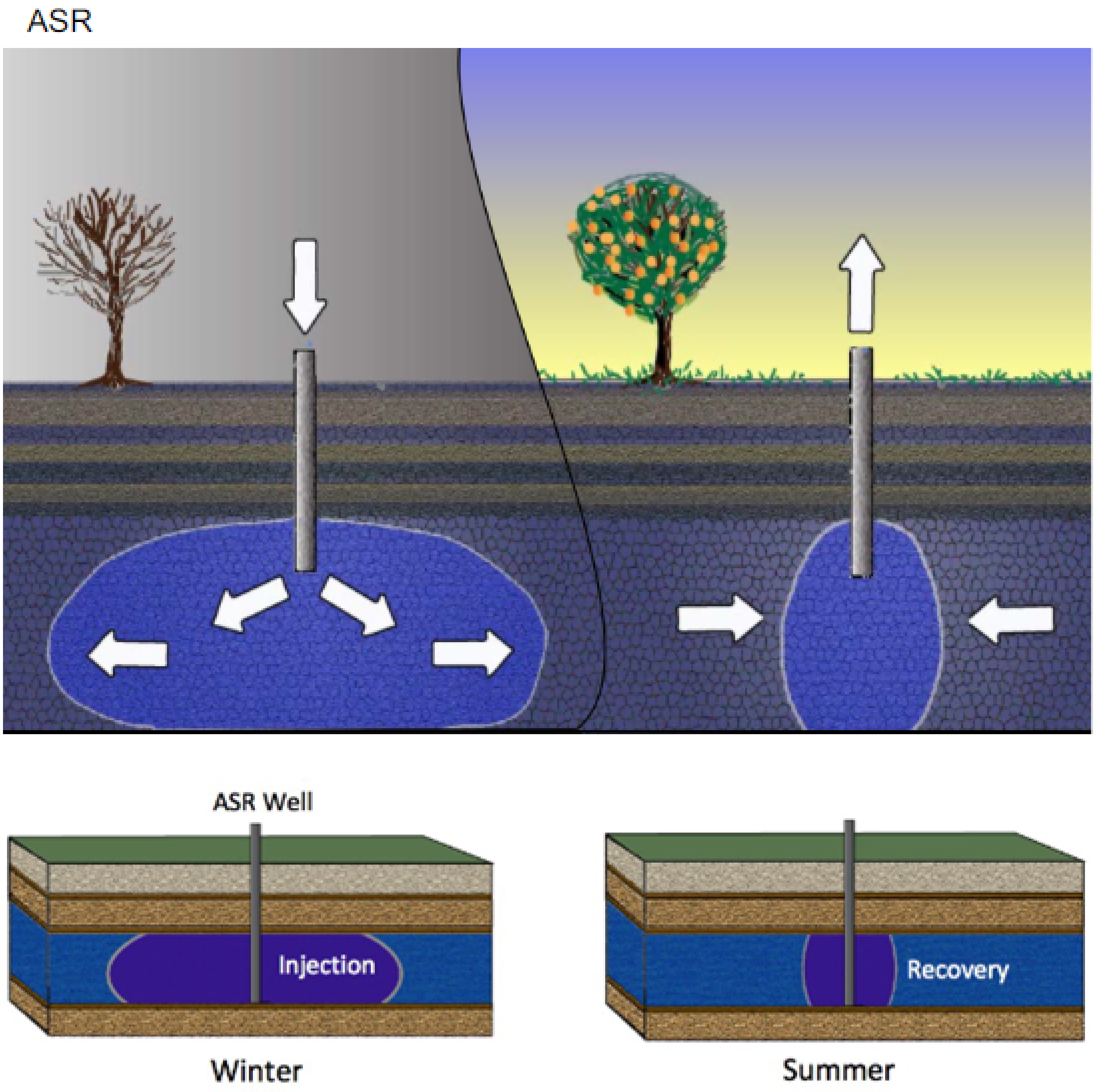


Figure 1. ASR system typically uses wells that are capable of injection and extraction.

Source: Gibson and Campana (2014)

Conceptually, ASR wells are typically used to inject water when surplus surface water is available, or demand is low (winter) and withdraw recharged groundwater during peak demand season (summer), as illustrated in the figure below. ASR wells may also be used to store water at night for recovery during the daily peak demand periods or during wet years and floods for recovery during dry years and droughts. Stored water may also be recovered during emergencies, such as waterline breaks, freezes, or power failures.

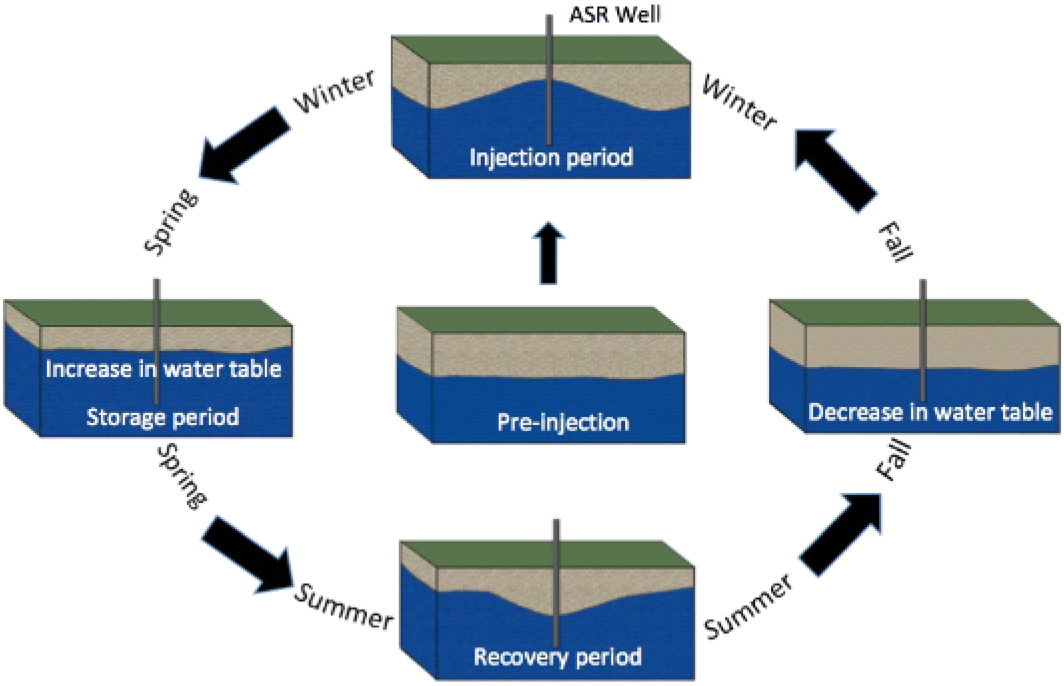


Figure 2. ASR wells inject water when surplus surface water is available and withdraw recharged water during peak demand season.

Source: Gibson and Campana (2014)

Aquifer Storage, Transfer, and Recovery (ASTR)

An ASTR system uses separate injection wells and extraction wells because the injected water migrates or “transfers” from the injection area to the extraction well (Figure 3). The primary advantage of ASTR over ASR is that it provides more uniform residence times and travel distances, which allow for more predictable attenuation of contaminants (Pavelic et al. 2005; Rinck-Pfeiffer, Pitman, and Dillon, 2005; Maliva 2020). The distance between the injection well and the extraction well, however, is typically small—around 300 feet or less—so that the extraction well is contained within the storage “bubble” radius of the recharge well. This distance is particularly important for attenuation in brackish and saline aquifers, or freshwater aquifers where there is a significant difference in water quality characteristics. The Parafield ASTR research project in South Australia is an example of an ASTR system that follows the Australian guidelines for MAR and demonstrated the ability to lower the salinity of the target brackish aquifer over the course of a couple years (Page et al. 2010).

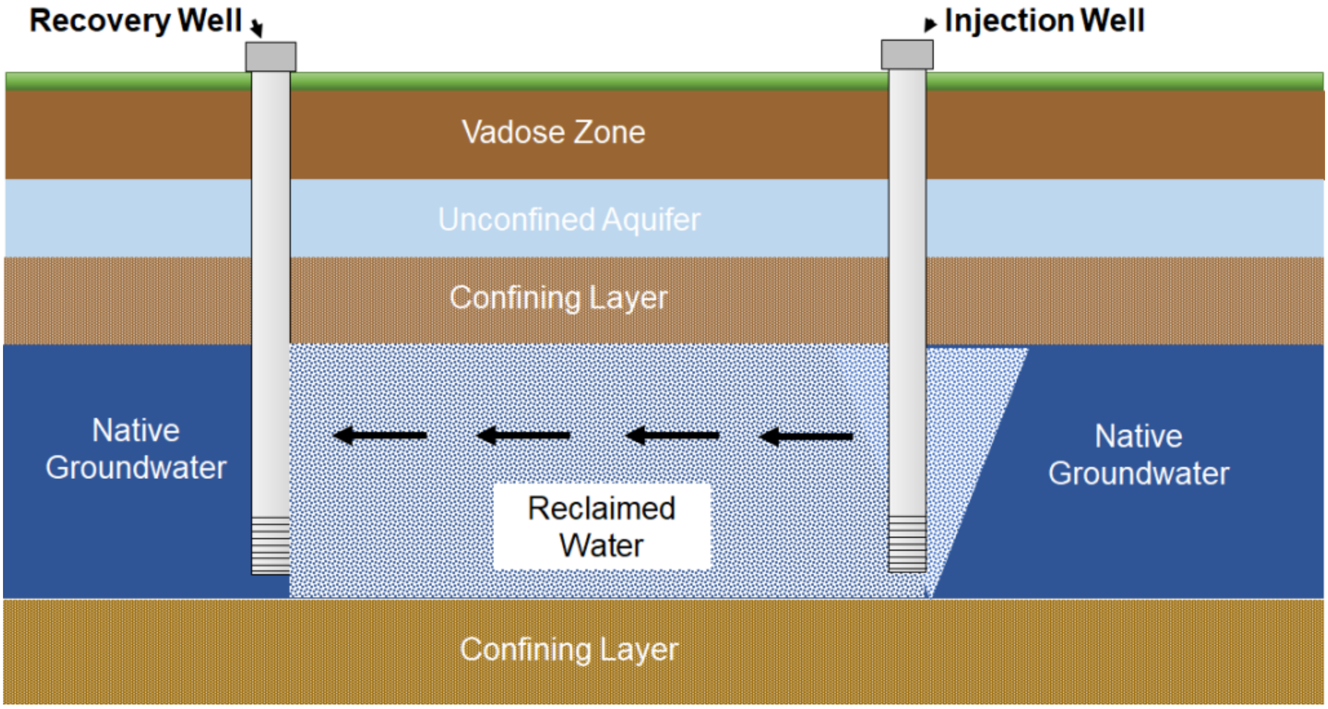


Figure 3. Conceptual diagram of ASTR system in a confined aquifer.

Saltwater Intrusion Barrier

Although rules and regulations vary by state for injection wells used for aquifer recharge and saltwater intrusion, in coastal areas saltwater intrusion into water supply and domestic wells is a common problem—particularly for areas where long-term pumping has significantly lowered the water table (NGWA 2023). To reduce the likelihood of saltwater intrusion, injections wells pump fresh water into an aquifer potentially affected by saltwater intrusion in an attempt to create a freshwater barrier. In some cases, the objective of injecting fresh water may solely be for reducing salinity of an aquifer or increasing water quality, and not to function as a barrier. An example of combating seawater intrusion with injection wells is provided in a case study of Orange County Water District's (OCWD) recharge program (Kiparsky et al. 2021). Another successful application of injection wells for mitigating seawater intrusion has been in operation in Los Angeles County since the early 1950s (Johnson 2007).

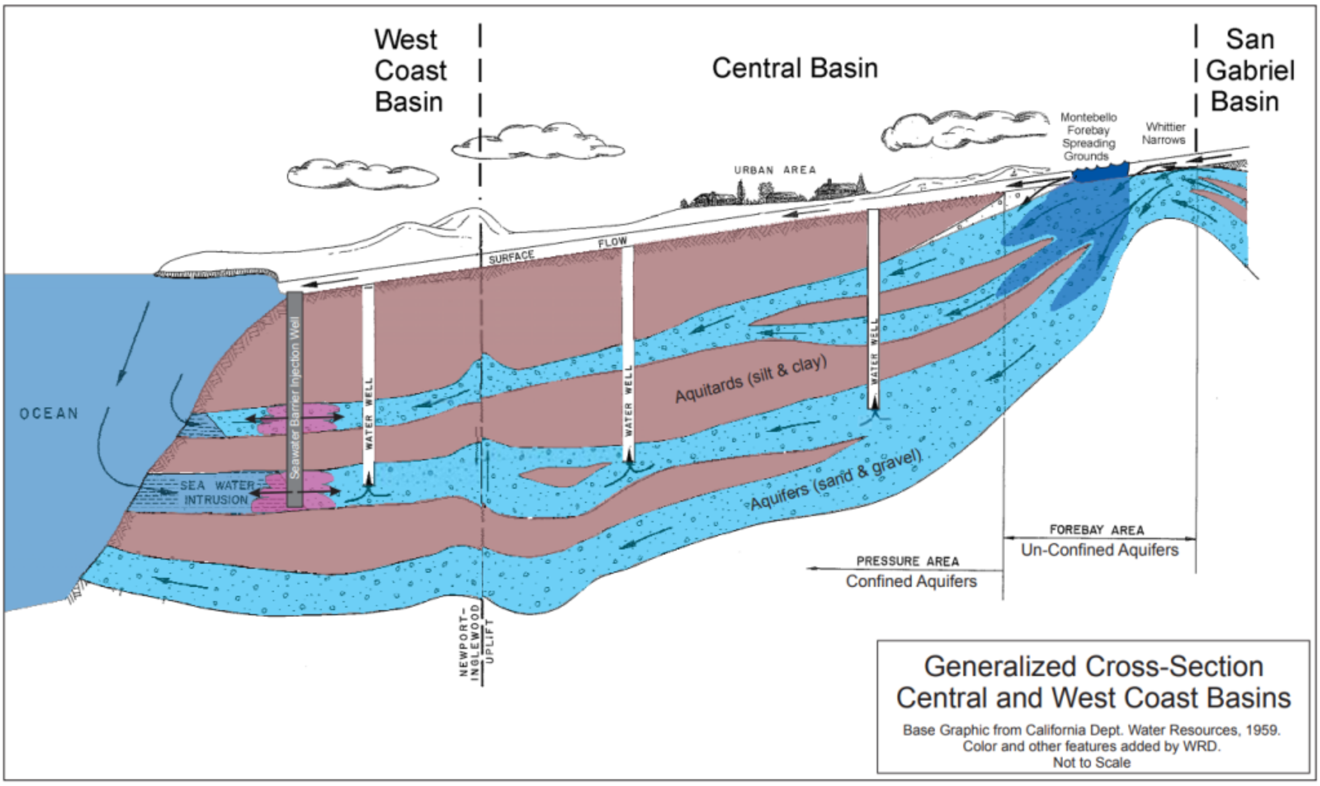


Figure 1.

Figure 4. Injection wells that are used to mitigate seawater intrusion in southern Los Angeles County, California.

Source: DWR (1959)

Today the West Coast Basin Barrier Project and Dominguez Gap Barrier Project are operated in by the Los Angeles County Department of Public Works and Water Replenishment District (WRD) (see Case Study 5.3). The West Coast Basin Barrier Project was designed and constructed in the early 1950s to prevent seawater from intruding into the underlying aquifers of the West Coast Groundwater Basin in Los Angeles County, while the Dominguez Gap Barrier Project injects clean water into the groundwater basin to prevent seawater from mixing into the drinking water supply. The Dominguez Gap Barrier is located along the Dominguez Channel in the cities of Wilmington and Carson. These projects are increasingly using recycled source water (advanced treated water (ATW)) to offset the reliance on surface water imported by the Metropolitan Water District of Southern California (MWD) from sources originating several hundred miles away (for example, the San Joaquin Delta in Northern California and the Colorado River). (*Figure 4*)

Subsidence Reduction

A common method to mitigate land subsidence involves repressurization of depleted aquifer layers. Injection wells are used to create a hydraulic barrier to ameliorate the extent of the cone of depression and generate an overpressure in geological units unaffected by pumping. This is done to build a hydraulic obstacle (or barrier) to mitigate or even reverse the compaction of aquitards and the subsequent changes in ground surface elevations (Gambolati and Teatini 2021). Aquitards are susceptible to subsidence. An example of this is in Long Beach, California, where injection wells have been relied upon for several decades to pressurize the aquifer to compensate for land subsidence due to oil production from shallow aquifers.

Advantages

As compared with other MAR technologies, injection wells have many advantages:

- The footprint of an injection well is relatively small; the wellhead is often a few feet in diameter. A slightly larger footprint will be necessary if a wellhouse is constructed as part of the system; however, the space for a wellhouse can be minimized to a 10-foot by 10-foot area. This small footprint allows flexibility in the location of the well installation.
- An injection well can be constructed to deliver the source water to a targeted aquifer that is hundreds or thousands of feet deep, or multiple aquifers, providing a significant amount of flexibility, especially as compared

to a surface infiltration method or a dry well.

- Unlike surface infiltration techniques or dry wells, an injection well can also be constructed to perform water extraction as well, as is typically done for ASR. The design of an ASR well, however, is different from the design of a well that is used only for injection. Another option is to construct a separate extraction well or well network downgradient of the injection well, which is the standard design for an ASTR system.
- The cost associated with constructing an injection well will vary depending on several factors: target aquifer depth, well diameter and materials, water treatment, and location (for example, an urban area). Due to the relatively fewer factors influencing the construction cost of an injection well, it could be considered a less expensive option (in comparison to the construction of a large reservoir for water storage).

Limitations

Limitations of injection wells include:

- Construction time for an injection well can also be considered a limitation because in comparison to an infiltration basin, drillers may be more difficult to schedule since it is a more specialized field as compared to earthmoving and infrastructure for conveyance of source water, lengthening the schedule and increasing costs.
- Injection wells will require routine operation and maintenance upkeep. Although a well-functioning injection well may run for years without any significant maintenance, an injection well will likely need more operation and maintenance attention than an infiltration basin.
- Another limitation of utilizing injection wells for aquifer recharge is the necessity for the investigation of favorable aquifers. The geochemical compatibility of the source water to be injected and the aquifer water must be evaluated to confirm that the recharge process does not negatively impact the aquifer (USEPA 2022d). Examples of negative impacts to groundwater quality due to injection of recharge water include the release of compounds, such as arsenic, particularly if the recharge water is relatively low in TDS.
- Construction costs for an injection well may be the least expensive option in comparison to the construction of a surface water reservoir. However, costs can be more significant when an injection well network is to be constructed, so the wells and their supporting infrastructure will generally cost more than other smaller recharge technologies. Also, injection wells can be less economical, costing more dollars per acre-foot of water delivered, if the conditions for an infiltration basin are available.

Performance

An injection well or injection well field can recharge water into a confined aquifer, which infiltration techniques using gravity feed cannot. This is similar to the soil infiltration capacity limitation of surface infiltration techniques. Injection of water into an aquifer; however, is dependent on the aquifer characteristics and injection pressures. Rancilio (1977) described in detail the typical design of a successful injection well, operating conditions and costs, injection rates and heads, clogging problems, and redevelopment of injection wells. High formation pressures can develop within the receiving aquifer, especially in confined aquifers, and significantly reduce how rapidly water can be recharged. An example range of typical injection rates for the Los Angeles seawater intrusion barrier is about 95–450 gpm (Rancilio 1977; Poland 1984).

Regulatory Considerations

The USEPA regulates the construction, operation, permitting, and closure of injection wells through the UIC program as required by the Safe Drinking Water Act (USEPA 2022c). Most states have primacy—authority to implement and oversee their own UIC programs; the USEPA directly implements programs in the remaining states (Figure 5) and tribal lands. For objectives such as ASTR or ASR, the state may have additional permitting and regulations in addition to those of the USEPA UIC program.

The USEPA conducted a study of Class V underground injection wells to develop background information the agency can use to evaluate the risk that these wells pose to underground sources of drinking water (USDWs) and to determine whether additional federal regulation is warranted (USEPA 1999).

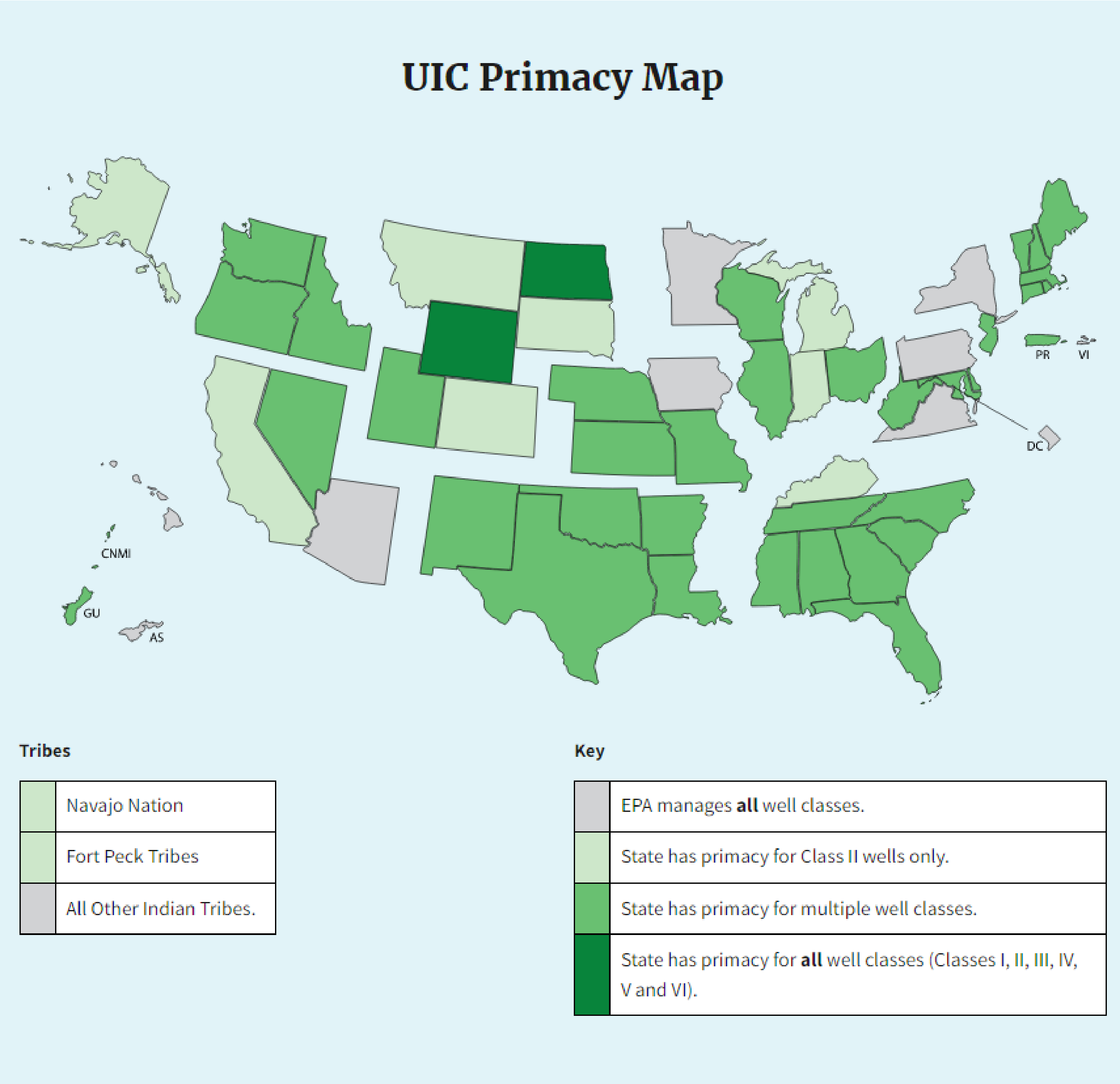


Figure 5. UIC program implementation (tribes are not depicted on map, colors for tribes relate to key—Navajo Nation and Fort Peck Tribes have primacy for Class II wells; USEPA manages all well classes for all other tribes).

Source: *USEPA (2022)*

A review of laws or agencies that may be involved in implementation of an injection well program includes the following:

- USEPA UIC program (Aquifer Recharge and Aquifer Storage and Recovery | USEPA), specifically injection wells that target USDW
- USEPA Source Water Protection (SWP) (Source Water Assessments | USEPA), including state source water assessment programs (SWAPs) under the Clean Water Act
- Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)
- state agencies
- local governments

- tribal governments

In California, the State Water Resources Control Board (SWRCB) has general waste discharge requirements for ASR projects that inject drinking water into groundwater (California Water Boards 2021), which include considerations for the California

Environmental Quality Act. Since 2015, the state has issued 22 temporary permits, primarily in the San Joaquin River watershed.

Stakeholder Considerations

Injection wells can have impacts on aquifers that provide significant water resources to an area. These can be of concern to stakeholders worried about supply and water quality. The source water may also concern stakeholders regarding water rights, source water protection (SWP), and water table fluctuations. The concerns are often addressed with modeling and analysis of water level, water quality, and tracer data. Periodic testing and monitoring of water quality and the injection well may also address public concerns. The Alamitos seawater barrier injection system, operated jointly by the Los Angeles County Department of Public Works, WRD, and OCWD, has some water that eventually migrates inland and is captured by production wells (effectively creating an ASTR component).

Lessons Learned

Injection wells can be critical components of a MAR program for recharge (replenishment) of confined and unconfined aquifers and can be coupled with recovery technologies (for example, ASR and ASTR) to provide greater water supply resilience and operational flexibility. Injection wells are well suited for introducing large volumes of water into compatible aquifers in short periods of time. An injection well program can also be a cost-effective way of managing an aquifer recharge program even in high population centers. The successful implementation of an injection well program requires a thorough aquifer characterization, an understanding of the geochemical compatibility of the source and aquifer waters, and effective monitoring and maintenance on the system.

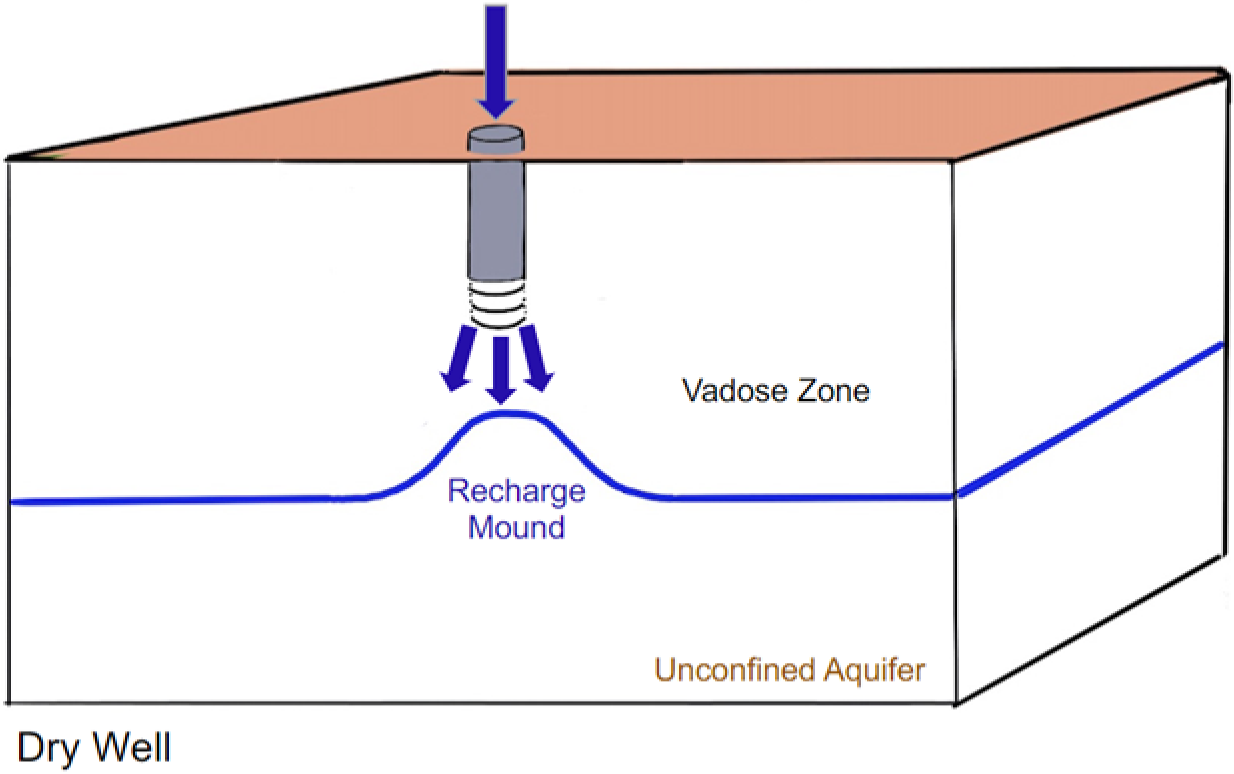
Case Studies (FS-3)

- San Antonio, Texas—San Antonio Water System H2Oaks Center ASR Project (SWIFT Home | HRSD.com) (see Case Study 5.4)
- DeLand, Florida—Using a Simple, Low-Cost, Injection Water Pretreatment System to Reduce the Concentration of Naturally Occurring Arsenic and Other Trace Metals in Recovered Water during ASR Operations, City of DeLand, Florida, Airport ASR Facility (see Case Studies 5.2)
- Moorpark, California—Las Posas Basin ASR program (Ventura County), Las Posas Basin-Groundwater Geek (Beamer, Kendall, and Mulligan 2012)

Dry Well Fact Sheet (FS-4)

Introduction

Dry wells are gravity-fed excavated pits, typically large diameter (up to 72-inch diameter or more), lined with perforated casing, and backfilled with gravel or stone (see figure below). Dry wells penetrate layers of impermeable soil with poor infiltration rates to reach more permeable layers of soil, allowing for more rapid infiltration of water. Dry wells may be proposed in places where space is at a premium and where there are impermeable surface soils. Urban settings where infiltration basins are too big may be ideal for dry wells. Historically they have been used in conjunction with low-impact development practices to reduce the harmful effects that traditional stormwater management practices have had on the aquatic ecosystem (Pi, Ashoor, and Washburn, undated). They are being used more and more for managed aquifer recharge (MAR) applications, such as augmenting a groundwater supply as the primary function, instead of disposing of stormwater. Dry wells were used on Long Island, NY, to inhibit saltwater intrusion. Care must be taken, however, to ensure the stormwater does not adversely affect the groundwater with contaminants in the form of sediments or chemicals; this can be addressed via pretreatment.



Although the design of a dry well is based on site-specific conditions, most dry wells are 30–100 feet deep and 3–6 feet wide at the surface. Dry wells are often (but not always) lined with perforated casings and can be filled with gravel or rock or left empty. Today, dry wells usually include some form of pretreatment to remove oil, particles, and associated contaminants, reducing the risk of clogging the wells and of creating a conduit to introduce contaminants into a shallow aquifer (E. C. Edwards et al. 2016). Dry well systems are being tested in Northern California using a sedimentation well for pretreatment that filters source water before infiltrating the water through a dry well (Figure 1). Dry wells are prevalent in Utah and Arizona.

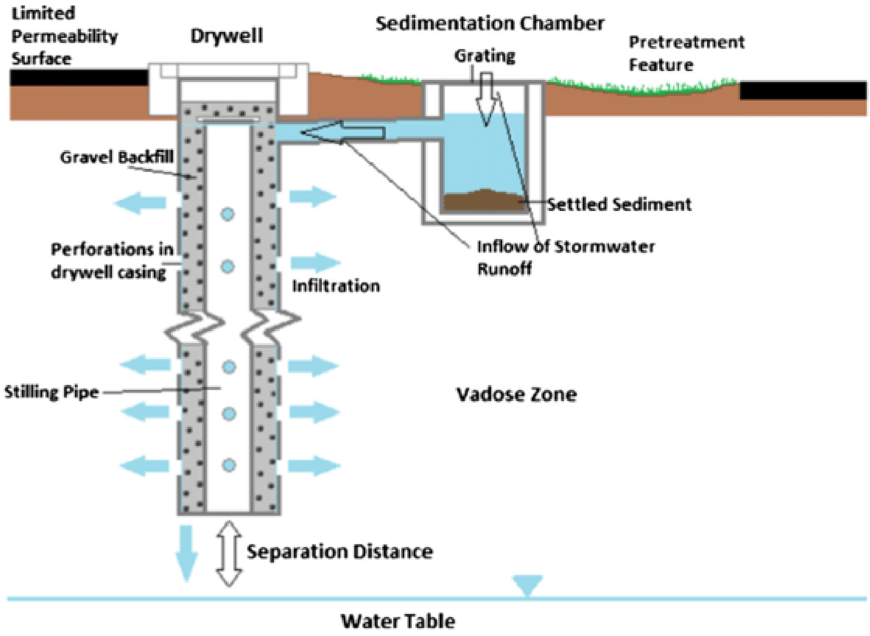


Figure 1. Dry well for stormwater management.

Source: (Edwards et al. 2016) Open Access (Creative Commons — Attribution-Non-Commercial-No Derivatives 4.0 International — CC BY-NC-ND 4.0)

Applicability

Dry wells are applicable in any situation where it is desirable to infiltrate source water into the vadose zone and subsequently into the groundwater. Dry wells are an alternative method to enhance recharge by allowing stormwater to bypass low-permeability layers near the surface and facilitating infiltration of stormwater into more permeable units of the subsurface (E. C. Edwards et al. 2016).

Dry wells have been extensively used for indirect potable reuse in the Scottsdale, Arizona, area to recharge regional groundwater aquifers with over 70 billion gallons of advance treated purified recycled wastewater since 1988 (and 1.7 billion gallons annually). The dry wells are used in Scottsdale Water Campus to recharge high quality water where the depth to groundwater is shallow, providing a more cost-effective approach than injection wells. Site-specific conditions highly influence whether dry wells are more favorable to other MAR technologies, and in urban settings where space is not readily available, dry wells are particularly well suited. Several of these applications include new developments, green streets, and urban retrofits.

Advantages

Dry well systems have the following advantages:

- Gravity flow dry wells are typically 30–100 feet deep and can be installed at a comparatively low cost when compared to injection wells or other technologies (for example, an ASR well that may extend hundreds (up to thousands) of feet in depth, such as the deepest Des Moines Water Works aquifer storage and recovery (ASR) well in Ankeny, Iowa, that extends more than 2,500 feet deep).
- The footprint is generally very small, often a 6-foot diameter manhole at the surface that looks like a common storm drain manhole. The small footprint allows for construction in tight spaces, including built-out urban areas. The equipment and materials required to construct a dry well are common and readily available in the construction industry.
- Construction time for a gravity flow dry well is relatively rapid—a matter of days vs. weeks or months.
- Recharge credits are possible for a private landowner. A water replenishment district (WRD) or utility will receive the benefit for other MAR technologies.
- Construction costs are typically far less than direct injection well technologies.

Limitations

Dry wells systems have the following limitations:

- Dry wells are very difficult, if not impossible, to clean out or rehabilitate once clogged with sediment. High pressure water injection with vacuum extraction may be used to remedy this situation. However, pretreatment of the source water (stormwater) to minimize TSS content is a must.
- Gravity flow dry wells are typically 30–100 feet deep, and it may be difficult to transmit recharge water to a deep aquifer due to intervening low-permeability layers. In contrast, ASR wells may extend up to thousands of feet in depth (as in Iowa, where several ASR wells are more than 2,500 feet deep) and penetrate the aquifer directly.
- Dry well functionality is dependent on the presence of permeable layers of soil that allow for more rapid infiltration of stormwater.
- A dry well cannot be pumped to extract groundwater. It is for infiltration only.

Performance

Use of dry well MAR technology is site-specific, and since the infiltration capacity of a gravity flow dry well is mainly dependent on the surrounding soils, knowing the infiltration characteristics of the soil is critical in determining whether a dry well is suitable for MAR at the site. Percolation (perc) tests or a dry well pilot test may be performed to evaluate the infiltration rate of the near-surface soil conditions for planning and design purposes. Infiltration studies at Fort Irwin, California, have led to the development of a modeling component for evaluating dry well recharge (Drywell Examples (pc-progress.com)

There are several factors that must be considered when assessing the effectiveness of a potential site for recharge. These include, but are not limited to, the properties of the surface and subsurface materials, topography, water conveyance infrastructure, and water availability (Goebel and Knight 2021).

A geologic assessment must be considered for suitability of infiltration at the site. Emerging technologies such as towed transient electromagnetic methods (tTEM), a surface geophysical imaging technique, have made subsurface investigation across large swaths of land much more viable. Assessment technologies might include, but are not limited to, the following methods: tTEM, AEM––airborne electromagnetic surveying, ERT––electrical resistivity tomography, CPT–cone penetrometer testing, and geotechnical drilling.

Initial data from several recent pilot projects in California indicate that a flow rate of 300–500 gpm (1.3 acre-feet/day) is a realistic recharge rate (E. C. Edwards et al. 2016). Dry wells can also be used to return water to aquifers: a single dry well can transmit up to 5 acre-feet of water per year to underlying aquifers, equivalent to the water needs of about 10 households (E. Edwards, Washburn, and Lock 2017).

Dry year and wet year recharge was estimated at 770 acre-feet/year and 8,700 acre-feet/year, respectively, based on a 2005 study examining the groundwater recharge impact of 3,763 dry wells that were installed in a growing Arizona city to drain 1,400 acres of stormwater retention basins (Graf 2015). The predevelopment groundwater recharge was 191 acre-feet of water per year, while the post development recharge through the dry wells was estimated at 2,100–3,100 acre-feet in an average rain year, demonstrating that the dry wells are a significant source of groundwater recharge.

Regulatory Considerations

The laws that address dry wells are the Clean Water Act, Safe Drinking Water Act (SDWA), and Comprehensive Environmental Response Compensation and Liability Act (CERCLA). The regulatory agencies involved in implementation of a dry well program include, depending on established primacy, the U.S. Environmental Protection Agency (USEPA), state agencies, local governments, and tribal governments.

Dry wells are considered Class V injection wells. The USEPA regulates the construction, operation, permitting, and closure of injection wells, including dry wells, through the Underground Injection Control (UIC) program as required by the SDWA. Many states have primacy or authority to implement and oversee their own UIC programs (Figure 2). For example, Washington and Oregon have well-developed programs where dry wells are used extensively. Otherwise, the USEPA either jointly or directly implements programs in the remaining states.

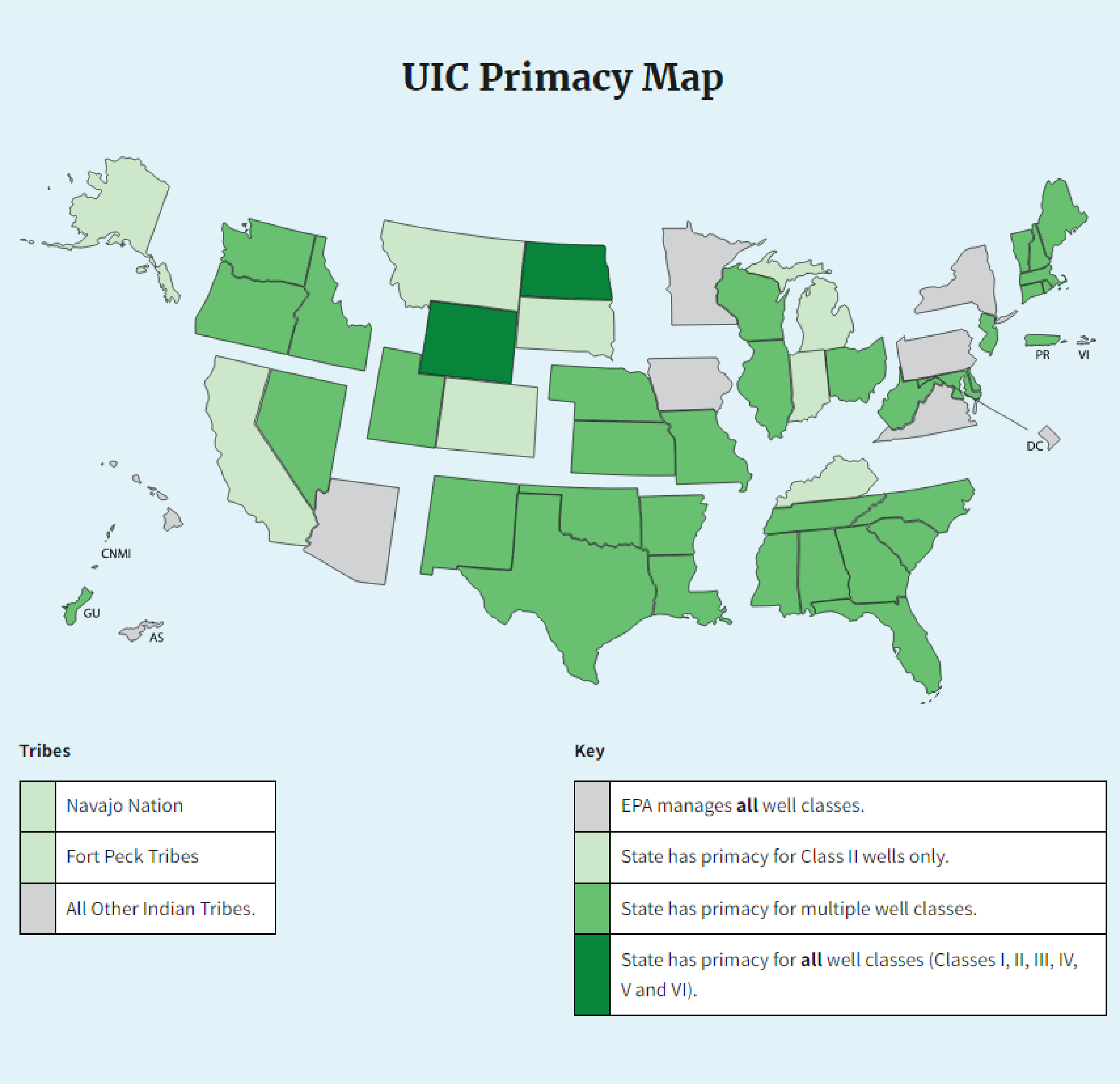


Figure 2. UIC program implementation (tribes are not depicted on map, colors for tribes relate to key—Navajo Nation and Fort Peck Tribes have primacy for Class II wells; USEPA manages all well classes for all other tribes).

Source: USEPA (2022)

Officials may be required to obtain a UIC permit for dry wells, or these wells may be authorized by rule and inventoried, depending on the state where the well is located. Dry wells are required to not endanger the underlying groundwater resource (drinking water), which must be demonstrated to the regulatory agency. As such, dry wells receiving stormwater are preemptively prohibited at some sites where the contaminants may adversely affect groundwater quality, including, for example, in areas involved with vehicle maintenance, airport de-icing activities, or storage or handling of hazardous materials or wastes. Dry wells also may not be used at contaminated sites when the stormwater recharge would increase the mobility of the contaminants at the site (Washington State Department of Ecology 2006). Siting criteria and setback restrictions, in addition to design, construction, operation, and maintenance requirements for dry wells, may also apply in certain jurisdictions.

Although the regulatory and political environment has some influence on differences in dry well programs between states, many of the differences are due to different geologic conditions (site-specific conditions). States with greater amounts of precipitation, high water tables, or bedrock near the ground surface often will not use dry wells extensively, so regulations are less defined. As stated in (Lock, Edwards, and Washburn 2017): “Pennsylvania, New Jersey, Washington, and Hawaii are a few of the others states with dry well regulations and guidelines. In New Jersey, some communities require dry well installation for all new and major remodels related to residential construction. They are typically designed to temporarily store and infiltrate roof runoff. Dry wells in New Jersey are prohibited in industrial or other areas where toxic chemicals might be used. In contrast, in Pennsylvania dry wells are permitted in industrial areas with restrictions, but not along roadways. In Washington, dry wells must be registered and constructed to specifications. The regulations of these states vary with respect to dry well design, use of pretreatment, separation from drinking water sources, distance from the water table, and other factors." Other states, especially those with less rain and deeper water tables, tend to have more detailed regulations because their groundwater resources are less abundant and/or under greater strain.

Stakeholder Considerations

The stakeholders should consider the capital cost as well as long-term maintenance costs of a pretreatment system. A discharge permit and UIC permit may be required, and the requirements for obtaining a permit vary between states. Land ownership and groundwater (and possibly stormwater) rights may need to be considered. Recharge credits are possible for a private landowner, and a water replenishment district or utility will receive the benefit. Potential groundwater contamination is a concern that must be considered. The source water and its compatibility with groundwater and the aquifer must be evaluated for pretreatment needs for dry well applications or potential liability for groundwater cleanup may be a consequence of inappropriate dry well applications.

Lessons Learned

Quantifying the amount of infiltrated water from dry wells that is recharged into the target aquifer is not straightforward due to the complexity of the hydrodynamics of unsaturated flow (Liang, Zhan, and Zhang 2018; Edwards et al. 2022). A robust pretreatment system should be considered in advance of the dry well to address long-term performance (clogging) and to minimize potential groundwater contamination from poor source water quality.

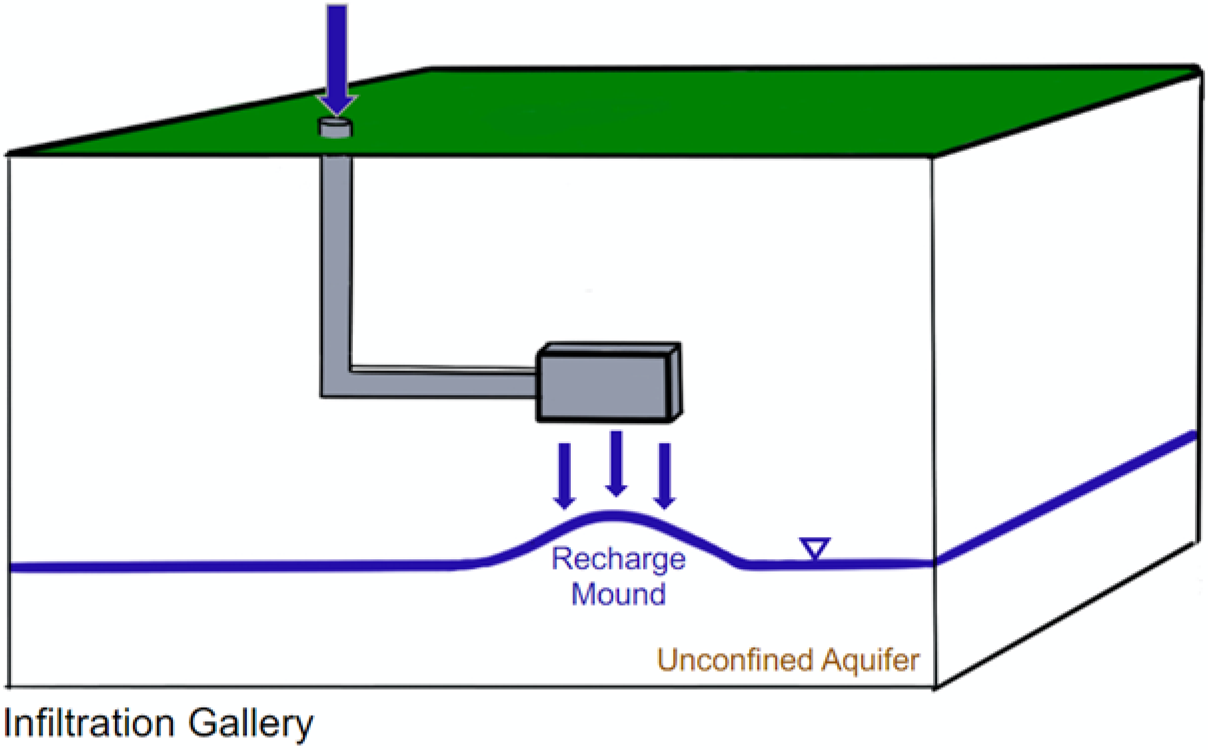
Case Studies (FS-4)

- Turlock, California—Mustang Creek Watershed Dry Well Pilot Study (see Case Study 5.8)
- Texas, New Mexico, Mexico—Hueco Bolson Recharge Project (The Hueco Bolson: An Aquifer at the Crossroads utep.edu).
- Lake Tegel, Berlin, Germany—(Hoffmann and Gunkel 2011) ScienceDirect: Bank filtration in the sandy littoral zone of Lake Tegel (Berlin): Structure and dynamics of the biological active filter zone and clogging processes | Elsevier Enhanced Reader.
- Scottsdale, Arizona—Advanced Water Purification—City of Scottsdale—Recycled Water (City of Scottsdale—Recycled Water (scottsdaleaz.gov). .
- Arizona—Stormwater Vadose Wells—Dry Wells for Stormwater Management: An Evolving Viewpoint | Water Resources Research Center | The University of Arizona.
- Eastern Washington—Washington State Stormwater Vadose Wells—Stormwater Manual for Eastern Washington: Guidance for UIC Wells that Manage Stormwater.
- Oregon—Stormwater Vadose Wells—Oregon's Experience with Dry Wells: The Underground Injection Control Program (ca.gov).
- New Jersey—Dry Wells—NJDEP| Stormwater | NJ Stormwater Best Management Practices Manual
- California—Dry Wells Uses, Regulations, and Guidelines in California and Elsewhere—Dry Wells: Uses, Regulations, and Guidelines in California and Elsewhere.
- Hawaii—Dry Wells—Potential effects of roadside dry wells on groundwater quality on the Island of Hawaii—Assessment using numerical groundwater models (Izuka 2011).
- Cochise County, Arizona—Palominas Flood Control and Recharge Project—Cochise Conservation and Recharge Network (arcgis.com).

Infiltration Gallery Fact Sheet (FS-5)

Introduction

Infiltration galleries (see figure below) typically consist of perforated pipes installed horizontally underground within permeable fill (gravel) material to rapidly infiltrate stormwater runoff and prevent flooding. Infiltration galleries can be used to support groundwater replenishment. In addition to allowing for the rapid movement of water into the ground, infiltration galleries can also be used to prevent flooding and erosion as a mechanism for controlling excess surface water in areas with groundwater storage availability.



There are several types of vadose zone infiltration gallery structures:

- French drains
- lateral galleries such as engineered channels, pipelines, or other structures to divert surface water into the ground
- vertical galleries such as engineered buried perforated cisterns, graveled slurry walls, or other subsurface structures to divert and infiltrate surface water to groundwater
- bedrock galleries such as tunnels

Applicability

Surface water infiltration, especially into a beneficially designated aquifer, may be subject to regulation under Class V underground injection permitting due to its potential as a contamination source. Contamination in surface water can be in the form of biological, physical, and/or chemical. Infiltration galleries are commonly designed to drain water efficiently and effectively, often without regard to the fate of the water once it enters the subsurface. Clean surface water and groundwater may flow into and out of infiltration galleries, where it can become contaminated if the facility is not maintained. For example, by diverting clean water to or via infiltration galleries away from mine workings and solid mine waste, generation of mining-influenced water (MIW) can be eliminated or reduced (Sloan, Cook, and Wallis 2023). However, assessment of the diverted water quality on a regular basis is needed to prevent violation of any associated permits and eliminate or reduce the possibility of contaminating an otherwise potable water source.

Infiltration galleries can be applied over a wide range of sites, ranging from simple channels and/or gravel-lined trenches to highly complex engineered surface and subsurface structures. They are applicable to a wide range of flow rates and water qualities. They can be constructed at the surface to divert and contain surface water and within the subsurface to control infiltration and reduce recharge area. Feulner (1964) discussed and provided case studies for several examples of infiltration galleries, including French drains, lateral galleries, vertical galleries, and bedrock galleries.

Advantages

Advantages of infiltration galleries include:

- Drainage of surface runoff related to agricultural and/or stormwater sources is accelerated, without requiring a depression in the land surface to store source water and recharge aquifer.
- The infiltration gallery can be sized for less frequent, but larger volume, infiltration events while minimizing surface footprint.

Limitations

Limitations of infiltration galleries include:

- Infiltration galleries are not well suited where impermeable subsurface geology hinders infiltration rates and is difficult to excavate through and make a hydraulic connection with permeable material that can accommodate recharge water into the aquifer.
- Generally, infiltration galleries are not suitable for U.S. Department of Agriculture Hydrologic Soil Groups “C” or “D” soils, and permeability of soils must be at least 0.5 in/hr (12 feet per day). USDA described soil in Group A as most permeable and soils in Group D as least permeable (USDA 2017; Bicknell 2018).

- The perforated pipes of infiltration galleries can be susceptible to clogging (due to suspended sediment and/or bacterial growth) and invasion by plant roots. There are options, however, for cleaning by backflushing with air lines. Infiltration galleries are subject to clogging too (Siriwardene, Deletic, and Fletcher 2007).

Performance

Infiltration galleries are proven technology for use as a managed aquifer technique by municipal, private, and governmental organizations. An example of infiltration galleries being used is in the off-river basins along Orange County Water District’s (OCWD) Santa Ana River recharge system, where OCWD demonstrated that horizontal perforated PVC pipes and dry wells installed beneath the basins increase infiltration rates by removing sediment from the stormflow source water (Hutchinson et al. 2017). This OCWD riverbed filtration system was designed and demonstrated to have a recharge rate of 2–5 feet per day, which compares with the average off-river basin infiltration rates of 0.1–0.7 feet per day. This system also demonstrated the ability to remove contaminants (a water quality improvement) in source water via soil aquifer treatment. Eighteen constituents of emerging concern were detected in the source water. The average removal was significant (greater than 80%) for six compounds, moderate (between 20% and 80%) for six compounds, and low or negligible (less than 20%) for the remaining six compounds (Figure 1) (Hutchinson et al. 2017).

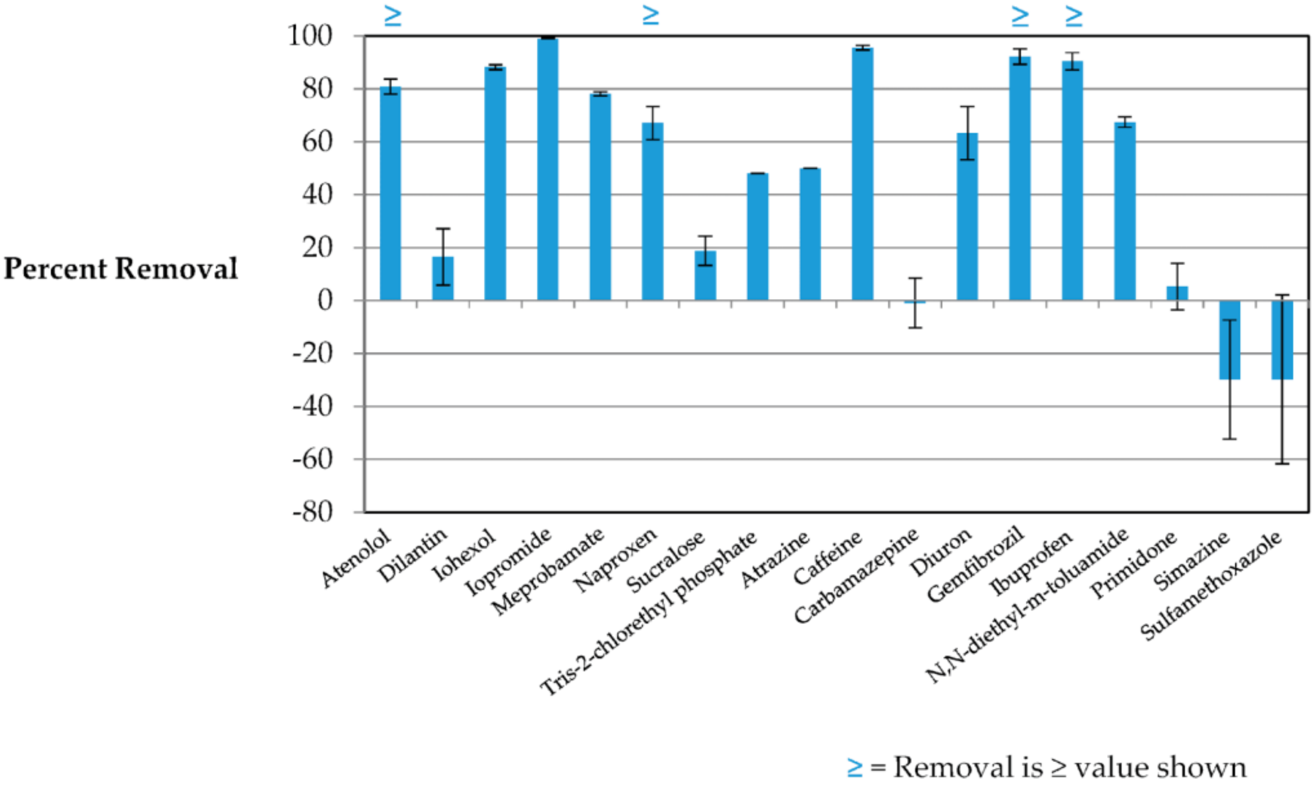


Figure 1. Removal of contaminants in source water via soil aquifer treatment.

Source: Hutchinson et al. (2017).

Regulatory Considerations

Infiltration galleries are often applied in conjunction with dry wells or diversion and retention structures to distribute and infiltrate captured stormwater. Engineering review and permitting, source water diversion, water rights, water infiltration, and wetlands impacts may be required. In California, there is increasing interest in capturing stormwater for recharge and has been done in Santa Clara County and Merced County (E. C. Edwards et al. 2016)

Stakeholder Considerations

Infiltration galleries and associated structures commonly involve significant surface disturbance that can lead to stakeholder concerns about land use, water rights, and disruption of ecological resources. Concerns may also be raised about source water protection, groundwater impacts, and water table fluctuations.

Lessons Learned

Infiltration galleries can be a cost-effective way of facilitating managed aquifer recharge (MAR). They are customizable to fit the needs and limitations of a project. Infiltration galleries and engineered structures require a thorough understanding of site subsurface conditions (including soil and local geological assessment) and careful monitoring to ensure that the systems are achieving the desired results.

Case Studies (FS-5)

- Evaluating two infiltration gallery designs for managed aquifer recharge using secondary treated wastewater (Bekele et al. 2013).
- Feasibility of farm-scale infiltration galleries for managed aquifer recharge in an agricultural alluvial aquifer of Northeast Arkansas (Godwin et al. 2022).

5. Case Studies

Case studies presented are designed to showcase a myriad of MAR elements and implementation as discussed in this document. The authors of each case study present the most unique aspects of their study, which may include operational or technical obstacles overcome, situational constraints, stakeholder issues, regulatory environment, or water quality issues and solutions identified. The uniqueness of each case study allows the opportunity for the reader to learn an aspect of each project that is not necessarily widely known and has not been previously discussed in the vast MAR literature. Table 5-1 provides a list of the case studies.

Table 5-1. Case studies and their approaches

Case Study	Name	Location	Approach
5.1	HRSD Sustainable Water Initiative for Tomorrow (SWIFT) Program	Southeast Virginia	Intended Use:
			-Water supply resilience
			-Improving groundwater quality
			-Mitigation against saltwater intrusion
			-Subsidence reduction
			-Reduction of nutrient discharges to surface waters
			Source water:
			-Municipal wastewater
			Water quality:
			-Pretreatment required
			Recharge technology(s):
			-Recharge well

5.2	Using a Simple, Low-Cost, Injection Water Pretreatment System to Reduce the Concentration of Naturally Occurring Arsenic and Other Trace Metals in Recovered Water during ASR Operations	Deland, Florida	Intended use:
			-Water supply resilience
			-Improving groundwater quality
			Source water:
			-Not applicable
			Water quality:
			-Pretreatment required
			Recharge technology(s):
			-ASR well
5.3	Seawater Intrusion/Replenishment in Southern Los Angeles County	Southern Los Angeles County, California	Intended use:
			-Water supply resilience
			-Improving groundwater quality
			-Mitigation against saltwater intrusion
			Source water:
			-Municipal wastewater
			-Imported water
			Water quality:
			-Pretreatment required (tertiary treated recycled water)
			Recharge technology(s):
			-Injection wells

5.4	San Antonio Water System H2Oaks Center ASR Project	Elmendorf, Texas (south of San Antonio, Texas)	Intended use:
			-Water supply resilience
			-Resilience/climate adaptation
			Source water:
			-Alternative aquifer
			Water Quality:
			-Pretreatment required
			-Post-treatment required
			Recharge technology(s):
			-Injection well
5.5	Salinas Valley Groundwater Basin	Monterey County, California	Intended use:
			-Water supply resilience
			-Use of floodwater (control of flood, agricultural)
			-Protection of riparian ecosystems/maintenance of minimum streamflow
			Source water:
			-Rivers/streams/lakes/reservoirs
			-Captured water
			Water quality:
			-No treatment required
			Recharge technology(s):
			-Enhanced streambed recharge

5.6	Idaho’s Eastern Snake Plain Aquifer MAR Program	Eastern Snake Plain, Idaho	Intended use
			-Water supply resilience
			-Use of floodwater (control of flood, agricultural)
			-Protection of riparian ecosystems/maintenance of minimum streamflow
			-Resilience/climate adaptation
			Source water
			-Rivers/streams/lakes/reservoirs
			Water quality:
			-No pretreatment required
			-No posttreatment required
			Recharge technology(s)
			-Infiltration pond
			-Wet well
			-Bank filtration
			-Sinkhole

5.7	South Hillsborough Aquifer Recharge Project (Apollo Beach)	Hillsborough County, Florida	Intended use:
			-Water supply resilience
			-Improving groundwater quality
			-Mitigation against saltwater intrusion
			Source water:
			-Recycled water (high-level disinfection public access-quality)
			Water quality:
			-Pretreatment required
			Recharge technology(s):
			-Injection wells
5.8	Mustang Creek Watershed Dry Well Pilot Study	Merced County, California	Intended use:
			-Water supply resilience
			Source water:
			-Captured water
			Water quality:
			-Pretreatment required
			Recharge technology(s):
			-Dry well

5.9	Walla Walla Basin Watershed	Oregon	Intended use:
			-Water supply resilience
			-Protection of riparian ecosystems/maintenance of minimum streamflow
			-Resilience/climate adaptation
			Source water:
			-Rivers/streams/lakes/reservoirs
			Water quality:
			-No treatment required
			Recharge technology:
			-Infiltration basin
			-Infiltration gallery

5.10	Clark Fork River Basin MAR Modeling	Deer Lodge, Montana	Intended use:
			-Water supply resilience
			-Protection of riparian ecosystems/maintenance of minimum streamflow
			-Resilience/climate adaptation
			-Agricultural
			-Water rights permitting support
			Source water:
			-Rivers/streams/lakes/reservoirs
			-Agricultural return flows
			Water quality:
			-No treatment required
			Recharge technology(s):
			-Dry well
5.11	Army Post Road ASR Well	Des Moines, Iowa	Intended use:
			-Water supply resilience
			Source water:
			-Rivers/streams/lakes/reservoirs
			Water quality:
			-Pretreatment required
			-Post-treatment required
			Recharge technology(s):
			-ASR well

5.12	South Metro Water Supply Authority Regional ASR Groundwater Model Scope of Work (August 17, 2022)	Aurora, Colorado	Intended use:
			-Water supply resilience
			Source water:
			-Rivers/streams/lakes/reservoirs
			Water quality:
			-Pretreatment required
			Recharge technology(s):
			-ASR well

5.1 HRSD Sustainable Water Initiative for Tomorrow (SWIFT) Program

Author: Jamie Heisig-Mitchell

Site Name: HRSD Sustainable Water Initiative for Tomorrow (SWIFT) Program

Location: Multiple locations in southeast Virginia

Operator(s): Hampton Roads Sanitation District (HRSD)

Permitting Agency(s): USEPA Region III Underground Injection Control Program

Current MAR Status: Currently operating a 1-million-gallon-per-day demonstration-scale advanced water treatment facility and MAR well in Suffolk, VA, at the SWIFT Research Center.

Year Constructed: 2018

Costs: $26M

Project Contact Information: Dan Holloway, HRSD hydrogeologist, dholloway@hrsd.com

Project Website/Publication Links: https://www.hrsd.com/swift

Purpose of MAR:

- Water supply resilience
- Improving groundwater quality
- Mitigation against saltwater intrusion
- Subsidence reduction
- Reduction of nutrient discharges to surface waters

Source Water:

- Municipal wastewater

Water Quality:

- Pretreatment required

Recharge Technology(s):

- Recharge well

Project Description

SWIFT is an innovative water treatment project in eastern Virginia designed to enhance the sustainability of the region’s long-term groundwater supply, further protect the region’s environment, and help address environmental pressures such as Chesapeake Bay restoration, sea level rise, and saltwater intrusion (Nylen 2021). At full-scale, SWIFT will be implemented at up to five of HRSD’s wastewater treatment facilities with a total recharge capacity of up to 100 million gallons per day.

MAR through the SWIFT program will provide a sustainable source of groundwater to much of eastern Virginia. The need for groundwater in eastern Virginia outstrips the available supply in the Eastern Virginia Groundwater Management Area, prompting the Virginia General Assembly to establish the Eastern Virginia Groundwater Management Advisory Committee and task it with developing, revising, and implementing a management strategy for groundwater in eastern Virginia. A multi-solution plan to address needs and improve management strategies was proposed in the committee report (EVGMAC 2017). Included in this solution set was an evaluation of alternate water sources of which the HRSD SWIFT program was noted as a mechanism for improving the sustainability of the groundwater supply.

The SWIFT program offers the additional benefit of reducing nutrient discharges to Chesapeake Bay. The nutrient reductions resulting from the SWIFT program are sufficient to balance the nutrient reduction needs of the Hampton Roads permitted stormwater localities (Municipal Separate Storm Sewer System (MS4) permittees). The required MS4 nutrient reductions would have necessitated stormwater retrofit projects on a compressed schedule, resulting in a large cost burden to the Hampton Roads community. With the available credits provided by the SWIFT program, localities can more cost-effectively manage stormwater controls through a normal redevelopment cycle and are able to prioritize spending on other community needs, such as climate change adaptation. At full build-out, the SWIFT program will have the capacity to reduce the amount of nutrients discharged to the Chesapeake Bay by up to 85%, equivalent to nearly 1.4 million pounds of nutrients annually, well surpassing the required MS4 reductions estimated at 110,000 pounds annually and surpassing even HRSD’s own discharge requirements by more than 1 million pounds annually.

Further, the SWIFT program is expected to reduce the rate of land subsidence related to the overuse of the aquifer and, in doing so, provide additional time for Hampton Roads localities to implement adaptive measures to address the observed effects of sea level rise. Land subsidence is exacerbated by over pumping from the Potomac Aquifer, resulting in an aquifer compaction rate of up to 3.7 mm/yr, as noted in a U.S. Geological Survey (USGS) report from Eggleston and Pope (2013). This same report found that land subsidence in the region contributes to more than half of the observed sea level rise and noted that increased recharge to the aquifer can mitigate aquifer compaction.

Receiving Aquifer

The target receiving aquifer for SWIFT is the Potomac Aquifer. At over 900 feet thick, it represents the deepest, thickest, and most extensive aquifer in Virginia's coastal plain (Figure 1). It is laterally extensive across the entire North Atlantic Coastal Plain, except for the area of the Chesapeake Bay Impact Crater. Approximately 75% of the withdrawals in the Virginia Coastal Plain Aquifer system come from the Potomac aquifer and cover many different uses, including potable and non-potable, public and private (Heywood and Pope 2009).

Figure 1. Location of Virginia's coastal plain.

Source: McFarland and Scott (2006)

As part of the feasibility study for the SWIFT program, HRSD evaluated multiple treatment trains for the advanced water treatment system to identify a train that would produce water of quality that would be compatible with the aquifer system while also providing treatment to meet the needs of public health protection (Martinez et al. 2022). With TDS in the Potomac Aquifer ranging from approximately 700 mg/L to 8,000 mg/L, aquifer compatibility was an important influence in technology selection. Early piloting of a reverse osmosis (RO) treatment train generated a final water product that differed significantly from the chemistry of the native groundwater. The resulting low ionic strength of the RO-treated water relative to the groundwater presents a considerable concern for successful injection operations. This incompatibility posed a high potential for permanent disruption and dispersal of clay particles, clogging pores within the aquifer and reducing aquifer permeability and ultimately injection well capacity.

Parallel piloting of an ozone/biofiltration train demonstrated that the final water was similar to the ionic strength of the upper portion of the Potomac Aquifer and overall, more compatible with the native groundwater. An exhaustive monitoring program also demonstrated the ozone/biofiltration train’s effective removal of pathogens and organic contaminants and compliance with proposed regulatory limits and required thresholds for compounds lacking a regulatory limit (Vaidya et al. 2019). The development of regulatory limits and monitoring requirements is described in further detail below.

In 2018, HRSD began operating a 1-million-gallon-per-day demonstration-scale recharge facility, known as the SWIFT Research Center (SRC), utilizing a coagulation/flocculation/ozonation/biofiltration/GAC adsorption/UV disinfection advanced treatment train. As of the end of September 2022, the facility has successfully recharged more than 600 million gallons to the Potomac Aquifer system. The SRC incorporates a groundwater monitoring network and soil aquifer treatment test columns to inform the fate and transport of solutes present in the recharged water. More information on this work can be found in Bullard et al. (n.d.) and Dziura (2022).

The first full-scale SWIFT facility is being constructed at HRSD’s James River facility, with an anticipated completion at the end of 2025. The full-scale SWIFT process is similar to that of the SRC and is identified in Figure 2. The key elements of the SWIFT treatment train at the 16 million gallons per day facility include coagulation-flocculation-sedimentation, ozone, biofiltration, granular activated carbon, and UV disinfection.

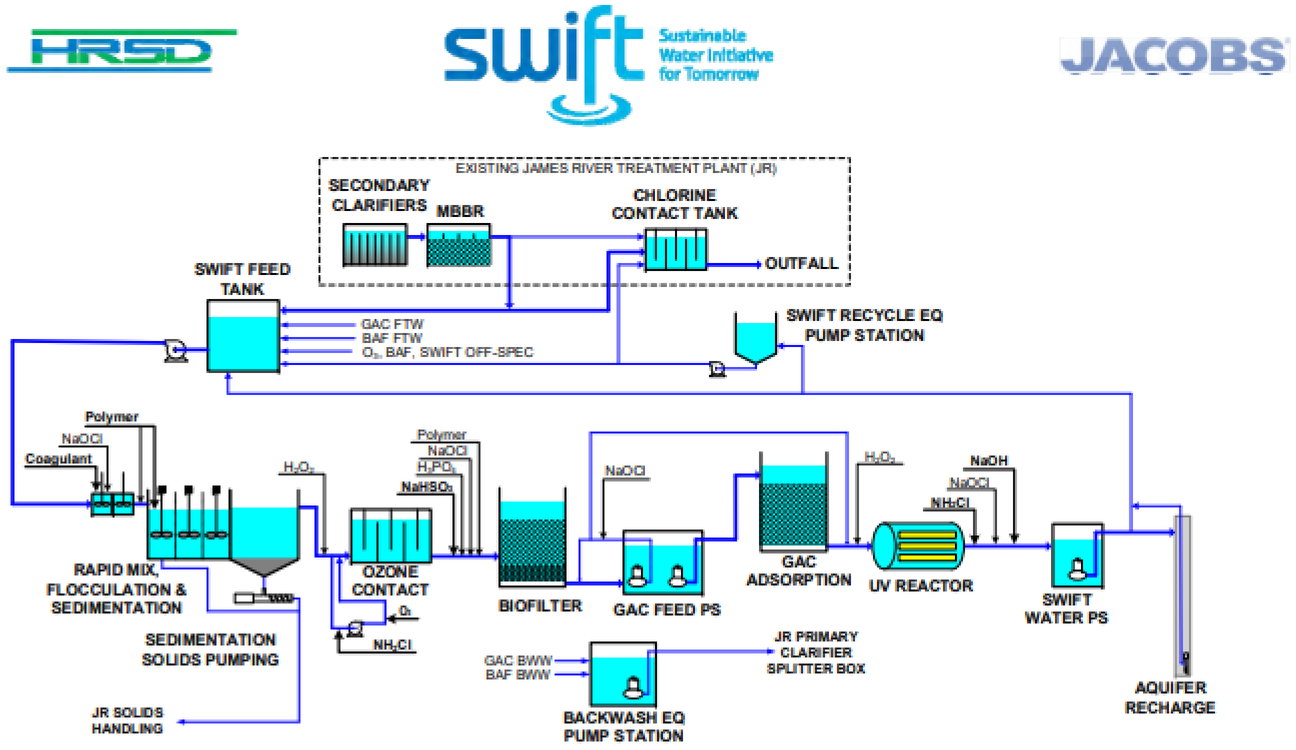


Figure 2. James River SWIFT process flow diagram.

Source: HRSD (2020)

Regulatory Considerations/Issues

The HRSD SWIFT program is permitted through the federal UIC program. Though the Commonwealth of Virginia does not have delegated authority for UIC, an independent oversight committee was convened through legislative action (Code of Virginia. § 62.1.271-275). This Potomac Recharge Oversight Committee (PAROC) serves as an advisory board and is responsible for ensuring that the SWIFT program, including its effects on the Potomac Aquifer, is monitored independently. Technical support to the PAROC is provided by the Potomac Aquifer Recharge Monitoring Laboratory, which is led by codirectors representing the academic institutions: Virginia Tech and Old Dominion University.

HRSD’s first SWIFT project, the 1-million-gallon-per-day demonstration-scale SWIFT Research Center, is authorized by rule under the federal UIC program. In the development of the SWIFT program, the selection of appropriate treatment processes, and the identification of an appropriate regulatory framework, HRSD engaged the expertise of an independent advisory panel through the National Water Research Institute (NWRI) and worked collaboratively with the Commonwealth agencies, the Virginia Department of Health (VDH) and the Virginia Department of Environmental Quality (VDEQ). While much of this regulatory framework is based on the SDWA requirements, in recognition that this program is a potable reuse project, NWRI recommended additional monitoring of indicator compounds as described in the Framework for Direct Potable Reuse (Mosher and Vartanian 2015). Much of this work formed the basis for the regulatory requirements proposed in the draft permit for HRSD’s first full-scale facility, the 16-million-gallons-per-day James River SWIFT (Table 1 and Table 2). NWRI also recommended that the SWIFT process be designed and operated to achieve at least 12 log removal value (LRV) for viruses and 10 LRV for Cryptosporidium and Giardia through a combination of advanced treatment processes and soil aquifer treatment (SAT). A summary of SWIFT process pathogen log removal requirements is depicted in Table 3.

Table 1. James River SWIFT regulatory limits

Parameter	**Regulatory Limit**
USEPA Drinking Water Primary Maximum Contaminant Levels (PMCL)	Meet all PMCL
Total Nitrogen (TN)	5 mg/L monthly average; 8 mg/L max daily
Turbidity	Individual filter effluent (IFE) <0.15 NTU 95% of time and never >0.3 NTU in two consecutive 15-minute measurements
Total Organic Carbon (TOC)	4 mg/L monthly average, 5 mg/L maximum instantaneous
Total Coliform	<2 CFU/100 mL 95% of collected samples within one calendar month, applied as the 95th percentile
E. coli	Non-detect
TDS	No limit

Table 2. Required monitoring for James River SWIFT nonregulatory indicators

Constituent	**Category**	**Threshold Value**	**Unit**	**Notes**
1,4-Dioxane	Public health	1	µg/L	CCL4; CA notification limit
17-β-Estradiol	Public health	0.9[1]	ng/L	CCL4
DEET	Public health	200	µg/L	MN health guidance value
Ethinyl Estradiol	Public health	280[1]	ng/L	CCL4
NDMA	Public health	10	ng/L	CCL4; CA notification limit

Perchlorate	Public health	6	µg/L	CA notification limit
PFOA[2]	Public health	4	ng/L	Draft PMCL
PFOS[2]	Public health	4	ng/L	Draft PMCL
TCEP	Public health	5	µg/L	MN health guidance value
Cotinine	Treatment effectiveness	1	µg/L	Surrogate for low molecular weight, partially charged cyclic chemicals
Primidone	Treatment effectiveness	10	µg/L	
Phenytoin	Treatment effectiveness	2	µg/L	
Meprobamate	Treatment effectiveness	200	µg/L	High occurrence in wastewater treatment plant effluent
Atenolol	Treatment effectiveness	4	µg/L	
Carbamazepine	Treatment effectiveness	10	µg/L	Unique structure
Estrone	Treatment effectiveness	320	ng/L	Surrogate for steroids
Sucralose	Treatment effectiveness	150	mg/L	Surrogate for water soluble, uncharged chemicals with moderate molecular weight
Triclosan	Treatment effectiveness	2,100	µg/L	Chemical of interest

[1] Threshold value identified in *Monitoring Strategies for Contaminants of Emerging Concern (CECs) in Recycled Water, Recommendations of a Science Advisory Panel, 2018; SCCWRP Technical Report 1032.* [2] Though no thresholds have been established, monitoring and reporting will include PFBA, PFHpA, PFHxS, and PFNA.

Table 3. Summary of treatment process pathogen log removal requirements.

Parameter	**Floc/Sed (+BAF)**	**Ozone**	**BAF+GACC**	**UV**	**Cl2**	**SAT[1]**	**Total**
Enteric Viruses	2	0	0	4	0	6	12
Cryptosporidium	4	0	0	4	0	6	14
Giardia	2.5	0	0	4	0	6	12.5

[1] At least 6-log credit for viruses, Cryptosporidium, and Giardia is expected through SAT based on the modeled travel time of the recharge water in the Potomac Aquifer system. Literature has demonstrated additional treatment of recharge water as it moves through an aquifer system; the California Department of Health Regulations Related to Recycled Water state that 1-log virus reduction credit is granted for every month the water is in the ground up to 6-log reduction (California Code of Regulations Title 22 §60320.108). A minimum 6-log removal of Cryptosporidium and Giardia is expected when achieving 6-log virus reduction. HRSD's soil column testing has confirmed this assumption.
Floc/Sed – flocculation/sedimentation; BAF – biologically active carbon filtration; GAC – granular activated carbon; UV – ultraviolet; SAT – soil aquifer treatment; C12 – carbon chain

PAROC was actively engaged in reviewing and affirming the regulatory monitoring requirements for James River SWIFT. As part of the James River SWIFT UIC permit application process, HRSD again sought input on monitoring requirements from NWRI, VDH, and VDEQ—the latter two agencies acting on behalf of the PAROC. Through this process, additional monitoring requirements were incorporated at the request of NWRI and/or PAROC. Male-specific and somatic coliphage monitoring was a requested addition from NWRI to serve as an indicator of viral pathogen reduction.

The HRSD SWIFT program offers a One Water solution, addressing challenges across multiple water sectors:

- meeting water supply needs by providing sustainable groundwater inputs,
- meeting the needs for additional nutrient reductions from our wastewater facilities and our local stormwater management programs, and
- supporting Chesapeake Bay restoration efforts.

This was all accomplished through a highly collaborative process and engagement with national experts, state and federal regulatory agencies and local stakeholders.

5.2 Using a Simple, Low-Cost Injection Water Pretreatment System to Reduce the Concentration of Naturally Occurring Arsenic and Other Trace Metals in Recovered Water during ASR Operations

Author: Gregg Jones

Site Name: City of DeLand, Florida, Airport ASR Facility

Location: Deland, Florida

Operator(s): City of DeLand

Permitting Agency(s): Florida Department of Environmental Protection, St. Johns River Water Management District, Volusia County Health Department

Current MAR Status: Pilot test. System no longer in service.

Year Constructed: 2005

Costs: A conservative cost estimate for the system is approximately $42,000. Operation and maintenance costs (O&M) were very minimal. The cost of the sodium hydrosulfide pretreatment chemical (NaSH) depends on the volume of water to be injected and its dissolved oxygen (DO) concentration. Based on typical DO concentrations in treated surface water, the annual cost of NaSH will range from approximately $9,000 to $18,000.

Project Contact Information: Gregg Jones, chief hydrogeologist, Brown and Caldwell (greggwjonespg@gmail.com)

Project Website/Publication Links: N/A

Purpose of MAR:

- Water supply resilience
- Improving groundwater quality

Source Water:

- Not applicable

Water Quality:

- Pretreatment required

Recharge Technology(s):

- ASR well

Project Description

Elevated levels of arsenic in water recovered in many ASR systems in Florida became a serious concern to regulatory agencies and water supply utilities following the Florida Department of Environmental Protection’s decision to reduce the arsenic drinking water standard from 50 parts per billion (ppb) to 10 ppb in 2006. Studies showed that mobilization of arsenic and other trace metals into stored waters occurred as oxygenated surface water was injected for storage into the low-oxygen environment of the Floridan aquifer. This caused minute quantities of naturally occurring arsenopyrite in the limestone matrix of the aquifer to become unstable and dissolve, which resulted in release of arsenic into the stored water.

A collaborative research effort in Florida that involved universities, state and federal agencies, and consultants determined that the mobilization of arsenic and other trace metals into stored waters could be significantly reduced by removing the oxidants from the water prior to injection/recharge. Methods investigated to remove oxidants from water involved relatively expensive technologies such as membranes and other gas stripping systems that experienced significant problems, including rapid membrane fouling.

A relatively simple and inexpensive process was eventually developed by (Pearce, Waldron, and Horvath 2009) that eliminated leaching of arsenic during ASR cycles by adding a sulfide compound into the injection-flow stream that maintained the low-oxygen conditions of the natural aquifer environment.

The process involves the mixing of sodium hydrosulfide (NaSH) into the recharge water prior to injection using standard chemical metering and mixing equipment at low concentrations (3–6 parts per million). The sulfide in the NaSH chemical combines with oxygen to form sulfate, which effectively removes free oxygen from the water to be injected. Upon injection, the low-oxygen environment in the Floridan Aquifer is preserved, which results in an arsenic concentration in recovered water that is well below the drinking water standard and will require little to no additional treatment prior to distribution.

Project Planning/Implementation

The NaSH process was tested at an ASR facility owned by the City of DeLand in 2009. Pilot testing involved ASR cycles of 5 million and 20 million gallons of recharge, storage, and recovery. Results of the testing showed that for both operational cycles, the concentration of arsenic in the recovered water was less than 1 ppb, much lower than the 10 ppb drinking water standard. Figure 1 is a photograph of the system including the totes that contain the NaSH chemical. The process has since been successfully employed at additional ASR sites in Florida, including the City of North Port and the City of Sanford.

The addition of NaSH to aquifers containing potable water has been accepted by the Florida Department of Environmental Protection and has received National Sanitation Foundation certification for use in drinking water systems. The NaSH process is low cost compared to other pretreatment processes that prevent arsenic mobilization. Components of the system include only standard chemical feed equipment, controls, and metering. Maintenance is very limited because there is no need for prefiltration or chemical cleaning systems, such as those necessary for membrane processes. The cost of chemicals is also relatively low, resulting in very significant savings over alternative treatment methods.

Figure 1. Photograph of the entire NaSH pretreatment system including the NaSH totes.

5.3 Seawater Intrusion/Replenishment in Southern Los Angeles County

Author: Brian Partington, Water Replenishment District, Lakewood, CA

Site Name: Seawater barrier projects along the west coast of Southern Los Angeles County, including West Coast Basin Barrier Project (WCBBP), Alamitos Gap Barrier Project (ABP), and Dominguez Gap Barrier Project (DGBP)

Location: Southern Los Angeles County, California

Permittees: Owner/operator: Los Angeles County Department of Public Works (LACPW); Monitoring entities: Water Replenishment District of Southern California (WRD) and West Basin Municipal Water District (WBMWD); Imported water: Metropolitan Water District of Southern California (MWD); and treated water: WRD, WBMWD, and Los Angeles Sanitation District (LASAN)

Permitting Agency(s): Los Angeles Regional Water Quality Control Board (LARWQCB)

Current Status: Seawater barriers have been in operation since the early 1950s.

Year Constructed: WCBBP was constructed in 1953; ABP was constructed in 1964; and DGBP was constructed in 1971.

Costs: Not available (1950s–1970s)

Project Contact Information: Los Angeles County Department of Public Works, (626) 458-6120

Project Website/Publication Links:

LACPW—https://dpw.lacounty.gov/wrd/Barriers/index.cfm?Project=Facility

ABP—https://geotracker.waterboards.ca.gov/profile_report?global_id=WDR100006793

DGBP—https://geotracker.waterboards.ca.gov/profile_report?global_id=WDR100000534

WCBBP—https://geotracker.waterboards.ca.gov/profile_report?global_id=WDR100039456

Purpose of MAR:

- Water supply resilience
- Improving groundwater quality
- Mitigation against saltwater intrusion

Source Water:

- Municipal wastewater
- Imported water

Water Quality:

- Pre-treatment required (fully advanced treated water—ATW)

Recharge Technology(s):

- Injection wells

Project Description

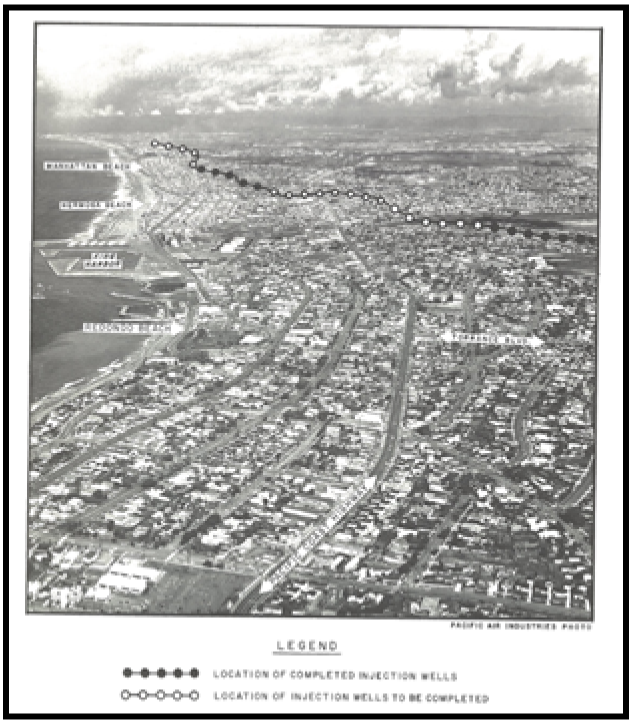


Figure 1: Location of the West Coast Seawater Intrusion Barrier Project.

Source: WRD (1965)

The project is located in southern Los Angeles County, California. Seawater intrusion barriers have been used locally to prevent seawater intrusion due to past overpumping and protect inland groundwater resources as early as 1953. Figure 1 shows how densely populated the coast is and the location of the West Coast Seawater Intrusion Barrier Project. The information in this case study provides basic information for one of the longest, continuously operating seawater intrusion barriers in the nation, which currently consists of (from oldest to youngest) the West Coast Basin Barrier Project (WCBBP), Alamitos Gap Barrier Project (ABP), and Dominguez Gap Barrier Project (DGBP). Together, the seawater intrusion barriers supply on average 28,000 acre-feet per year of imported water and/or advanced treated recycled water to prevent seawater intrusion and provide replenishment to the Central Basin and West Coast Basin (CBWCB). Imported water has been used in the past for replenishment; however, this water source is currently only used when recycled water is not available for advanced treatment at each advanced wastewater treatment facility used to supply ABP, DGBP, and WCBBP. Collectively, these water sources (import and recycled) have provided a significant source of replenishment water for over 4 million people in two of the most heavily used groundwater basins in the United States.

Receiving Aquifer

The seawater intrusion barriers shown on the left side of Figure 2 are located along the coast and inject treated water into numerous aquifers present in the CBWCB. Aquifer replenishment is needed to support local groundwater use, because the amount of water pumped from the basin far exceeds the natural yield of the aquifers in the CBWCB. In the past, over pumping resulted in seawater intrusion and barriers were installed to protect inland pumping wells. The system has been successfully operated since the early 1950s.

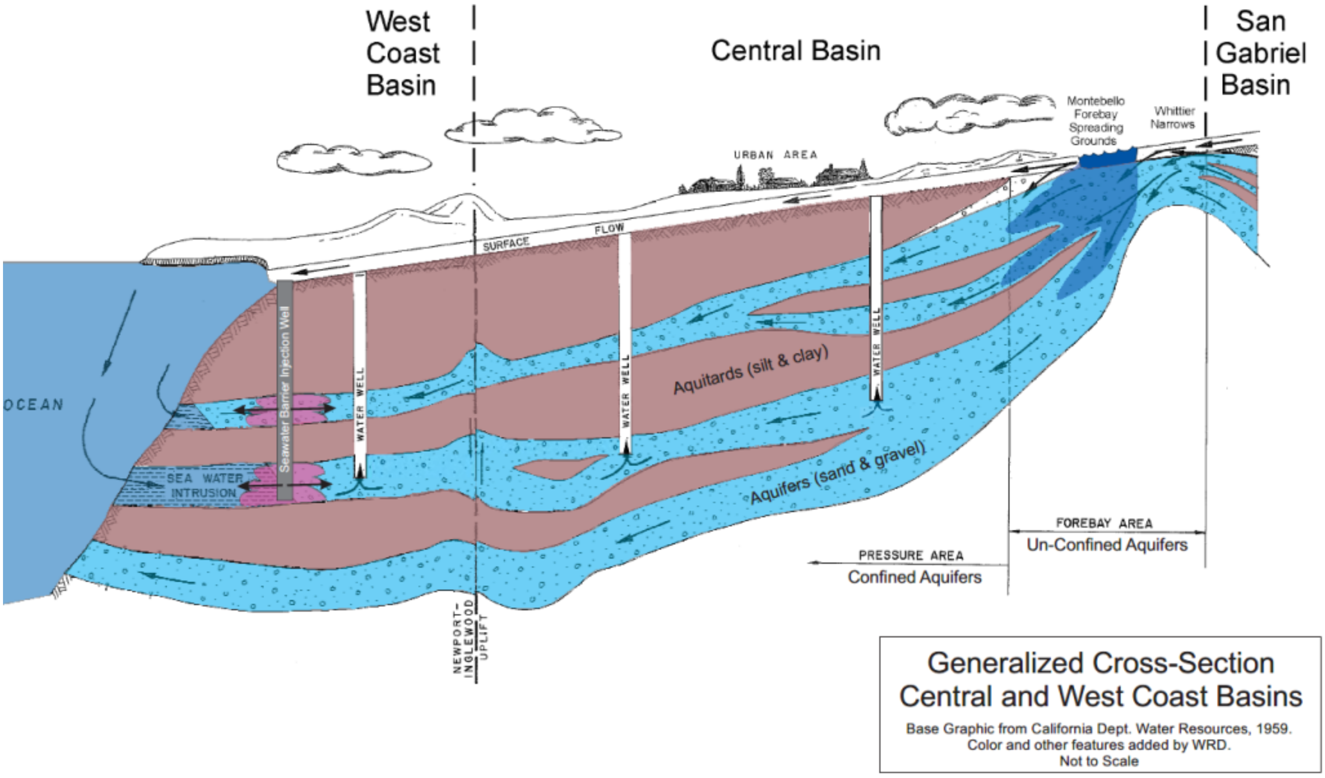


Figure 2. Seawater intrusion barriers.

Source: DWR (1959)

Water Quality

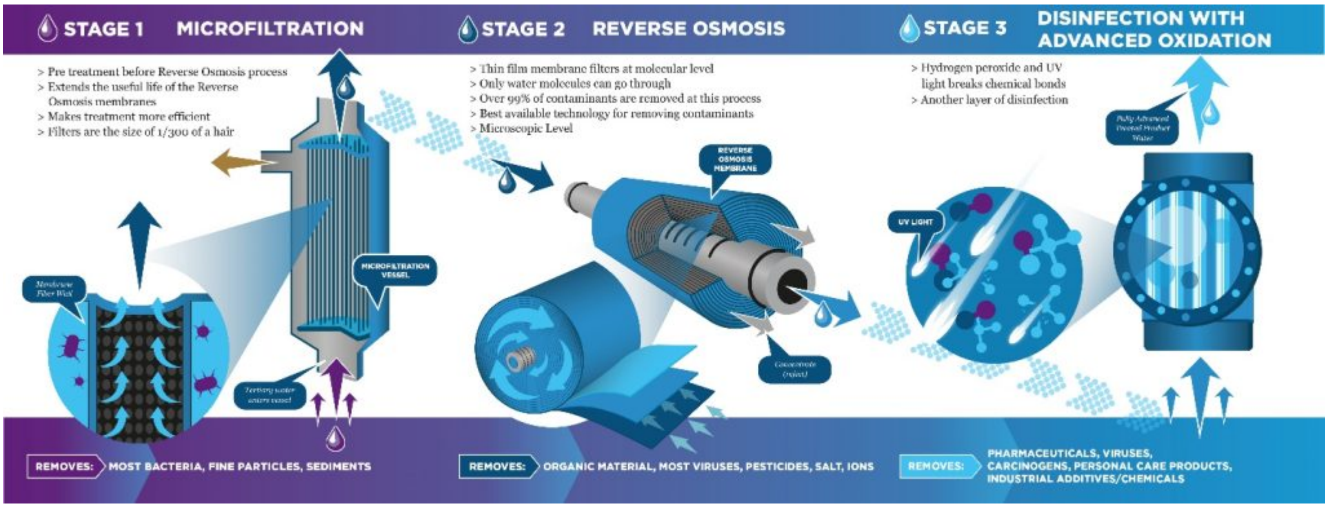
Overall, the water supplied to the seawater intrusion barriers is of high quality, and with the addition of recycled water, it must meet the recycled water policy requirements for California. These requirements are outlined in the California Code of Regulations, Title 22. Relevant links are provided as follows:

- https://www.waterboards.ca.gov/board_decisions/adopted_orders/resolutions/2018/121118_7_final_amendment_oal.pdf
- https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/lawbook/RWregulations_20181001.pdf

Figure 3. Aqueduct systems in California.

Source: Courtesy of Metropolitan Water District

For many years, imported water was used as the primary source water for the seawater intrusion barriers as supplied by the Colorado River and/or the State Water Project. This water travels hundreds of miles (Figure 3) and requires a lot of energy to convey it through an existing aqueduct system to southern Los Angeles County. Furthermore, episodic, and often persistent drought conditions are common in the southwestern United States. This results in less water being available for replenishment during drought periods, and as a result, many agencies have invested heavily in developing recycled water projects, with increased emphasis in California. As a result, use of imported water for injection at the seawater intrusion barriers has been declining the past few decades now that all three seawater barriers are fully permitted to receive 100% advanced treated recycled water (Figure 4) when source water is available to supply treatment facilities operated by WRD, LASAN, and WBMWD.



> Pre treatment before Reverse Osmosis process
> Extends the useful life of the Reverse Osmosis membranes
> Makes treatment more efficient
> Filters are the size of 1/300 of a hair

> Thin film membrane filters at molecular level
> Only water molecules can go through
> Over 99% of contaminants are removed at this process
> Best available technology for removing contaminants
> Microscopic Level

> Hydrogen peroxide and UV light breaks chemical bonds
> Another layer of disinfection

Figure 4. Advanced treatment process used to treat recycled water at the Albert Robles Center for Water Recycling and Environmental Learning.

Source: Courtesy of Water Replenishment District

In 2020, the LARWQCB required all indirect potable reuse projects to implement a phased monitoring program for the presence of various contaminants of emerging concern (CECs). The monitoring program was developed in accordance with recommendations from a 2018 Science Advisory Panel on CECs in Recycled Water. A link to the report and permit is provided below:

- https://ftp.sccwrp.org/pub/download/DOCUMENTS/TechnicalReports/1032_CECMonitoringInRecycledWater.pdf
- https://documents.geotracker.waterboards.ca.gov/regulators/deliverable_documents/3604276359/09242020%20MFSG%20CECMRP%20Amend%20Final%20w%20Att%20CI-5728.pdf

Performance

The seawater barriers are owned and operated by the LACPW. A summary of the seawater barriers and the total amount of water recharged (to date) is shown in Table 1.

Table 1. Seawater barriers information

Source: WRD (2022)

Information	WCBBP	DGBP	ABP
Year First Used	1953	1971	1964
Overall Length (miles)	9	6	2.2
Number of Injection Wells	160	94	60
Number of Observation Wells	300	257	220
Total Recharge in Acre-Feet (1959 to 2021)	1,906,628		
Note: Total recharge includes import (1,622,231 acre-feet) and recycled (284,397 acre-feet) from 1959 to 2021.			

Hundreds of groundwater monitoring wells are located proximal to each seawater intrusion barrier and are used to track chloride concentrations (changes over time) and groundwater elevations in relation to a protective elevation. The goal of each key monitoring well is to maintain water levels at or above the protective elevation. Example cross sections are provided in Figure 5 and Figure 6 showing how effective the barriers have been at reducing chloride concentrations at the Dominquez Gap Seawater Intrusion Project, in this case between 1972 and 2022.

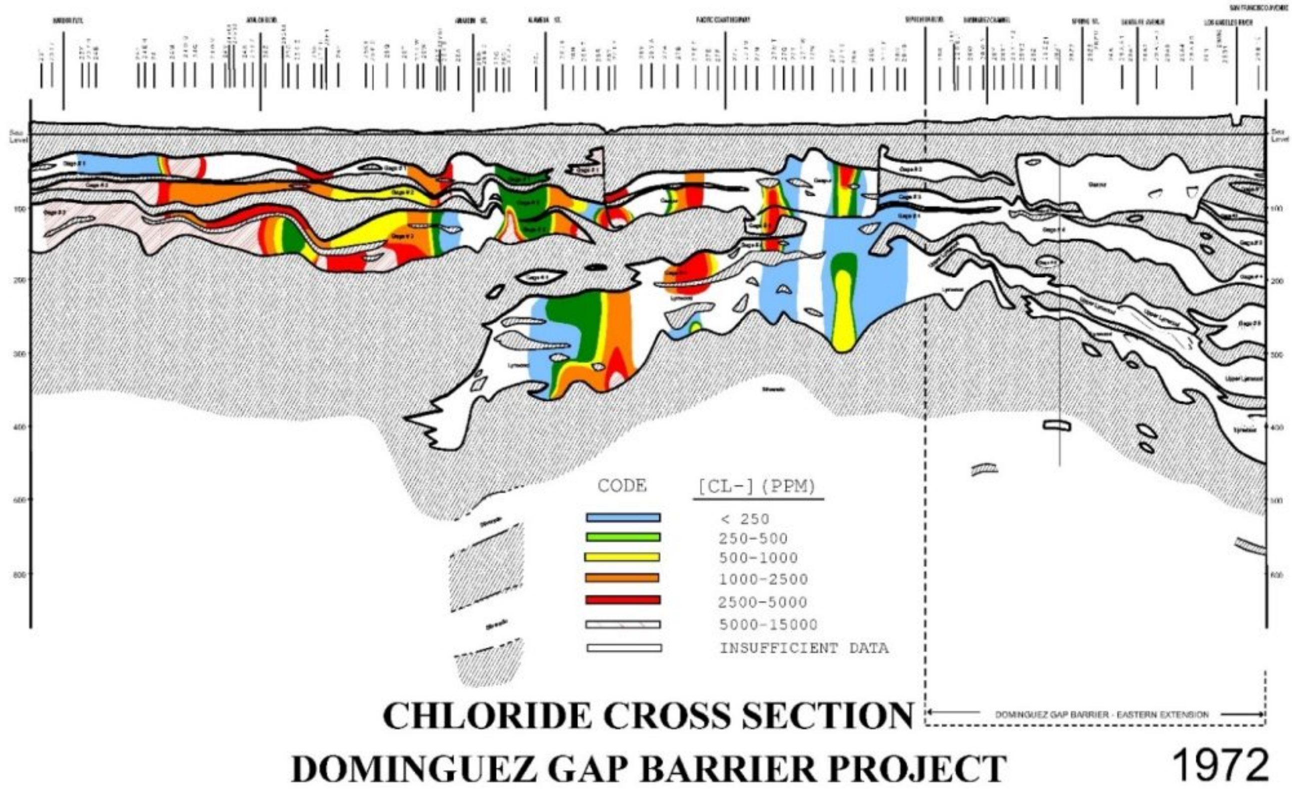


Figure 5. Example cross section showing chloride concentrations control in 1972

Source: Courtesy of Los Angeles County Public Works

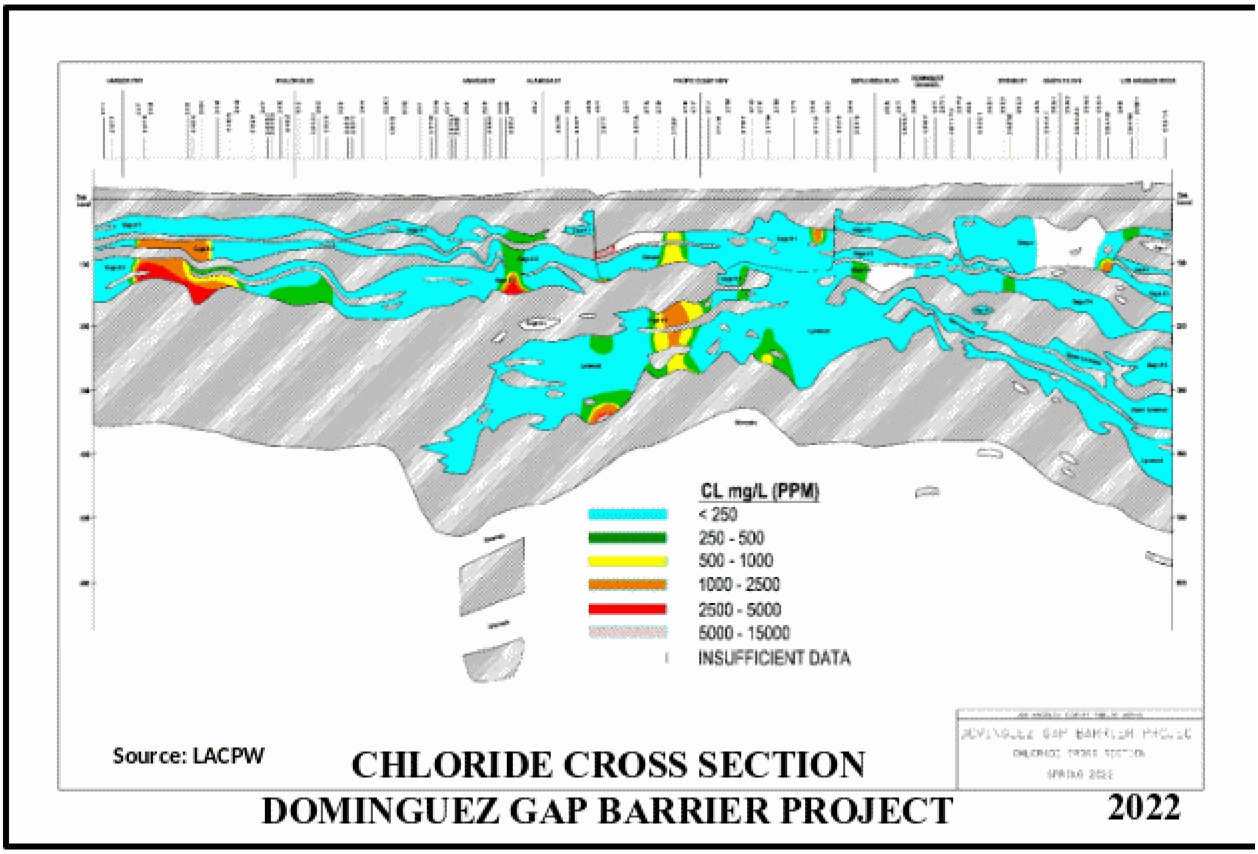


Figure 6. Example cross section showing chloride concentrations control in 2022

Source: Courtesy of Los Angeles County Public Works

Regulatory Considerations

The permitting process can be lengthy, and regulations continue to evolve in California. The permits for this case study were issued jointly to various co-permittees, which generally include a monitoring entity (WRD and WBMWD), recycled water supplier (Los Angeles County Sanitary District (LACSD) and LASAN), advanced treatment facility operators (WRD, LASAN, WBMWD), and seawater intrusion barrier owner/operator (LACPW). The permits have changed over the years as the regulatory community has become more comfortable with the benefits of using recycled water in a predominantly semiarid climate and has shifted toward allowing use of (when available) 100% ATW.

Operational Considerations

The seawater barriers are owned and operated by the LACPW. A well maintenance program was developed to remove accumulated sediment and microbial buildup approximately every 2 years (or as needed) to ensure optimal injection rates are maintained at ABP, DGBP, and WCBBP. Surface leakage has occurred in some aging wells, requiring additional maintenance ranging from minor retrofits to well destruction/replacement. Barrier infrastructure (pipelines, injection wells, and observation wells) is also inspected periodically to identify areas of potential concern and the results are documented in a condition assessment report.

5.4 San Antonio Water System H2Oaks Center ASR Project

Author: Lorrie Council, Texas Commission on Environmental Quality (TCEQ)

Site Name: H2Oaks Center

Location: Elmendorf, Texas (south of San Antonio, Texas)

Operator(s): San Antonio Water System (SAWS)

Permitting Agency(s): TCEQ

Current MAR Status: Active

Year Constructed: 2004 facility online

Costs: $250,000,000

Project Contact Information: Robert Escobar, SAWS manager, and Kevin Morrison, SAWS project coordinator

Project Website/Publication Links:

- https://www.saws.org/your-water/management-sources/aquifer-storage-recovery/

Purpose of MAR:

- Water supply resilience
- Resilience/climate adaptation

Source Water:

- Alternative aquifer

Water Quality:

- Pretreatment required (chlorine not required for injection; added by SAWS)
- Post-treatment required (chlorine)

Recharge Technology(s):

- Injection well

Project Description

The SAWS H2Oaks ASR project stores “excess” groundwater for which SAWS has the groundwater rights to use. This excellent-quality groundwater is stored underground in a confined aquifer (reservoir) south of the City of San Antonio. The source water storage is achieved using a large, multi-well ASR project to store the water until it is needed and the water is later recovered via the ASR wells. This ASR project benefits the San Antonio community by ensuring drinking water is available for use during drought and during peak summer water demand periods. Unlike surface water reservoirs, water stored in an ASR project is not subject to evapotranspiration losses.

The ASR project is located on the SAWS H2Oaks Center site, which is an approximate 3,200-acre facility owned by SAWS (Figure 1). The H2Oaks Center ASR has the capacity to store about 233,000 acre-feet of drinking water in a confined aquifer reservoir. The H2Oaks Center also has a brackish water wellfield and associated reverse osmosis water treatment plant that provides an additional water source to the City of San Antonio.

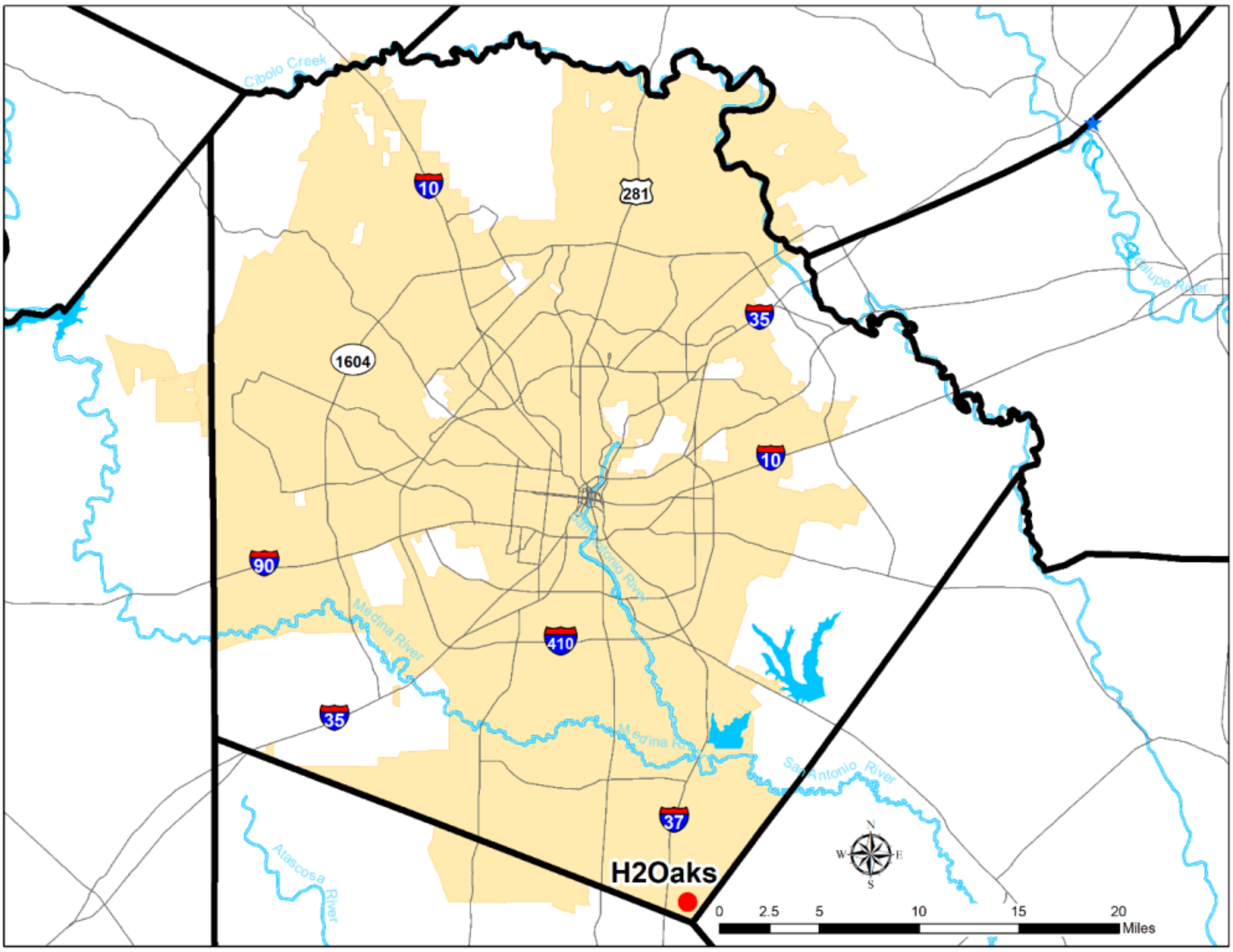


Figure 1. Regional location map: San Antonio Metro Area and H2Oaks ASR project.

Source: Morrison (2022)

Receiving Aquifer

The Carrizo Aquifer is within the Tertiary (Eocene) Carrizo Formation. It is a confined aquifer that occurs at depths beginning ~ 400–700 feet below land surface at the H2Oaks Center ASR project site. The Eocene-age Reklaw Formation is the upper confining unit for the Carrizo Aquifer. The Carrizo Formation is a medium- to very coarse-grained sandstone that includes friable to locally indurated noncalcareous thick bedded sand units.

The H2Oaks ASR has capacity to store 74 million gallons per day. SAWS has installed 29 of 34 permitted ASR wells on the ~3,200-acre facility (Figure 2). The ASR wells have pumping yields that range from 1,200 to 2,000 gallons per minute (gpm). Although the thickness of the Carrizo Sand at the project location is greater, the total thickness of the screened sands in the 29 ASR wells ranges from 145 to 291 feet. The depths to the top of the screens range from 370 to 547 feet below land surface. The average porosity of the Carrizo sands is ~35%.

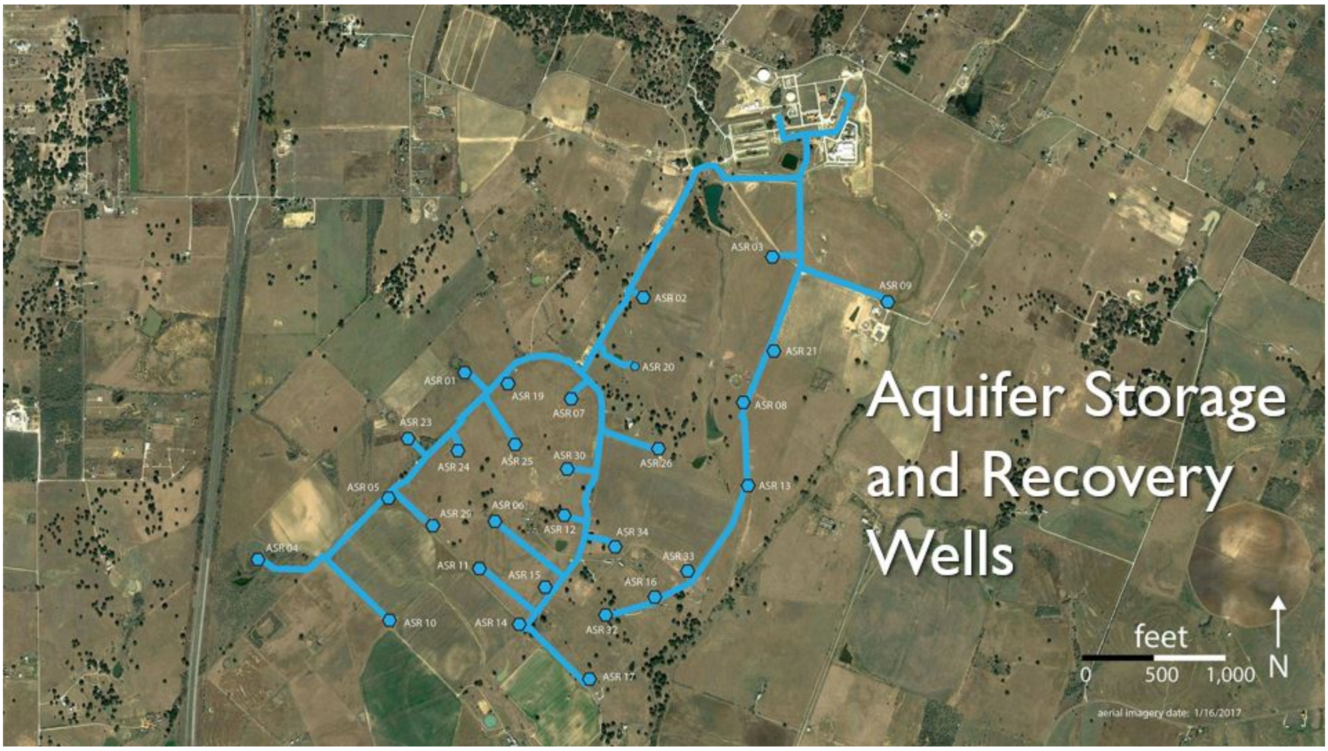


Figure 2. SAWS H2Oaks ASR well fields.

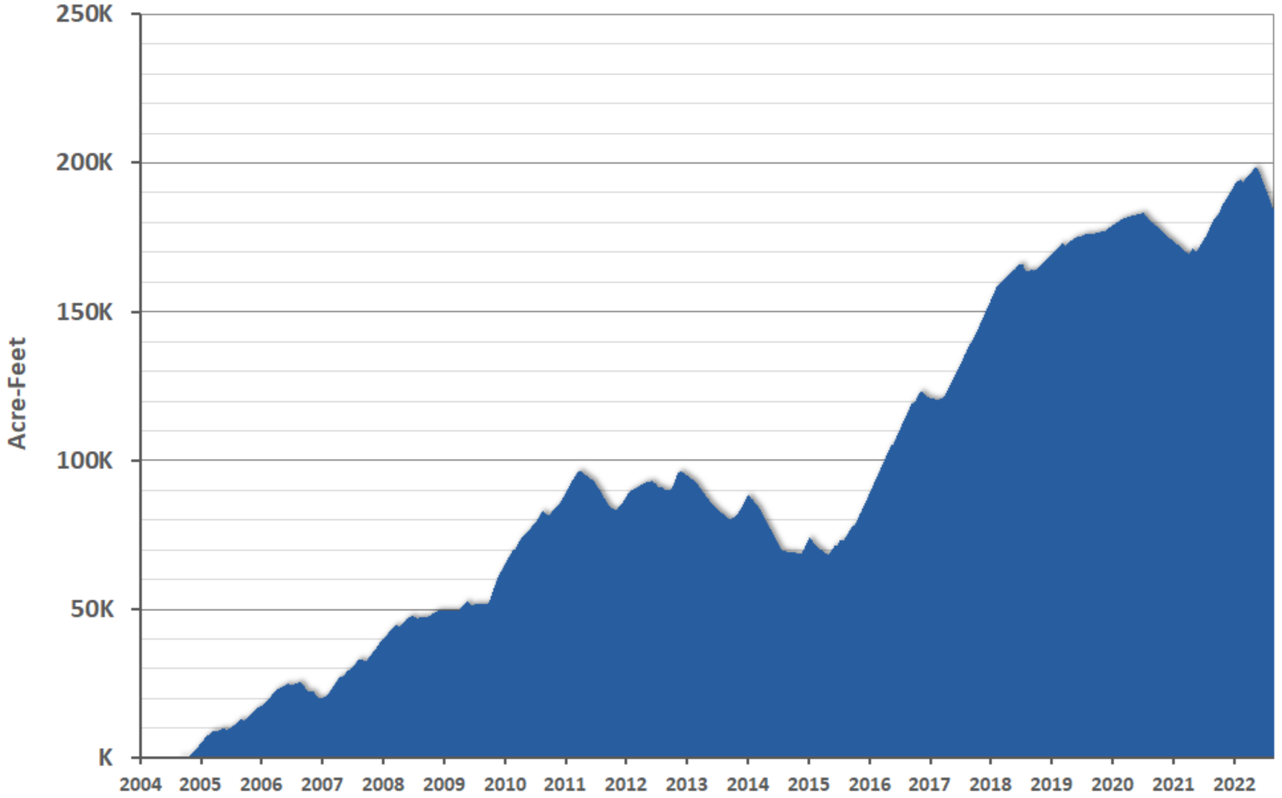
Source: Morrison (2022)

Water Quality

Source water from the Edwards Aquifer in San Antonio is very high-quality groundwater, and it is stored in the ASR project in the Carrizo Formation. Native groundwater in the Carrizo has higher total dissolved solids (TDS) than the Edwards Aquifer groundwater and has naturally high levels of iron and manganese. Stored water recovered from the ASR project is chlorinated before distribution, and if ASR well production captures native Carrizo groundwater, then treatment for naturally high levels of manganese and iron may be required. The water treatment facility at the H2Oaks ASR project can handle treatment of blended water, including alkalinity adjustments, an aeration system, solids contact clarification, filters, and solids handling.

Performance to Date

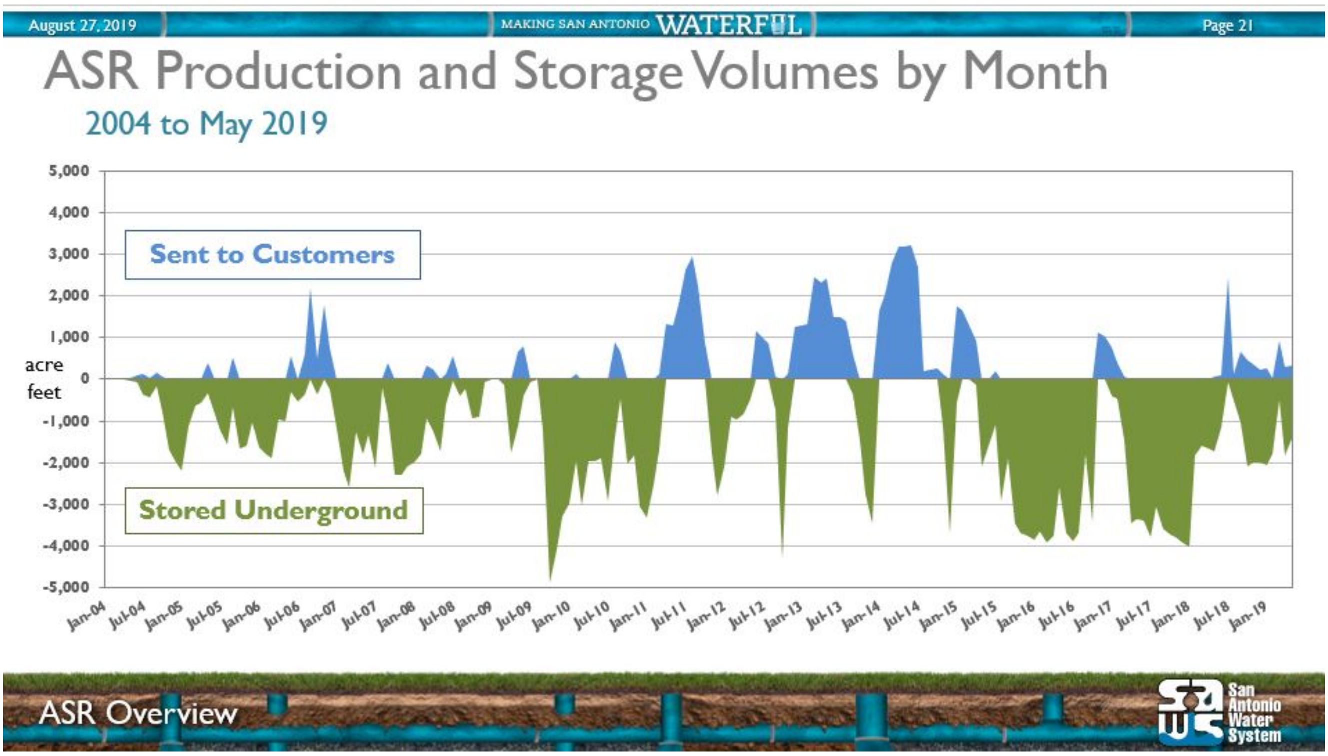
The H2Oaks ASR has performed quite well and has operated predominantly in a drought storage mode rather than a seasonal leveling mode. The SAWS H2Oaks ASR water in storage chart (Figure 3) and SAWS H2Oaks ASR production and storage volumes by month chart (Figure 4) depict the ASR water in storage (through August 2022) and ASR production and storage volumes by month (2004 to May 2019). Water in storage has been equivalent to the annual water delivery requirement SAWS has for the City of San Antonio. The ASR project has provided great operational flexibility to the utility in servicing its water customers. The production and storage volumes by month graphic is very informative and shows the dynamics to date of the ASR project through mid-2019.



Source: San Antonio Water System

Figure 3. SAWS H2Oaks ASR water in storage.

Source: Morrison (2022)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ASR Production and Storage Volumes by Month

2004 to May 2019

ASR Overview

San Antonio Water System

Figure 4. SAWS H2Oaks ASR production and storage volumes by month.

Source: Thompson (2019)

Project Planning/Implementation

Stakeholder Consideration/Issues

SAWS met with landowners and well users in the area during the planning and early implementation phases of the ASR project. Some mitigation was done for nearby eligible well owners to proactively address potential adverse impacts. Wells were individually assessed for mitigation options, such as no mitigation, lower pump, drill replacement well, and connect to water system. As a result, 166 wells were included in this mitigation effort: lowered pump (53), connected to water system (17), drilled new well (83), and no mitigation required (13).

Costs

As of 2019, SAWS estimates it has invested $250,000,000 in the H2Oaks ASR project, which includes 29 total ASR wells, 30 million gallons per day water treatment facility, and seven Carrizo Aquifer wells. Mitigation costs totaled $6,677,000 and included well diagnostics, pump lowering, a replacement well, SAWS meter connection, well plugging, and miscellaneous operational expenses (Thompson 2019). Of this amount, $52 million was for construction of the ASR wellfield, while the remainder was for the pipeline and pumping system to convey the water to and from the ASR wellfield, and for the treatment facilities to treat the high iron and manganese in the water produced from the seven Carrizo Aquifer production wells along one side of the property (Snyder et al. 2022).

Lesson(s) Learned

During the summer of 2022, SAWS conducted a “max recovery” test of the system to determine the ability to aggressively recover (produce) stored water and determine impacts from extended maximum recovery of water from the ASR project. This work served as an extended pump test and the data collected was used to update SAWS’ ASR hydrogeologic model. SAWS also took and analyzed several water chemistry samples during this time. The conclusions of the test were that there is not a lot of movement of stored Edwards Aquifer water within the ASR project boundaries, but there appears to be some mixing occurring on the west end of the project. Over the years, the west side of the ASR project had not received as much Edwards Aquifer water as the east side of the project. SAWS used the updated hydrogeologic model to determine the optimal recovery pumping rate and duration to achieve the balance between storage, recovery, and minimizing downgradient drift of the stored water, while avoiding negative impacts during recovery to nearby wells.

SAWS personnel obtained approval for longer term maintenance and repair of a few ASR wells that have been in service since 2004. To address corrosion issues with the ASR wells, SAWS installed stainless steel liners in the upper portion of two ASR wells that had been operating since project startup in 2004. Additionally, several of the ASR well pumps were replaced. For future ASR wells, SAWS plans to revise its materials of construction to include more corrosion-resistant casing materials.

5.5 Salinas Valley Groundwater Basin

Author: Anthony Daus

Site Name: Salinas Valley Groundwater Basin

Location: Monterey County, California

Operator(s): Monterey County Water Resources Agency (MCWRA) and the Salinas Valley Basin Groundwater Sustainability Agency

Permitting Agency(s): California State Water Resources Control Board, California Department of Water Resources, National Oceanic and Atmospheric Administration (NOAA), Federal Energy Regulatory Commission (FERC), and U.S. Army Corps of Engineers

Current MAR Status: Active MAR release of stored surface water from two large reservoirs

Year Constructed: 1957—Nacimiento Reservoir; 1967—San Antonio Reservoir

Project Contact Information: MCWRA, (831) 755-4860

Project Website/Publication Links:

- https://www.co.monterey.ca.us/government/government-links/water-resources-agency
- https://svbgsa.org/about-us/

Purpose of MAR:

- Water supply resilience
- Use of floodwater (control of flood, agricultural)
- Protection of riparian ecosystems/maintenance of minimum streamflow

Source Water:

- Rivers/streams/lakes/reservoirs
- Captured water (floodwater, stormwater, precipitation/overland flow/runoff, harvested rainwater)

Water Quality:

- No treatment required

Recharge Technology(s):

- Enhanced streambed recharge

Project Description

The Salinas Valley is the largest coastal groundwater basin in Central California and one of the most important agricultural areas in California. The northwest-trending valley is V-shaped with mountains on the southwest and northeast emptying into the Pacific Ocean near Monterey, California. The valley is drained by the Salinas River and its tributaries and includes rangeland, intensive year-round agricultural activities, and urban development.

Groundwater in the basin is divided into four subareas that include both confined aquifers in the north and unconfined aquifers in the south (Figure 1). The areas are extensively used for agriculture and include several urban areas, including the City of Salinas. Groundwater pumping dates to approximately 1890 and is used for municipal supply and irrigation. As a result, parts of the basin are in overdraft with seawater intrusion extending up to 8 miles inland from the coast.

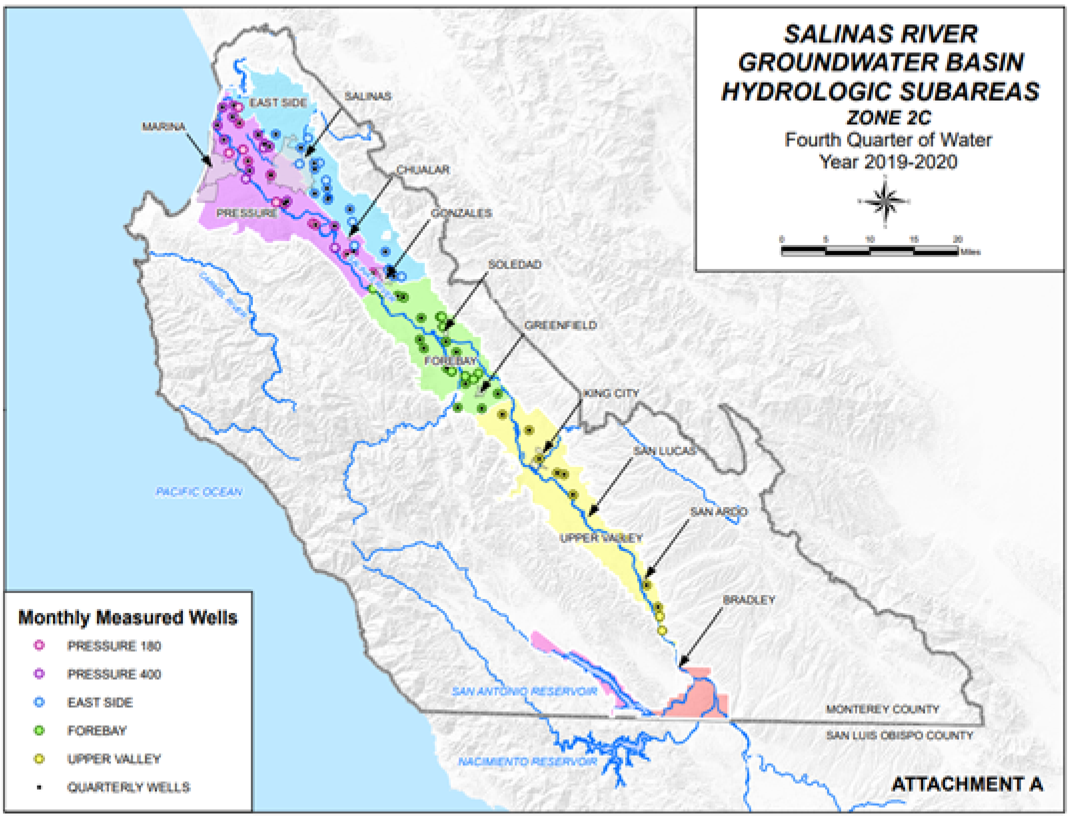


Figure 1. Salinas River Groundwater Basin and hydrologic subareas.

Source: *Monterey County Water Resources Agency (2023)*

Recharge from streams represents 50% of the average 504,000 acre-feet/year of annual recharge to the groundwater basin. The flow in the Salinas River is managed using two reservoirs, the Nacimiento and San Antonio reservoirs. The water collected and stored by the reservoirs originates as runoff from the coastal mountain range to the west. The reservoirs are managed for multiple purposes, including groundwater recharge, flood control, and to sustain native steelhead populations (an anadromous fish). There are current plans to construct an interlake tunnel that will allow MCWRA to transfer water from Nacimiento Reservoir to San Antonio Reservoir. This $48,000,000 project will allow the MCWRA to store additional water for release during dry periods.

Receiving Aquifer

The basin is divided into four subbasins or subareas. From south to north the subbasins include the Upper Valley, Forebay, Pressure, and Eastside subareas (Figure 2). The Upper Valley and Forebay subarea aquifers are unconfined and recharged primarily by the Salinas and Arroyo Seco rivers and to a lesser degree by direct precipitation. The East Side subarea is unconfined and semiconfined and recharged by direct precipitation, while aquifers in the Pressure subarea are confined and semiconfined and subdivided into the shallow aquifer, the 180-foot aquifer, the 400-foot aquifer, and the deep aquifer (Figure 2). The Pressure area aquifers are recharged by underflow from the adjacent Forebay area. The basin is currently experiencing a long-term decrease in aquifer storage due to overpumping. The Pressure and Eastside subareas are experiencing saltwater intrusion from the Pacific Ocean due to overpumping.

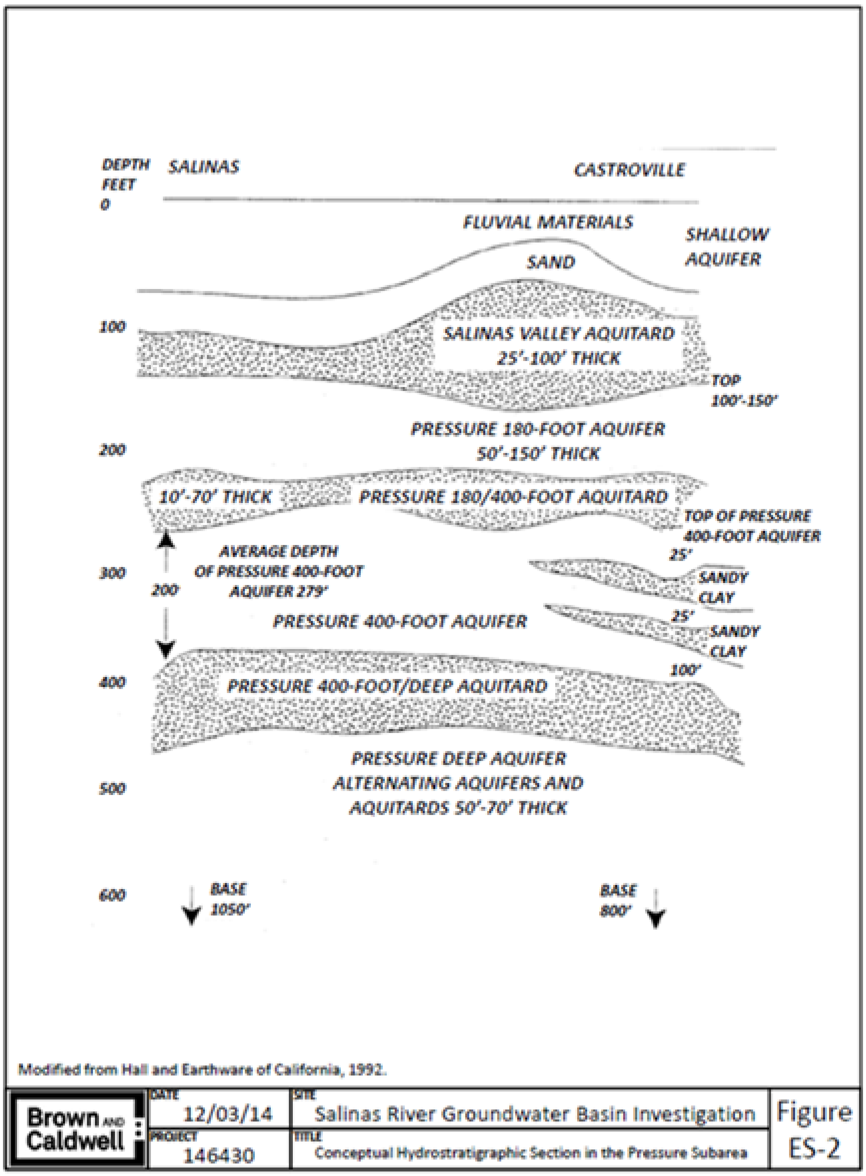


Figure 2. Aquifers in the Pressure subarea.

Source: *Brown and Caldwell (2015)*

Water Quality

The Salinas Valley Groundwater Basin is impacted by nitrates throughout; they are particularly high in the East Side, Forebay, and Upper Valley subareas. There are active programs to reduce the spread of nitrates by mitigating sources and removing abandoned or inactive wells that provide for vertical migration of shallow impacted groundwater to deeper water-bearing zones. Saltwater intrusion in the Pressure and Eastside subareas (north) has significantly impacted a large part of the coastal portions of the basin (Figure 3). Saltwater intrusion started in the 1930s and continues to extend into the basin with time. Efforts to control saltwater intrusion have consisted of reducing groundwater extractions in the Pressure subarea through in lieu recharge (providing recycled water and surface water in lieu of groundwater pumping) and groundwater pumping reductions.

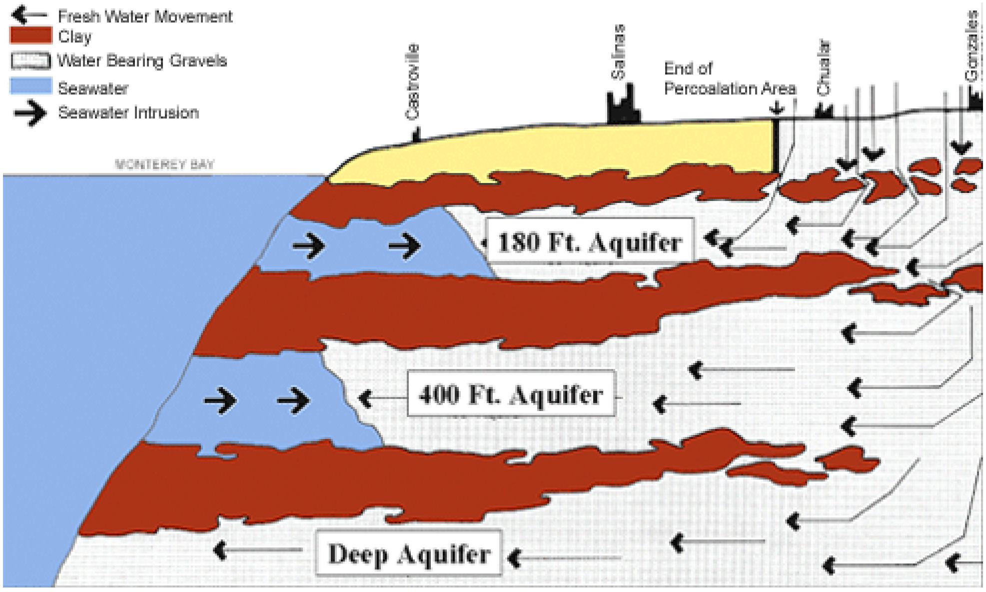


Figure 3. Seawater Intrusion into the Salinas Valley Groundwater Basin

Source: *Monterey County Water Resources Agency (2023)*

Performance to Date

Between April and October, the reservoir releases water to the Salinas River, resulting in recharge through the bottom of the streambed. In 2021, these losses through the bottom of the Salinas streambed amounted to approximately 1,237 acre-feet per day. Saltwater intrusion continues to impact the northern portion of the basin with efforts underway to reduce its progression. Efforts to reduce saltwater intrusion include providing recycled wastewater for use as irrigation water and the operation of the rubber dam to seasonally store Salinas River water for delivery as irrigation water, thus reducing the need to pump groundwater (in lieu recharge). Future surface water diversions are planned to divert up to 135,000 acre-feet per year of Salinas River water to reduce groundwater pumping in the northern part of the basin. Overall portions of the basin remain in overdraft due to the intensive groundwater pumping to support the agricultural interests. Steps are currently underway under the Sustainable Groundwater Management Act (SGMA) to make the groundwater supply a sustainable resource.

Regulatory Considerations/Issues

Permitting: Permitting agencies include, but are not limited to, the U.S. Army Corps of Engineers, NOAA, FERC, the State Water Resources Control Board, the California Department of Water Resources, and the California Department of Fish & Wildlife

Water Rights: Groundwater in the basin is not adjudicated but is subject to the Sustainable Groundwater Management Act of 2014 (DWR 2023).

Accounting: Surface water resources in watershed are managed by the Monterey County Water Resources Agency, and groundwater resources are managed by the Salinas Valley Basin Groundwater Sustainability Agency (SVBGSA) under SGMA.

Operational Considerations/Issues

Releases from the reservoirs are operated under separate rule curves established for each reservoir. The SVBGSA manages the groundwater basin and is tasked with implementing the Groundwater Sustainability Plan with sustainability reached by 2040. Given the integrated nature of surface water and groundwater resources, there are nearly 30 stakeholders involved in the management of water resources in the Salinas Valley. This requires frequent communication and outreach on all decision-making.

5.6 Idaho's Eastern Snake Plain Aquifer MAR Program

Author: Wesley Hipke

Site Name: Eastern Snake Plain Aquifer (ESPA) MAR Program

Location: Southern Idaho

Operator(s): Idaho Water Resource Board (IWRB)

Permitting Agency(s): MAR facilities do not require permitting in Idaho; however, water rights with the beneficial use of recharge from Idaho Department of Water Resources (IDWR) is required to conduct recharge. Related to water quality injection wells, an underground injection control permit was required from IDWR, and Idaho Department of Environmental Quality (IDEQ) requires recharge basins to have an approved groundwater quality monitoring program.

Year Constructed: Pilot program 2009–2014; full-scale program started in 2014.

Purpose of MAR:

- Water supply resilience
- Use of floodwater (control of flood, agricultural)
- Protection of riparian ecosystems/maintenance of minimum streamflow
- Resilience/climate adaptation

Source Water:

- Rivers/streams/lakes/reservoirs

Water Quality:

- No pre- or post-treatment required

Conveyance of Source Water to MAR:

- Pump stations
- Diversion structures
- Canals/trenches/arroyo

- In-channel recharge
- Pipeline

Recharge Technology(s):

- Infiltration pond
- Wet well
- Bank filtration
- Sinkhole

Water Recovery and End Use:

- Aquifer recharge
- Irrigation
- Stream base flow
- Ecosystem/habit

Receiving Aquifer:

Eastern Snake Plain aquifer (ESPA)

Project Description

The ESPA Recharge Program is a state-run program in the Eastern Snake Plain region of Idaho. The program has been tasked with developing a MAR program to recharge an average of 250,000 acre-feet/year. To do so, the IWRB uses surface water rights and partners with canal and irrigation companies utilizing existing infrastructure to conduct MAR and deliver water to developed recharge basins and injection/recharge wells.

Benefits: The primary benefit is to mitigate the ESPA, which has been declining since the 1950s. The decline is a result of increased groundwater pumping, increased efficiencies in irrigation practices, and prolonged droughts. MAR is a key component to providing a sustainable water supply throughout the area. Stabilizing the aquifer has a direct impact on surface water flow, creating additional hydropower generation and environmental and recreational benefits.

Size of Project: ESPA covers over 10,000 acres. MAR occurs in canals (the largest being over 60 miles long), and individual recharge sites ranging from 1 acre to over 300 acres.

Current MAR Status: Since the start of the full-scale program in 2014, the program has recharged 2,300,00 acre-feet to date from numerous recharge sites.

Hydrogeological Setting

The ESPA primarily consists of layered basalt flows with discontinuous interbedded sedimentary deposits (Wood and Low 1986). These basalts can be highly fractured with extensive lava tubes and rubble zones throughout (Kuntz, Covington, and Schorr 1992). This causes hydraulic conductivities to be highly variable, ranging from 0.1 to 24,000 feet/day (Ackerman 1991). The ESPA also has a strong hydrological connection to the Snake River through connected reaches and large springs that discharge into the Snake River (Kjelstrom 1995).

Storage Potential: 200–300 million acre-feet

Geochemical Considerations: Agricultural runoff: total coliform, nitrate, nitrite, *E. coli*

Minerology: Basalt

Mobilization of Metals or Contaminants: Potential agricultural contaminants, such as total coliform, nitrate, nitrite, and *E. coli,* are present in conveyance systems but are greatly reduced from natural attenuation as water infiltrates through the vadose zone during recharge. No adverse effects to water quality in the aquifer have been observed.

Seasonal Variability: MAR activities generally begin after irrigation (October) and continue until April. When there is sufficient surface water to meet senior water rights, MAR activities can continue into the irrigation season.

Location Considerations: The IWRB has partnered with numerous irrigation companies to facilitate recharge, so recharge timing must be convenient for the irrigation companies.

Impacts to Proximal Facilities: No negative impacts to proximal facilities have been observed.

Effects on Current Water Users: Negative effects on current water users are minimal because the water right used for MAR is junior to most water users. MAR diversion does reduce the water available for hydropower in the winter months; however, MAR activities result in increasing surface water flow throughout the year.

Water Quality:

Source Water Quality: The Snake River and Big and Little Wood River provide the source water for this program. Sampling of the source water during MAR activities has detected no contaminants over MCL. No pretreatment was required.

Performance to Date

Project Metrics: Fall 2014 through spring 2023: 2,130,000 acre-feet recharged to date. Average since 2014: 236,700 acre-feet recharged per year.

Volume Water Recharged/Extracted: 2,377,000 acre-feet recharged, IWRB related natural flow and storage water from other entities.

Permitted vs. Actual Performance or Availability of Water: During “dry” years the program can currently recharge all the available water (approx. 500 cfs). During “wet” years water availability can range from 1,000 cfs to over 20,000 cfs. Currently, the program has a recharge capacity of 2,000–4,000 cfs, depending on when water is available.

Average Infiltration Rates/Seasonal Variations: If water is available before the irrigation season, canals can be used to conduct MAR, along with “off-canal” sites. However, once irrigation deliveries begin, only “off-canal” sites can be used. The infiltrations rates at “off-canal” sites can vary significantly, from 10 cfs up to 650 cfs.

Stakeholder Consideration

Water Planning: The IWRB worked with stakeholders to develop the ESPA Comprehensive Aquifer Management Plan (CAMP) to address the decline in the aquifer. The ESPA CAMP was adopted in 2009 and was designed to add an additional 600,000 acre-feet/year to the ESPA.

Community: The IWRB has significant, ongoing involvement with all the ESPA stakeholders.

Environmental Justice: The IWRB has established an Environmental Technical Working Group with key stakeholders to discuss and study potential environmental-related impacts associated with the IWRB’s MAR program.

Social Sustainability: This region accounts for between a quarter and a third of Idaho’s gross product. The design of the CAMP is to ensure this area has a sustainable water supply for the future.

Operational Constraints

Adjacent Business/Users: Agriculture and recreation

Mounding: Depth to groundwater varies significantly over the region from a few feet to over 300 feet. To date in the areas where MAR has occurred, mounding has not been an issue.

Contaminated Sites: N/A

Energy Requirements: To date, energy requirements are minimal, as most sites are gravity-fed.

Operational Costs: There is not a cost for the water that is recharged; however, there are conveyance and operational costs. Since the start of the full-scale program the cost has been $9.34 per acre-foot of water recharged. Adding in the additional capital cost for developing increased recharge capacity raises the total program cost to approximately $20 per acre-foot of water recharged.

Regulatory Consideration

Permitting Requirements: The doctrine of prior appropriation governs water rights in Idaho. Entities that wish to use surface or groundwater in Idaho must apply for a water right permit and demonstrate the water will be put to beneficial use. Idaho law explicitly recognizes groundwater recharge as a beneficial use of surface water. However, right of way permits from the Bureau of Land Management (BLM) have been required for many of the sites, since they reside on land managed by BLM. Additionally, IWRB must get the approval of a groundwater quality monitoring plan (GWQMP) from IDEQ to conduct recharge at basin MAR sites. Injection wells require a UIC permit from IDWR.

Water Rights: IWRB has recharge water rights and has applied for additional water rights on the Snake, Big Wood, and Little Wood rivers.

Accounting: Idaho does not have statutes for a recharge accounting or credit system. However, MAR can be used as part of a mitigation plan to reduce impacts for groundwater pumping on a yearly basis.

Description of Evaporation and Evapotranspiration: Evaporation and evapotranspiration (EET) are minimal because recharge occurs in the winter months when potential EET and actual EET are low.

How Are Losses Calculated and/ or Measured: EET losses are not calculated.

Meters and Calibration of Meters/Frequency: Several times a year

Reporting Agencies that Oversee the Accounting: Idaho Department of Water Resources

Contingency Plans

Exceedance for Water Quality/Aquifer Water Quality Parameters: Outlined in the approved groundwater quality monitoring program (GWQMP) or the UIC permit. Generally, if a sample is above a specified action level, the location is resampled. If still above the action level, the IWRB halts recharge activities and works with the regulating agency to develop a plan of action.

Emerging Contaminants: Currently, sampling is not required by either water quality regulating agency.

Structure Failures: The recharge sites are monitored daily. If a problem arises, water can be diverted to unused portions of the canal system or other canal systems can be used if they are available. Otherwise, the water is not diverted from the river.

Lessons Learned

Implementation: Stakeholders’ participation/support is crucial. Monitoring is extremely important to provide the data necessary to demonstrate the effectiveness/impact of the program and to adaptively manage the program to meet changing needs.

Operations & Maintenance

- Maintenance and operational techniques—Data loggers and gauging stations are checked frequently, and software is updated as needed.
- Planned maintenance schedule—Before and after recharge begins.
- Operator training—ESPA MAR program staff and canal companies provide training to their operators related to recharge activities.
- Equipment—Generator to purge wells for water quality sampling. All other equipment is owned and operated by the canal companies that deliver recharge water.
- Sedimentation—Sedimentation has not been a problem to date.

Funding Sources

IWRB receives money from the state of Idaho and the federal government. The IWRB will also share the cost of projects with partners, such as canal companies.

Supporting Figures/Drawings

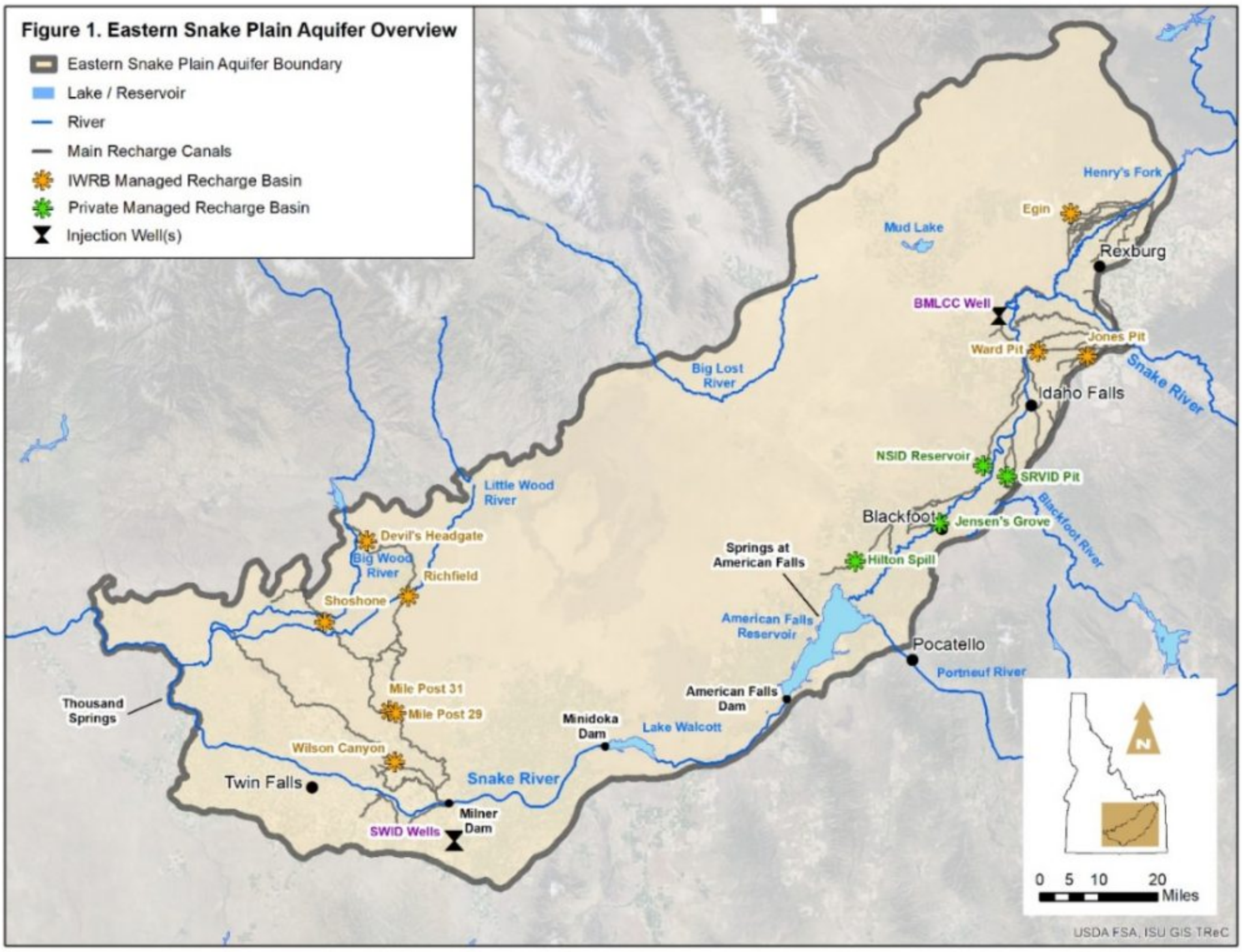


Figure 1. Regional map.

Source: Stewart-Maddox, Noah et al. (2018)

5.7 Pilot Study for the Injection of Highly Treated Reclaimed Water to Create Saltwater Intrusion Barriers and Enhance Groundwater Supplies, Hillsborough County, Florida

Author: Gregg Jones

Site Name: South Hillsborough Aquifer Recharge Project (Apollo Beach)

Location: Hillsborough County, Florida

Operator(s): Hillsborough County Public Utilities

Permitting Agency(s): Florida Department of Environmental Protection (FDEP), Southwest Florida Water Management District (SWFWMD)

Current MAR Status: Pilot testing is now complete and additional injection wells are being constructed.

Year Constructed: 2015

Costs: Not available

Project Contact Information: Jeff Greenwell, section manager, Hillsborough County Public Utilities

Project Website/Publication Links:

- https://www.hillsboroughcounty.org/en/government/county-projects/highlighted-cip-projects/aquifer-recharge-projects
- https://www.tampabaywater.org/supply/projects/south-hillsborough-wellfield/

Purpose of MAR:

- Water supply resilience
- Improving groundwater quality
- Mitigation against saltwater intrusion

Source Water:

- Reclaimed water (high-level disinfection public access-quality)

Water Quality:

- Pretreatment required

Recharge Technology(s):

- Injection wells

Project Description

The Floridan Aquifer is the principal source of water in most of north and central Florida. The aquifer has been severely depleted by pumping for public and private water supplies, changes in weather cycles and precipitation patterns, and increases in sea level. As groundwater withdrawals have increased, saltwater has intruded into the freshwater portions of the aquifer in coastal southern Hillsborough County. This has resulted in the abandonment of coastal wells. To reduce the rate of intrusion of saltwater into the aquifer, the SWFWMD has banned additional groundwater withdrawals in the region.

In 2009, Hillsborough County Public Utilities started investigating the potential to inject its high-level disinfection public access-quality reclaimed water into the Floridan aquifer to:

- act as a barrier to saltwater intrusion
- create a path to the restoration of local groundwater levels
- support a long-term and sustainable solution to water management challenges in the Hillsborough County Public Utilities service area

In coordination with the FDEP and SWFWMD, Hillsborough County embarked on a reclaimed water indirect aquifer recharge pilot project in non-drinking-water portions of the Floridan aquifer in the southern coastal area of the county.

The project pumps highly treated reclaimed water into the saltwater zone that separates the water under Tampa Bay from the fresh water in the aquifer (Figure 1). The recharged water creates a freshwater barrier that not only helps to prevent intrusion of saltwater but also helps impound fresh groundwater several miles inland, which improves the environment and water levels upstream of the recharge area. The recharge wells that pump reclaimed water into the aquifer are near the coast and several miles seaward of public supply wells that pump fresh groundwater from the aquifer. Groundwater in the aquifer naturally flows toward the Gulf of Mexico, which pushes the reclaimed water away from the areas where public supply wells are located. The county operates multiple monitoring and injection wells to regularly track aquifer water levels and water quality.

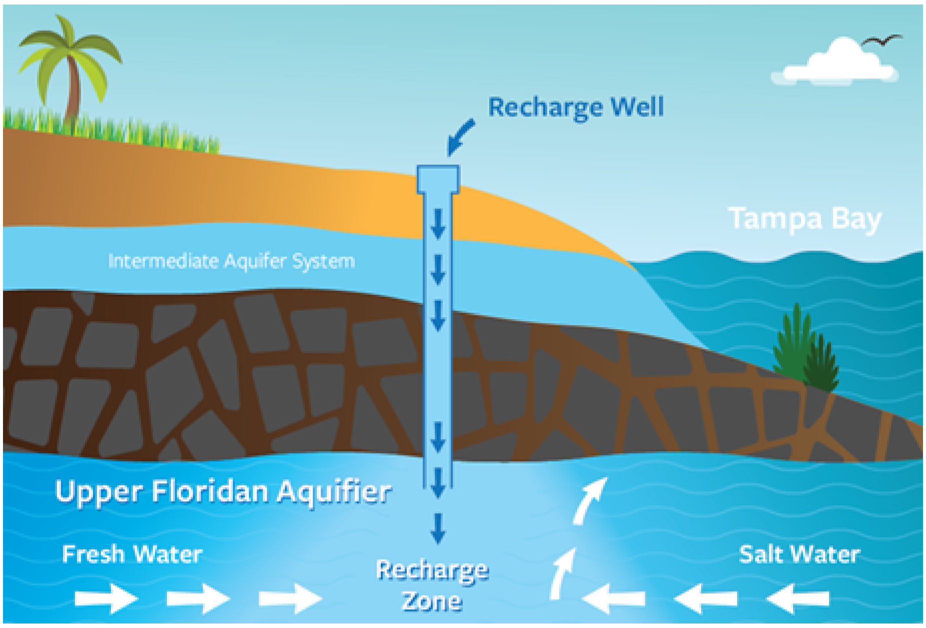


Figure 1. Salinity barrier concept in the Upper Floridan Aquifer, Hillsborough County, Florida.

Source: Hillsborough County (2023)

Project Planning/Implementation

Data from the South Hillsborough County Aquifer Recharge Project has shown significant recovery of fresh groundwater storage levels, a halt to saltwater intrusion, and seasonal stabilization in the aquifer in the area of recharge. Water quality testing has shown no negative impacts where freshwater withdrawals occur.

Upon successful completion of pilot testing, Hillsborough County will add three recharge wells to the three that are currently operational, which will result in a reclaimed water injection capacity of at least 10 mgd. This will allow the Southwest Florida Water Management District to make approximately 6.15 mgd of groundwater withdrawal credits available to Hillsborough County. Tampa Bay Water, the major supplier of potable water for public water systems in the Tampa Bay area, will purchase and use the credits for the development of a new public supply wellfield (Figure 2). The wellfield will consist of eight new production wells, piping, water treatment facilities, a storage tank, and pumping facilities. Figure 2 shows the location of the recharge wells and the proposed South Hillsborough wellfield within Hillsborough County.

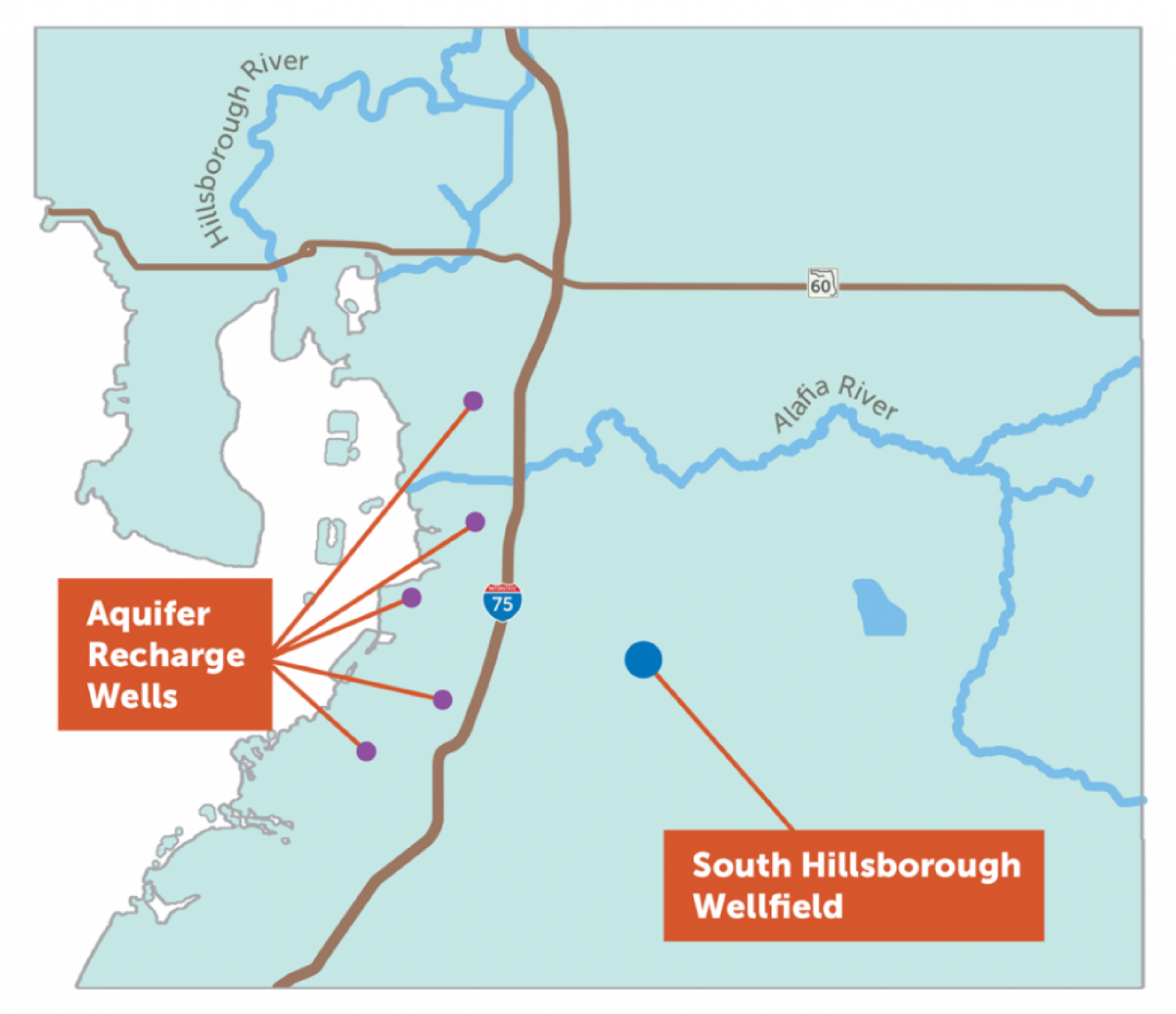


Figure 2. Location of recharge wells and proposed South Hillsborough wellfield.

Source: [*Hillsborough County (2023)*]

5.8 Mustang Creek Watershed Dry Well Pilot Study

Author: John Lambie, principal hydrogeologist

Site Name: Mustang Creek

Location: Merced County, CA

Operator(s): Eastside Water District

Permitting Agency(s): State Water Board and Merced County Department of Environmental Health

Current MAR Status: Pilot study

Year Constructed: 2020

Costs: Not available

Project Contact Information: John Lambie

Project Website/Publication Links: NA

Purpose of MAR:

- Water supply resilience

Source Water:

- Captured water

Water Quality:

- Pretreatment required

Recharge Technology(s):

- Dry well

Project Description

The Mustang Creek project is located near East Avenue and Oakdale Road in Merced County, California. It is a pilot study designed to establish whether dry wells can be cost-effective in introducing captured floodwater into the Turlock Subbasin Aquifer. Project data, including impacts to baseline water quality, infiltration and cost-effectiveness of dry wells, and the ability to introduce water to the subsurface into different geological strata, will be collected over a period of 2 years.

Three dry wells with flow meters are installed (Figure 1) at various depths and monitored for (1) surface water quality for mineralogy, (2) groundwater chemistry for changes in ions and inorganics in first groundwater, (3) the quantity of water infiltrated, and (4) groundwater hydraulic heads in the local and nearby region (Figure 2).

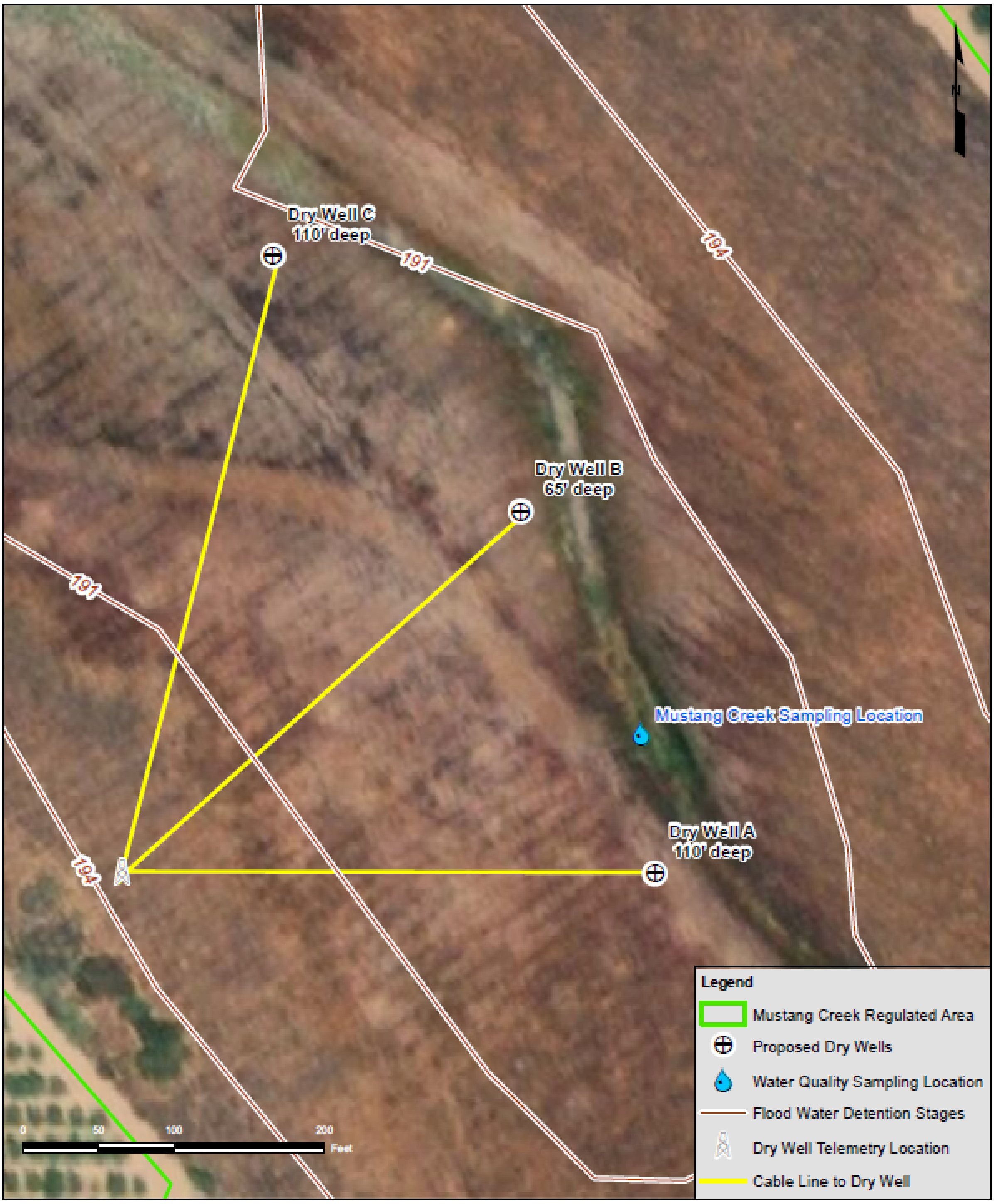


Figure 1. Installed dry well locations and depths.

Source: *Lambie (2020)*

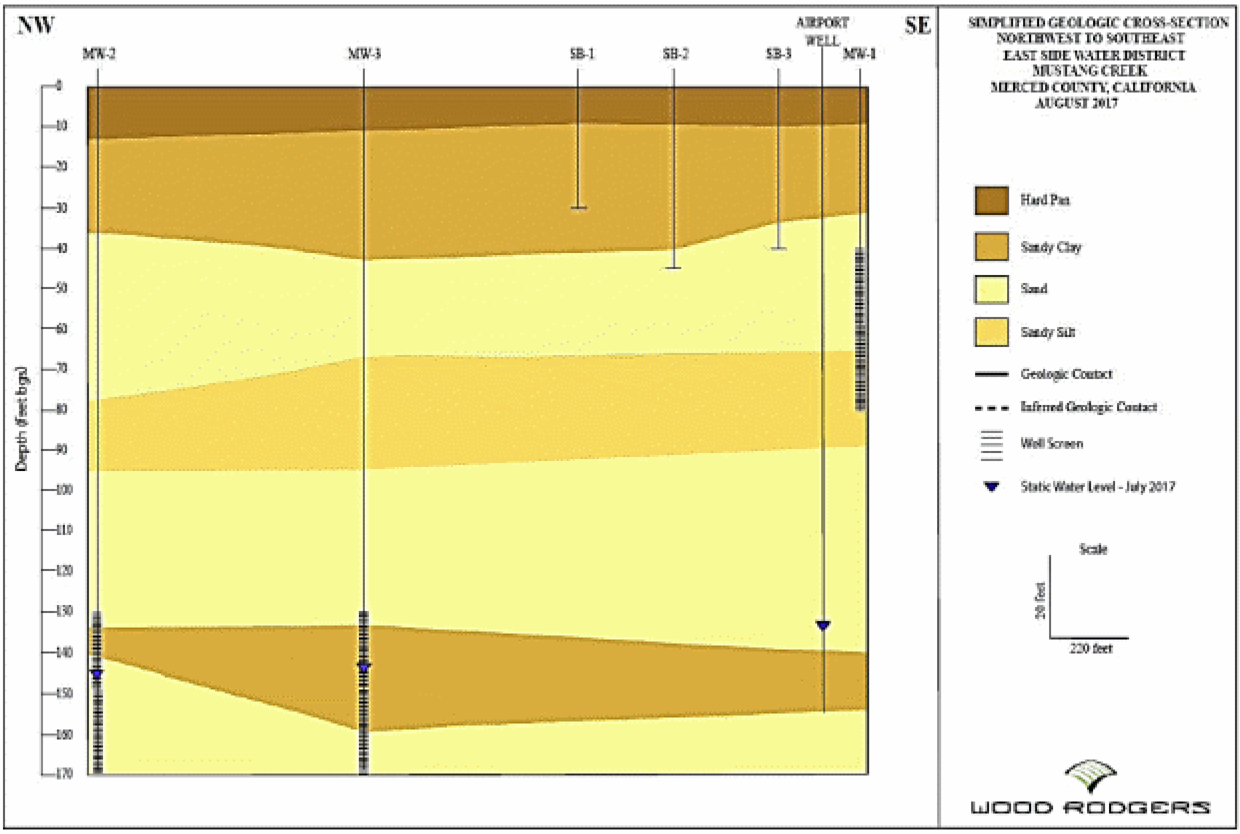


Figure 2. Geologic cross section at project site.

Source: Lambie (2020)

Receiving Aquifer

The Turlock Subbasin is defined and regulated under California's Sustainable Groundwater Management Act (SGMA) (Figure 3). The SGMA requires that groundwater sustainability plans (GSP) be developed by local groundwater sustainability agencies so that groundwater conditions are not adversely impacted in the Turlock Subbasin. Further, the SGMA requires that water supply and demand met by groundwater usage is sustainable over the long term. This pilot project for dry wells and the broader program of intentional and MAR projects will be important components in the GSP water budgets. This can help water users of all types better manage water resources within the area to withstand droughts and minimize the need to fallow land or alter land uses due to a lack of water supplies.

There are five relatively small watersheds within the basin where surface and near-surface conditions may be conducive to groundwater recharge above native or existing conditions of recharge. In these watersheds native surface water may be available as floodwater or diffused stormflow (water that does not and cannot reach a watercourse). These five watersheds range in size from 6.5 square miles to 21.5 square miles, with the largest of them being Mustang Creek.

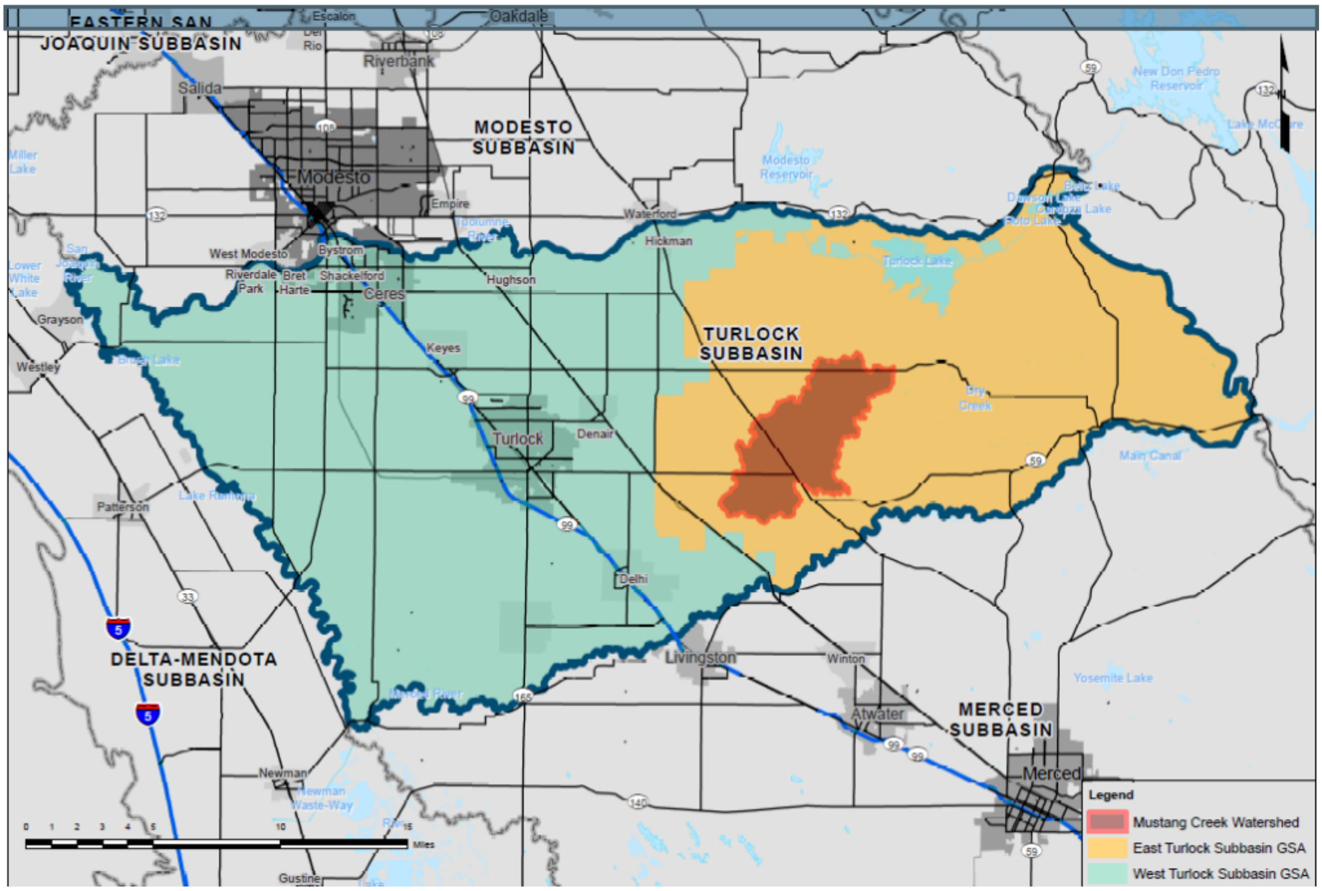


Figure 3. Location of receiving aquifer, Turlock Subbasin.

Source: Lambie (2020)

Water Quality

The USGS conducted extensive studies of groundwater and surface water in the region with a series of four or more focused on the water resources of Mustang Creek (Figure 4). The Eastern San Joaquin Water Quality Coalition has been conducting surface water quality testing of Mustang Creek since 2008. In 2014 the Eastside Water District (EWD) conducted investigations and preparatory work for some form of MAR at the secondary detention basin. Most recently, the East Turlock Subbasin Groundwater Sustainability Agency began a series of groundwater monitoring of their agency area, with three wells being monitored as of fall 2019 and another from the 2014 EWD work.

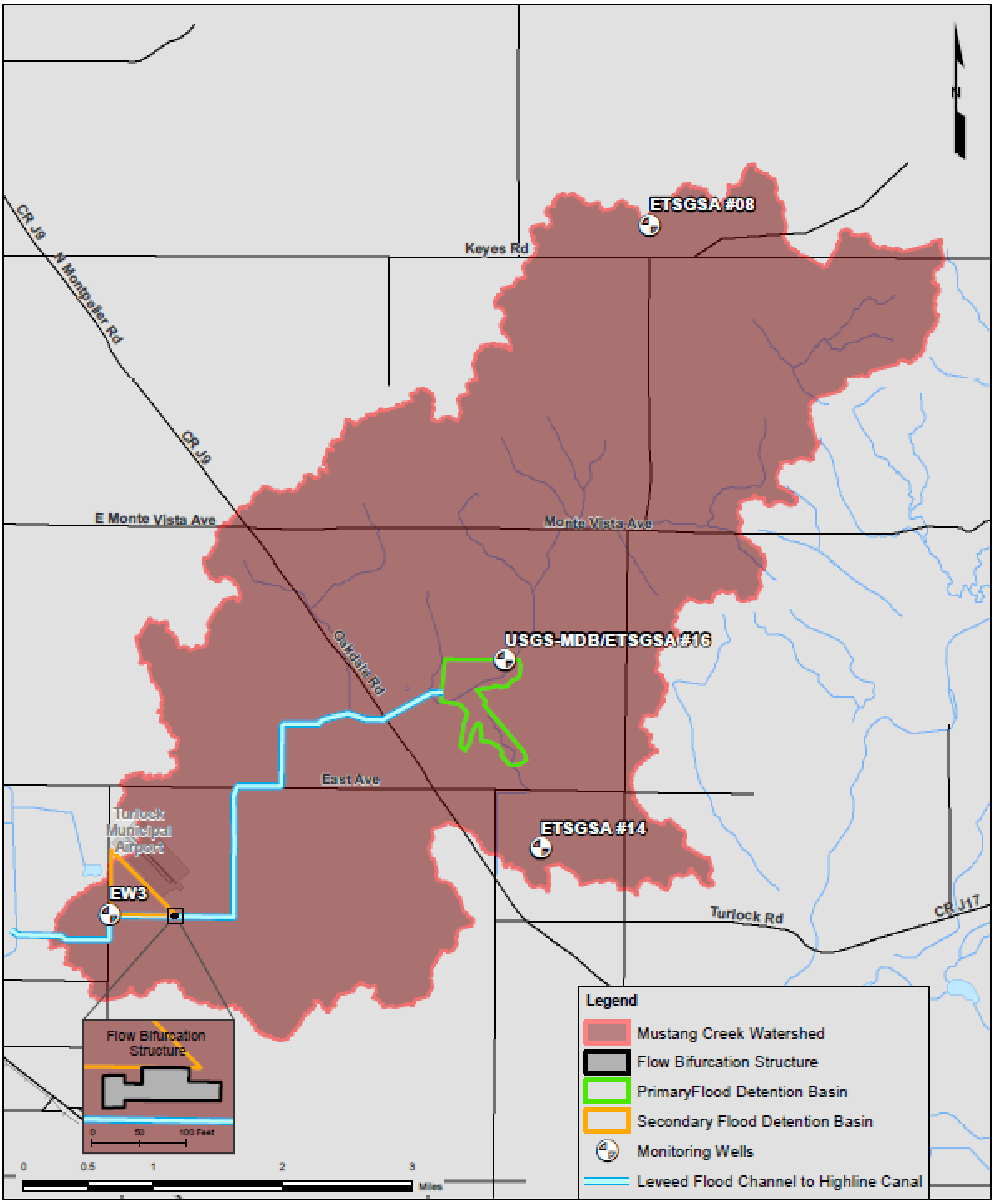


Figure 4. Mustang Creek watershed.

Source: *Lambie (2020)*

To provide the most relevant and recent assessment of water quality conditions in the detained waters of Mustang Creek, the engineer developed a baseline water-quality standard in 2020, taking samples from the surface as well as from the USGS well. A full description of the sampling methods and results (general chemistry, pesticides, nutrients) can be found in Lambie (2020).

The field sampling scope for February 2020 was to collect one set of surface water quality samples from the primary detention basin on Mustang Creek and one set of groundwater quality samples from the USGS monitoring well at the primary detention basin (USGS MDB). Samples were also collected for baseline analysis of dissolved organic carbon, select metals, nitrogen, orthophosphate, major ions, biochemical oxygen demand (BOD), pH, and total dissolved solids (TDS).

The installed dry wells include a pretreatment chamber (Figure 5). The pretreatment chambers are designed to provide for surficial removal of sediment and organic debris but also to provide vadose zone treatment to percolating water before it reaches the groundwater table. This additional vadose zone treatment is important to reduce or mitigate water quality concerns associated with use of floodwater and other surface water.

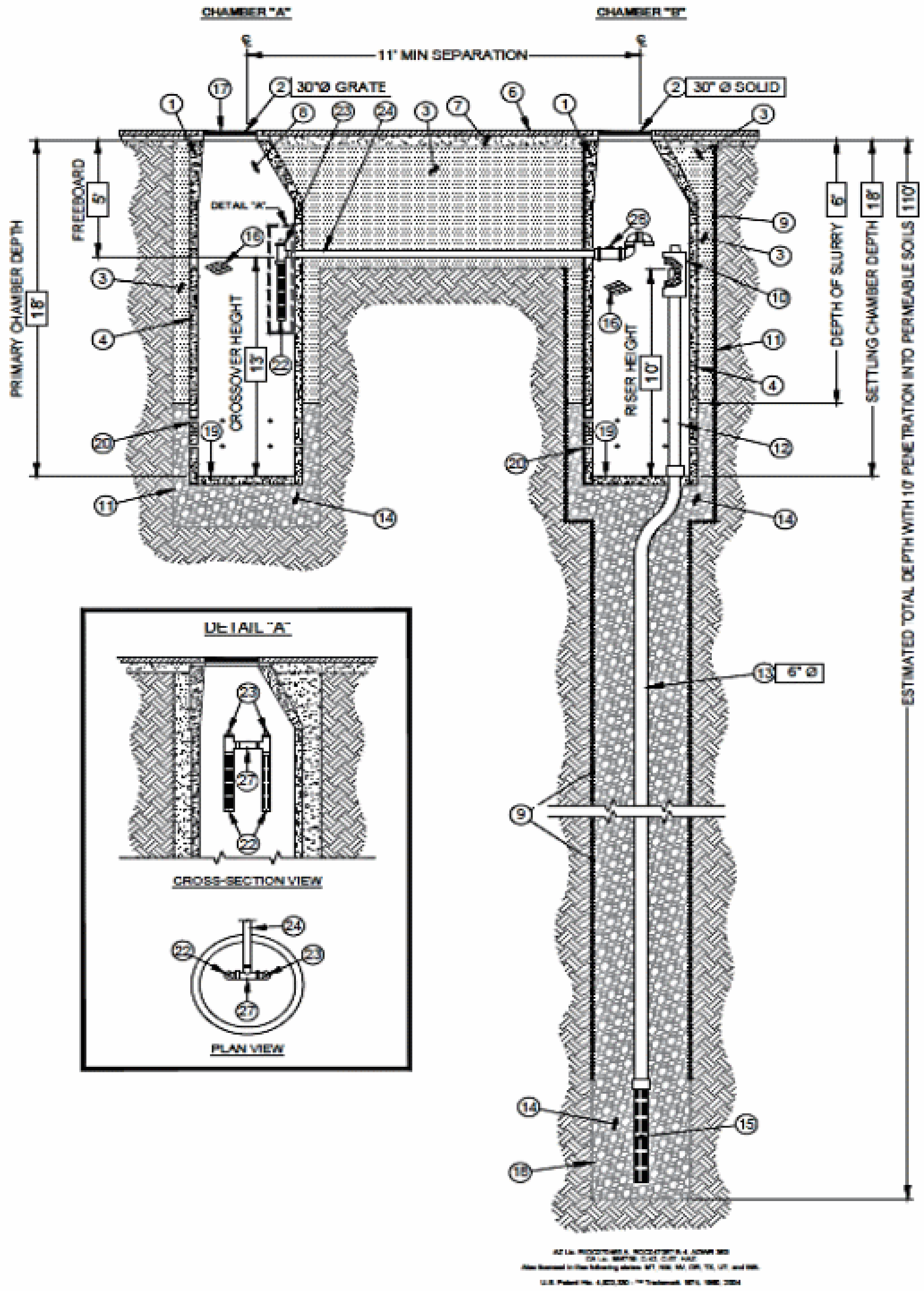
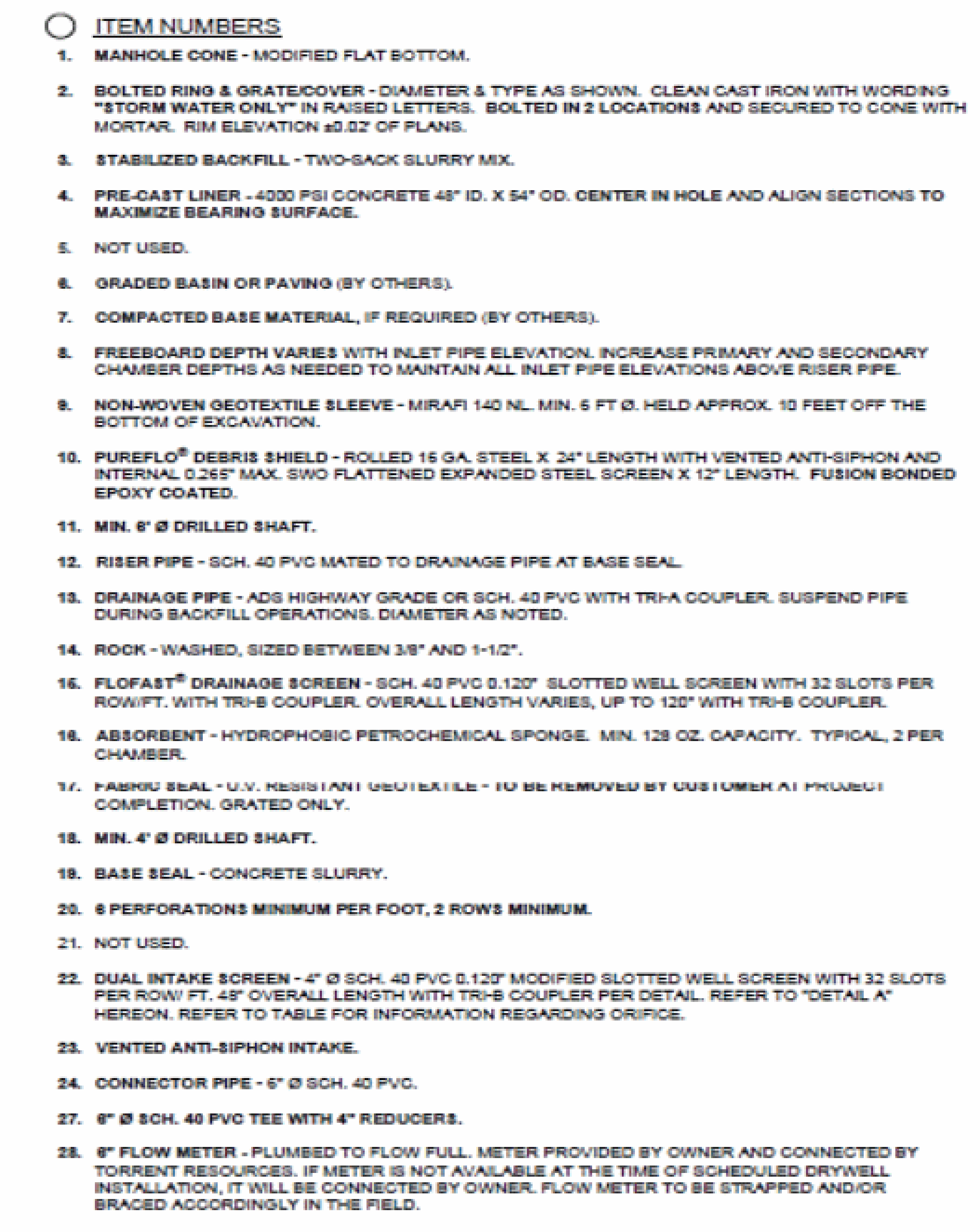


Figure 5. Detail of installed dry well.

Source: *Torrent Resources (2019)*



○ ITEM NUMBERS

1. MANHOLE CONE - MODIFIED FLAT BOTTOM.
2. BOLTED RING & GRATE/COVER - DIAMETER & TYPE AS SHOWN. CLEAN CAST IRON WITH WORDING "STORM WATER ONLY" IN RAISED LETTERS. BOLTED IN 2 LOCATIONS AND SECURED TO CONE WITH MORTAR. RIM ELEVATION ±0.02' OF PLANS.
3. STABILIZED BACKFILL - TWO-SACK SLURRY MIX.
4. PRE-CAST LINER - 4000 PSI CONCRETE 48" ID. X 54" OD. CENTER IN HOLE AND ALIGN SECTIONS TO MAXIMIZE BEARING SURFACE.
5. NOT USED.
6. GRADED BASIN OR PAVING (BY OTHERS).
7. COMPACTED BASE MATERIAL, IF REQUIRED (BY OTHERS).
8. FREEBOARD DEPTH VARIES WITH INLET PIPE ELEVATION. INCREASE PRIMARY AND SECONDARY CHAMBER DEPTHS AS NEEDED TO MAINTAIN ALL INLET PIPE ELEVATIONS ABOVE RISER PIPE.
9. NON-WOVEN GEOTEXTILE SLEEVE - MIRAFI 140 NL. MIN. 5 FT Ø. HELD APPROX. 10 FEET OFF THE BOTTOM OF EXCAVATION.
10. PUREFLO® DEBRIS SHIELD - ROLLED 16 GA. STEEL X 24" LENGTH WITH VENTED ANTI-SIPHON AND INTERNAL 0.265" MAX. SWO FLATTENED EXPANDED STEEL SCREEN X 12" LENGTH. FUSION BONDED EPOXY COATED.
11. MIN. 6' Ø DRILLED SHAFT.
12. RISER PIPE - SCH. 40 PVC MATED TO DRAINAGE PIPE AT BASE SEAL.
13. DRAINAGE PIPE - ADS HIGHWAY GRADE OR SCH. 40 PVC WITH TRI-A COUPLER. SUSPEND PIPE DURING BACKFILL OPERATIONS. DIAMETER AS NOTED.
14. ROCK - WASHED, SIZED BETWEEN 3/8" AND 1-1/2".
15. FLOFAST® DRAINAGE SCREEN - SCH. 40 PVC 0.120" SLOTTED WELL SCREEN WITH 32 SLOTS PER ROW/FT. WITH TRI-B COUPLER. OVERALL LENGTH VARIES, UP TO 120" WITH TRI-B COUPLER.
16. ABSORBENT - HYDROPHOBIC PETROCHEMICAL SPONGE. MIN. 128 OZ. CAPACITY. TYPICAL, 2 PER CHAMBER.
17. FABRIC SEAL - U.V. RESISTANT GEOTEXTILE - TO BE REMOVED BY CUSTOMER AT PROJECT COMPLETION. GRATED ONLY.
18. MIN. 4' Ø DRILLED SHAFT.
19. BASE SEAL - CONCRETE SLURRY.
20. 6 PERFORATIONS MINIMUM PER FOOT, 2 ROWS MINIMUM.
21. NOT USED.
22. DUAL INTAKE SCREEN - 4" Ø SCH. 40 PVC 0.120" MODIFIED SLOTTED WELL SCREEN WITH 32 SLOTS PER ROW/ FT. 48" OVERALL LENGTH WITH TRI-B COUPLER PER DETAIL. REFER TO "DETAIL A" HEREON. REFER TO TABLE FOR INFORMATION REGARDING ORIFICE.
23. VENTED ANTI-SIPHON INTAKE.
24. CONNECTOR PIPE - 6" Ø SCH. 40 PVC.
27. 6" Ø SCH. 40 PVC TEE WITH 4" REDUCERS.
28. 6" FLOW METER - PLUMBED TO FLOW FULL. METER PROVIDED BY OWNER AND CONNECTED BY TORRENT RESOURCES. IF METER IS NOT AVAILABLE AT THE TIME OF SCHEDULED DRYWELL INSTALLATION, IT WILL BE CONNECTED BY OWNER. FLOW METER TO BE STRAPPED AND/OR BRACED ACCORDINGLY IN THE FIELD.

Figure 5. Detail of installed dry well—cont'd.

Source: Torrent Resources (2019)

Regulatory Considerations/Issues

Current injection well regulations as defined by the U.S. Environmental Protection Agency require users to register dry wells as Class V injection facilities. Merced County Department of Environmental Health (MCDEH) as of September 2019 required that "recharge/injection wells" undergo a specific well construction/destruction permit process in accordance with Merced County Code (Chapters 9.27 and 9.28). The MCDEH permit process includes the establishment of and adherence to a monitoring and reporting program (MRP) as specified by the Central Valley Regional Water Quality Control Board (CVRWQCB). The CVRWQCB regards introduction of surface waters to dry wells as water and not waste or wastewater and develops appropriate MRPs to protect beneficial uses of groundwater.

Performance to Date

The dry wells are fed via gravity flow, and delivery of water is dependent upon rain events. Observed infiltration rates for a single dry well have exceeded 350 gallons per minute during significant rain events. Monitoring of infiltration rates is in real time.

5.9 Walla Walla Basin Watershed

Author: Maria Daugherty

Site Name: Walla Walla Basin Watershed Council

Location: Walla Walla River Watershed located in Washington and Oregon

Operators: Walla Walla Basin Watershed Council (WWBWC), Hudson Bay District Improvement Company, Fruitvale Water Users Association, and Walla Walla River Irrigation District.

Permitting Agencies: Oregon Department of Water Resources and Washington Department of Ecology

Current MAR Status: Active

Year Constructed: 2004

Costs: $10,000/year for the operation and maintenance of all Oregon recharge sites

Project Contact Information: Walla Walla Basin Watershed Council (541-938-2170)

Project Website/Publication Links:

https://wwbwc.org/index.php/recharge#anspach

Purpose of MAR:

- Water supply resilience
- Protection of riparian ecosystems/maintenance of minimum streamflow
- Resilience/climate adaptation

Source Water:

- Rivers/streams/lakes/reservoirs

Water Quality:

- No treatment required

Recharge Technology:

- Infiltration basin
- Infiltration gallery

Project Description

Aquifer and watershed boundaries rarely follow political borders, yet political borders often dictate the occurrence of MAR locations. In the Walla Walla watershed, collaboration among landowners, state agencies, and others helped the Walla Walla Basin Watershed Council (WWBWC) develop an effective bi-state recharge project to enhance the Walla Walla River. The WWBWC works to protect the Walla Walla River system, which is located in northeast Oregon and southeast Washington. An underlying alluvial aquifer maintains a high degree of hydraulic connectivity to the streams on the valley floor and generally follows a predictable path from east to west but is a transboundary watershed shared by the states of Oregon and Washington (Figure 1).

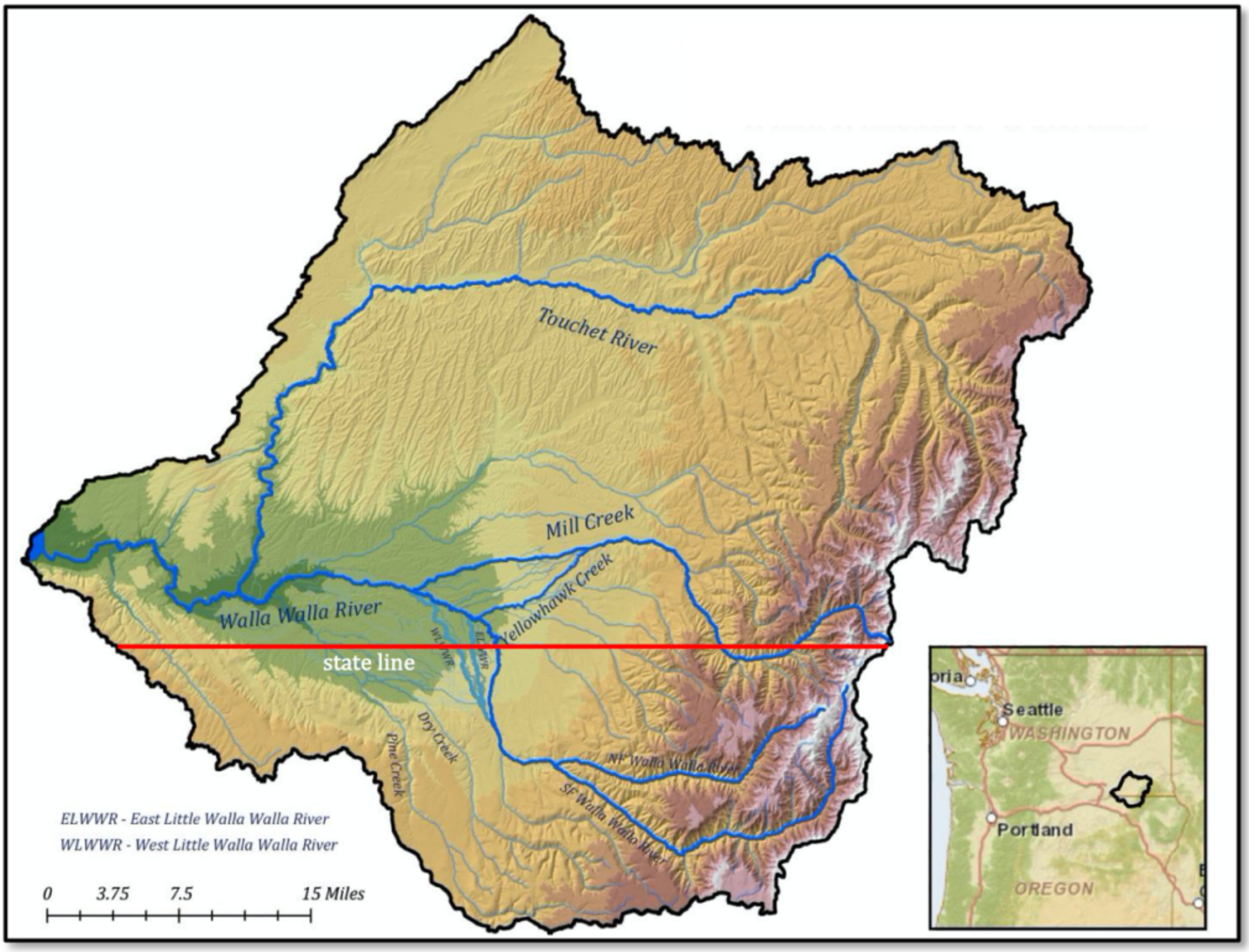


Figure 1. Distributary stream network of the Walla Walla River, which is a transboundary watershed shared by the states of Oregon and Washington.

Source: WWBWC (2020)

An increase in development caused water levels in the Walla Walla River to drop, which degraded habitat conditions for steelhead and bull trout, ultimately resulting in both species being categorized as threatened under the Endangered Species Act. Although initial measures were taken to recover streamflow conditions, with irrigators agreeing to leave surface water in the river, streamflows were still insufficient for aquatic life. In addition to restoring lost floodplain function due to channelization and flood control, it was determined that groundwater mitigation was required to achieve river restoration, as it was estimated that seepage loss to groundwater along some stretches of the river was greater than 30% (Figure 2).

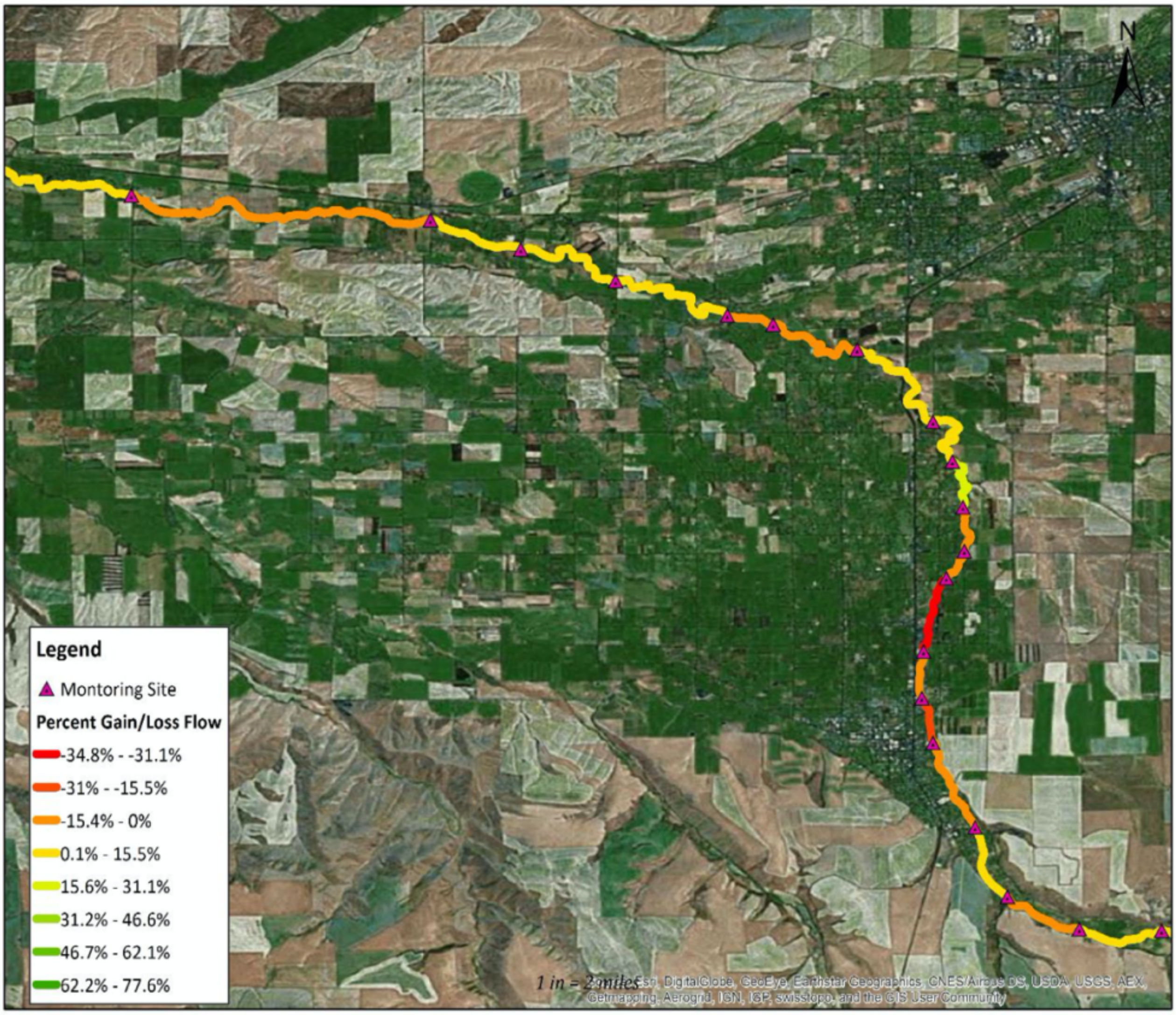


Figure 2. Average gains or losses in flow of a segment of the Walla Walla River during seepage runs conducted 2004–2016. Gains (positive values are greens and yellows) indicate groundwater discharging to the river. Losses (negative values are reds and oranges) indicate surface water seeping into the ground.

Source: WWBWC (2017)

The WWBWC created an aquifer recharge project to address declining groundwater conditions; however, since the watershed and alluvial aquifer cross state borders, it became apparent that a bi-state approach would increase ecological benefits gained through multiple MAR locations (Figure 3). A total of 19 recharge projects have been implemented throughout the Milton-Freewater alluvial fan via infiltration galleries and ponds designed to recharge the aquifer. From 2004 to 2020, approximately 85,000 acre-feet of recharge volume has been added into the Walla Walla Basin from the Oregon MAR project (Figure 4).

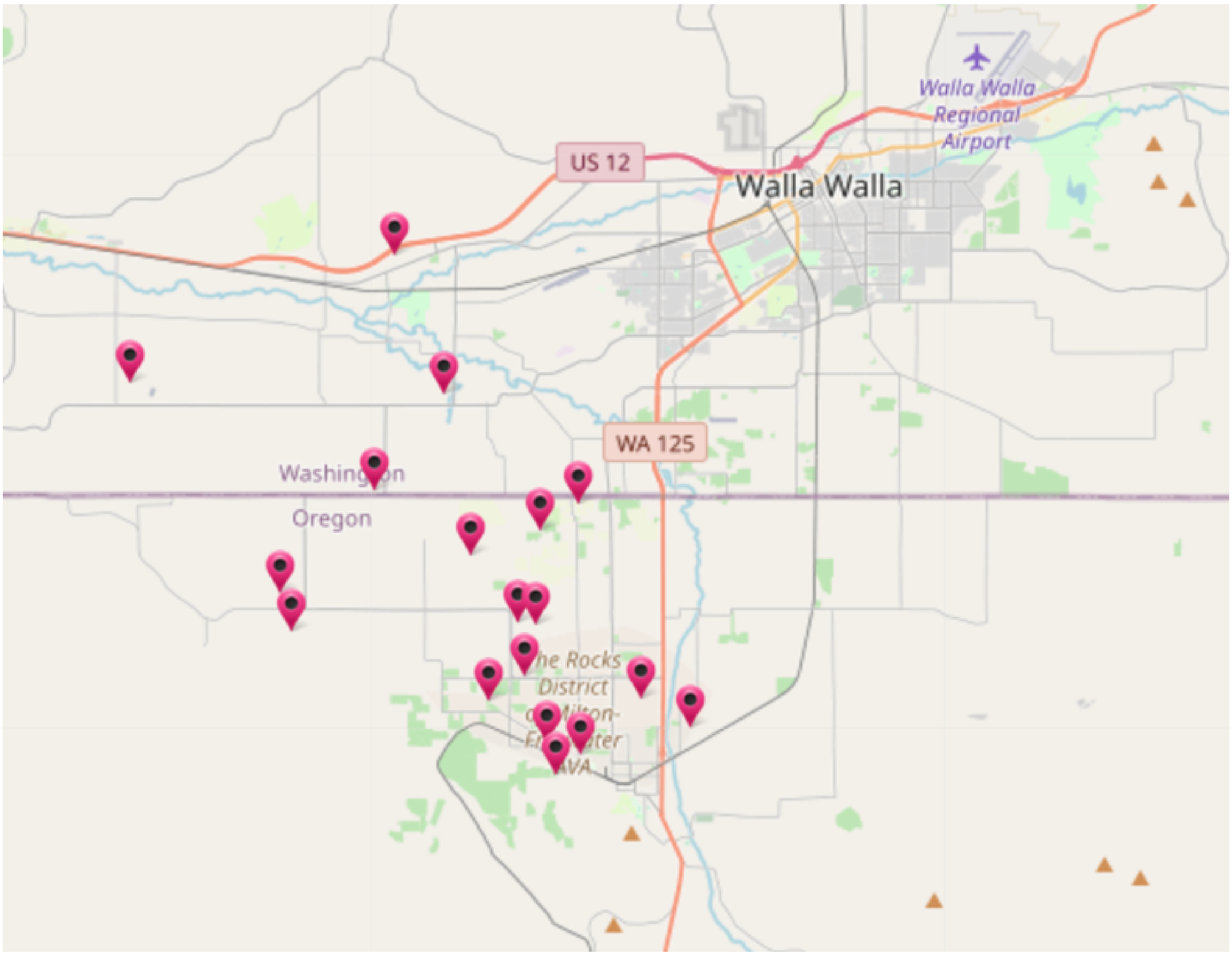


Figure 3. Recharge locations of the WWBWC.

Source: [*WWBWC (2023)*]

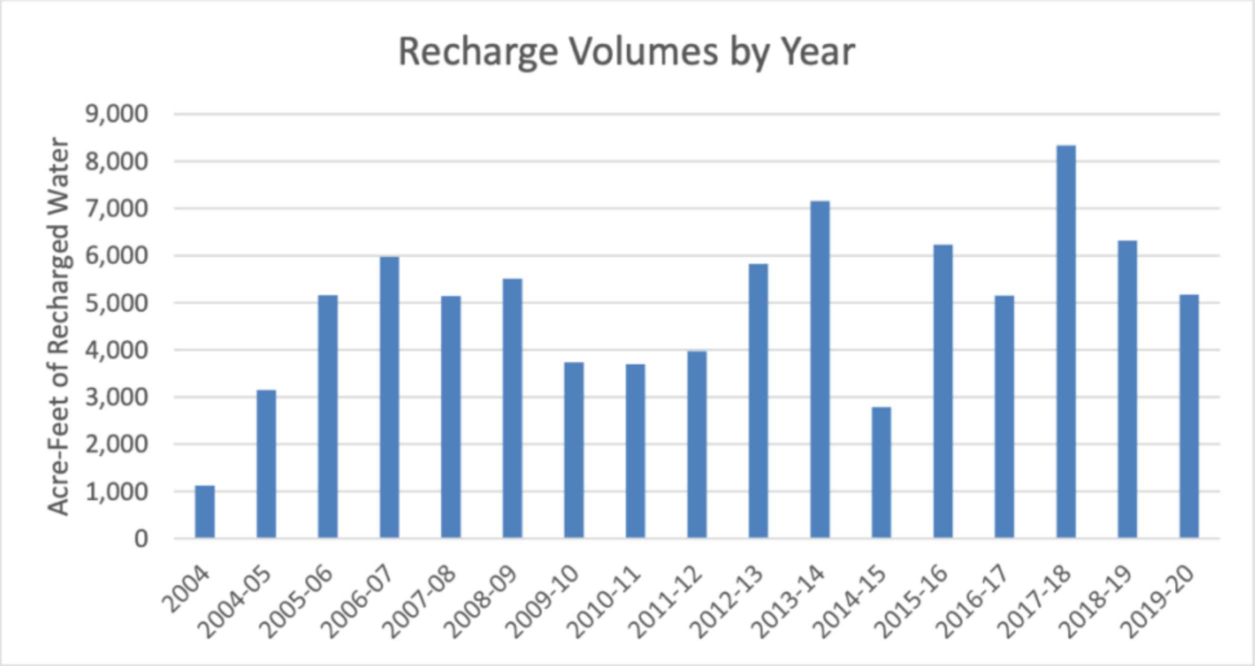


Figure 4. Cumulative recharge volume of the Oregon Walla Walla Basin MAR project (14 recharge sites).

Source: [*WWBWC (2020)*]

Currently, the sites are operated under a limited license issued by the Oregon Water Resources Department. Recharge operations in Washington are on hold due to various issues, such as maintenance to prevent clogging, grant money tied directly to fish habitat restoration (rather than MAR operations), and the changing of property ownership. When Washington recharge sites are in operation, the Washington Department of Ecology will oversee water quality criteria.

The variation in recharge water volume greatly depends on water availability and landowner participation; although some sites contribute relatively small portions to the aquifer, they were designed to recharge the alluvial aquifer via conveyance losses from open ditches when delivering water to the sites (Figure 5). Source water for 14 aquifer recharge sites in Oregon was obtained from the Walla Walla River in Milton-Freewater, Oregon, under a limited license agreement with the Oregon Water Resources Department and delivered throughout existing irrigation delivery systems to each site's turnout.

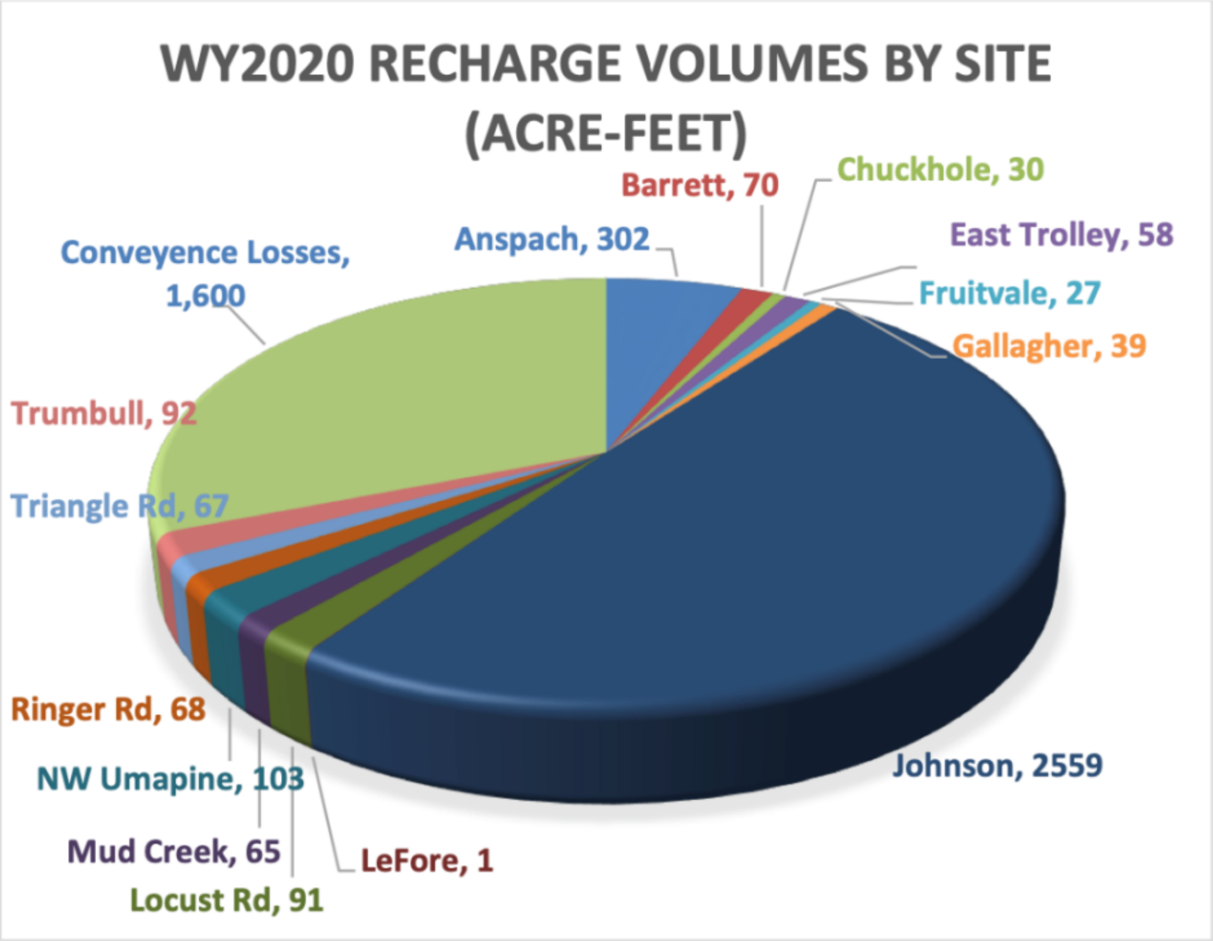


Figure 5. Recharge volumes by site during water year 2020.

Source: WWBWC (2020)

The Johnson site (Figure 6) is the largest recharge location, constructed in 2004, and includes 10 spreading basins and three active infiltration galleries. The site was developed under a phased approach that involved the initial construction of the infiltration basins, with the final phase including the addition of infiltration galleries (Figure 7). The four different infiltration gallery designs were installed to create a cost-benefit analysis of the different design types to determine each design's longevity. From 2004 to 2020, the Johnson site has recharged over 51,000 acre-feet.

Figure 6. The Johnson Aquifer recharge site.

Source: WWBWC (2023).

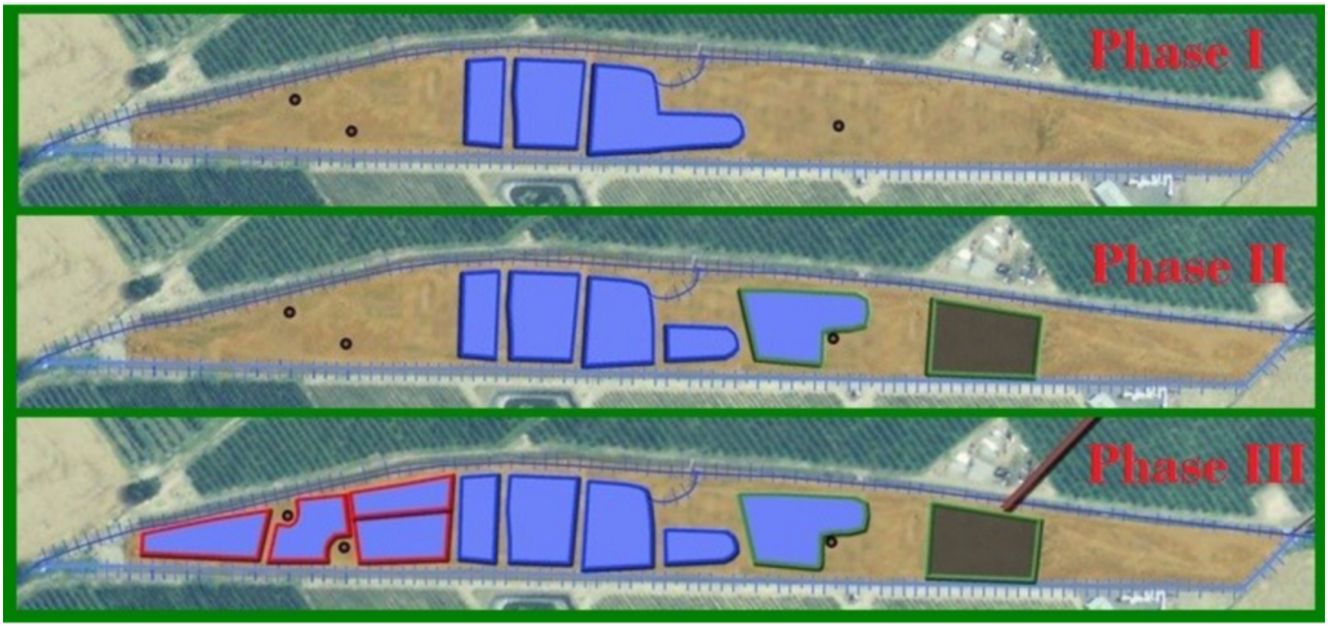


Figure 7. Phased approach of MAR at the Johnson site.

Source: WWBWC (2023)

Lessons Learned

Groundwater declines in the Walla Walla Basin have caused springs and domestic wells to dry up and have produced a steep gradient of seepage losses from the numerous hydraulically connected streams and rivers on the valley floor. In addition to restoring floodplain function lost with channelization and flood control, Walla Walla's MAR project is a vital tool in the suite of restoration actions needed to improve in-stream flows and aquatic habitat for threatened and endangered native fish species.

Other Considerations

Considering the volumes of recharge versus achieving project success requires analysis of many factors, including realistic timelines. For example, the WWBWC 2013 Aquifer Recharge Strategic Plan stated that the following benefits were expected if annual volume recharged reached 20,000 acre-feet:

“Reversing the loss of storage within the alluvial aquifer will minimize seepage loss in the valley’s rivers and streams, increase spring performance and related groundwater input to surface water features, and allow groundwater resources of the alluvial aquifer to continue to be used as a sustainable resource with a secondary or alternative-use benefit to surface water.” (WWBWC 2013, p. 79).

To date, the target volume has not yet been achieved (Figure 4); however, the foundational structure exists to achieve this goal, because collaboration among the WWBWC, state agencies, landowners, and other stakeholders in the watershed is in place to meet demand, while utilizing MAR to continue improving ecological conditions. The foundational structure of collaboration, especially in a transboundary watershed, is paramount to achieving measured success.

5.10 Clark Fork River Basin MAR Modeling

Authors: Ian Magruder and Scott Payne

Site Name: Clark Fork River Basin MAR Modeling

Location: Deer Lodge, Montana

Operator(s): Montana Department of Natural Resources and Conservation and Clark Fork River Basin Task Force

Permitting Agency(s): Montana Department of Natural Resources and Conservation

Current MAR Status: Alluvial Water Accounting System (AWAS) MAR modeling is complete.

Year Completed: 2015

Costs: $50,000 total, approximately one-third or $17,000 for case study portion

Project Contact Information: Scott Payne, WWC Engineering, 406-842-7224 spayne@wwcengineering.com

- **Project Website/Publication Links:** Clark Fork Kootenai (mt.gov); Clark Fork Water Supply Report Series I—Water Supply and Mitigation Options; Clark Fork Water Supply Report Series I—Attachment 1 Modeling Report

Purpose of MAR:

- Water supply resilience
- Protection of riparian ecosystems/maintenance of minimum streamflow
- Resilience/climate adaptation
- Agricultural
- Water rights permitting support

Source Water:

- Rivers/streams/lakes/reservoirs
- Agricultural return flows

Water Quality:

- No treatment required

Recharge Technology(s):

- Dry well

Project Description

Water availability in the Clark Fork River Basin in Western Montana is in short supply for new uses, including development, population growth, and fishery restoration projects. This case study evaluates how MAR can be used to support a project that would increase in-stream flow for fish in a dewatered river. We demonstrate using an analytical streamflow-groundwater model to assist with planning and permitting the project.

Figure 1 shows the many limitations on water availability for new uses and shows the location of this case study, near Deer Lodge, MT. The limitations on new water use include legislative and administrative rule closures and controlled groundwater areas, all of which are legal tools to protect existing uses in a watershed that does not have sufficient water to satisfy existing uses, a situation often referred to as overallocation. Existing water rights may also limit any newly permitted water use because those existing water rights must be satisfied first under the prior appropriation water right legal framework; these are referred to as limiting water rights. Montana, where the case study is located, uses the prior appropriation system, like most western U.S. states do.

Under Montana water law, where the existing water supply is overallocated, new and changed water use requires a mitigation plan to reallocate water and eliminate any depletion of surface water that would adversely affect another water user. The mitigation plan takes an existing permitted water use and changes it in a manner that protects all other existing water uses. MAR using retired irrigation water is commonly used to satisfy mitigation plans. The mitigation plan requires hydrological accounting for the changes in flows resulting from changes in water use, something that is far from simple to accomplish. New water uses have been stymied in part by the complexity of the water accounting required to permit a new or changed water use through Montana Department of Natural Resources and Conservation (DNRC).

To address this, DNRC, in coordination with the Clark Fork River Basin Task Force, funded a water supply report with the goal to demonstrate three different hypothetical mitigation scenarios (Kirk Engineering & Natural Resources, Inc. 2015a and Kirk Engineering & Natural Resources, Inc. 2015b). We refer to these in this case study as the DNRC publications. We modeled and authored the DNRC publications and present a summary of one of the scenarios here because it both highlights the benefits of MAR and demonstrates the use of modeling to evaluate and fine-tune a proposed application of MAR.

In the DNRC publications, both the MAR plan and the water right mitigation plan were developed using a computer program that performs the required hydrological accounting. Two of the hypothetical scenarios relate to mitigating residential development, and the third scenario evaluates improving in-stream flow for fisheries in a dewatered portion of the Clark Fork River, which is the topic of this case study.

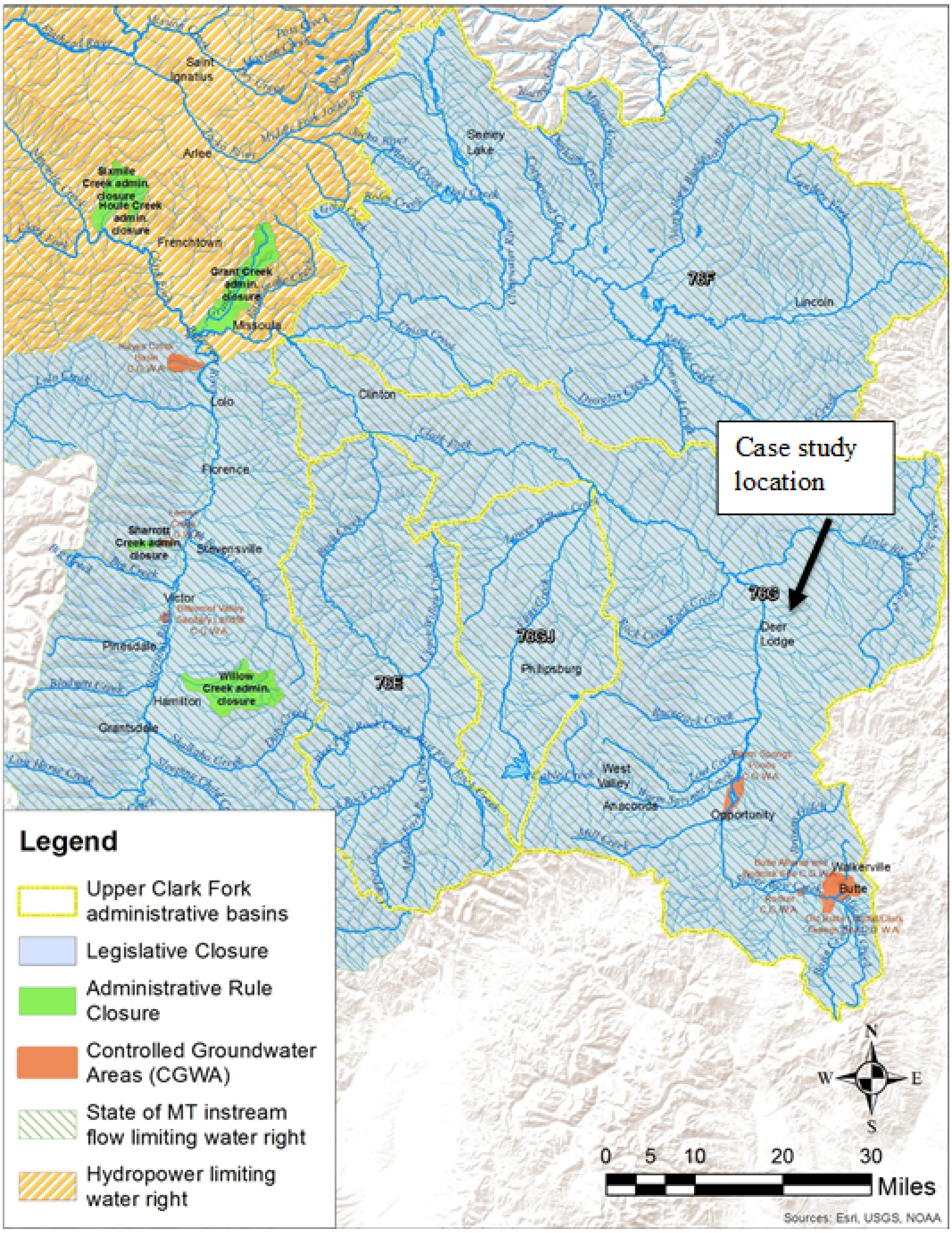


Figure 1. Case study location and limitations on new and changed water use.

Source: Kirk Engineering & Natural Resources, Inc. (2015)

Model Description

The Alluvial Water Accounting System (AWAS) model (Schroeder 1987 and IDS Group 2013) was used. AWAS is a simplified analytical modeling tool, is open source, and is a good alternative to more complex and time-consuming groundwater models. AWAS is commonly used to simulate MAR in riverine and unconfined aquifer settings because local hydrogeologic conditions are reasonably approximated in this simplified model (Kirk Engineering & Natural Resources, Inc. 2015a; Milman, Bylo, and Blomquist 2021). The model is used to compute streamflow depletion or accretion caused by pumping a well or recharging an aquifer. The AWAS user manual and free software can be downloaded from the Integrated Decision Support Group, part of the Water Center at Colorado State University: The Integrated Decision Support Group—Projects (colostate.edu).

Project Planning—Water Rights

In Montana, the ability to obtain a water right for a new use is not solely based on whether water is "physically available" but is also governed by a host of complex state water right laws and regulations that identify whether water is deemed "legally available" in relation to any stream, river, or aquifer.

States that have a prior appropriation system like Montana will likely have similar but slightly different water permitting challenges to those described here. The prospective water planner must consider which water rights are available to change to mitigation and if those water rights can supply sufficient water in the timing, amount, and location required by law to protect other existing water rights. To this end, modeling MAR is a practical tool that can be used to plan and support a permittable new or changed water use. A brief review of legally available water is needed to provide context for how and why MAR is simulated for the case study.

In Montana, water right changes from irrigation to in-stream flow for fisheries can change the crop consumptive evapotranspiration portion of an existing water right to protectable in-stream flow below the point of diversion (§85-2-408, Montana Codes Annotated). We call these changes "protectable" in-stream flow because it is backed by a water right and junior appropriators can be called on to make sure the water remains instream.

"Return flow" in this case study means the groundwater recharge caused by irrigation inefficiencies, such as ditch leakage and field loss, that returns to surface water. Under Montana water law, water right changes must mitigate changes to agricultural return flows that would adversely affect other water rights holders. This is somewhat counterintuitive; a brief explanation is that the long history of irrigation practice in Montana is itself a primary source of recharge to groundwater and that recharge bolsters streamflow, especially during late summer when streamflow is most limited. Our modeling analysis is in part focused on mitigating any reduction in agricultural return flow for which another appropriator has a water right.

The water rights analysis is further complicated by the requirement to consider the irrigated evapotranspiration and groundwater agricultural return flow as they existed in 1973 when the Montana Water Use Act became law. This is a nuance of Montana water law that exists because the Water Use Act essentially sets water rights in stone as of the 1973 date, even though the law allows any irrigator to change the method of irrigation, such as changing flood to center pivot to allow for modernization of farm production and greater irrigation efficiency. Once a person seeks to change that water right—for instance, from irrigation to an instream use—the water right changes, and the mitigation plan must consider the water right as it existed in 1973.

Modeling a Water Use Change from Irrigation to In-stream Flow in Deer Lodge, Montana

The modeling in this case study simulates a water right change from irrigation to in-stream flow augmentation for fisheries along a dewatered reach of the Clark Fork River. The Clark Fork River is chronically dewatered in this reach during summer irrigation season, and just several weeks of extremely low flow and high-water temperature can severely impact the fishery. It is common for conservation interests to seek to buy irrigation water and change the water rights into a protectable in-stream flow to maintain a minimum flow in the river that supports fish.

The modeled scenario takes a portion of a 290-acre irrigated hayfield out of production and looks at three potential alternatives for changes to the water right and mitigation. Each alternative is modeled to see if it meets the legal requisite of no net depletion that adversely affects other water rights, as required by the governing water law. The alternatives are as follows.

Alternative 1. Retires 50 acres of the current pivot acreage and leaves the irrigation water in stream.

Alternative 2. Retires sufficient acreage from current center pivot to create a minimum of 0.5 cfs of protectable in-stream flow during August and attempts to mitigate the change in agricultural return flow by leaving the irrigation water in stream.

Alternative 3. Retires sufficient acreage from current center pivot to create a minimum of 0.5 cfs of protectable in-stream flow during August and mitigates the change in agricultural return flows with MAR by routing irrigation water into a drainfield.

Streamflow reduction in the Clark Fork River is not allowed from July through March due to other limiting water rights., further details of which are provided in the DNRC publications.

The historic water use of this water right was flood irrigation beginning in 1870, but it was changed to center-pivot irrigation in the early 1990s. The change to center-pivot irrigation radically changed the amount and timing of water use, the area irrigated, and the groundwater agricultural return flow. All the changes caused by this previous change to more efficient center-pivot irrigation must be accommodated in the mitigation plan.

Streamflow changes under the three alternatives were evaluated monthly, assuming evapotranspiration and agricultural return flows are relatively consistent over the course of a month. The modeled streamflow change stabilizes to a new equilibrium condition approximately 6 years after the irrigation change owing to the time it takes groundwater head to equilibrate.

The modeling exercise shows that the first two alternatives are not feasible because streamflow is depleted in a manner that impacts existing water rights. Only Alternative 3 mitigates streamflow depletion during the months of October to March, because the irrigation water right can be recharged during the May through October period of use allowed for the water right. We describe only Alternative 3 in detail here because it is most relevant to the topic of MAR. Detailed results for Alternatives 1 and 2 are available in the DNRC publications. Alternative 3 meets both legal requirements of no stream depletion from July through March and the project goal of increasing streamflow by 0.5 cfs during August, when low flow and high-water temperature are most damaging to the fishery, as shown in Figure 2.

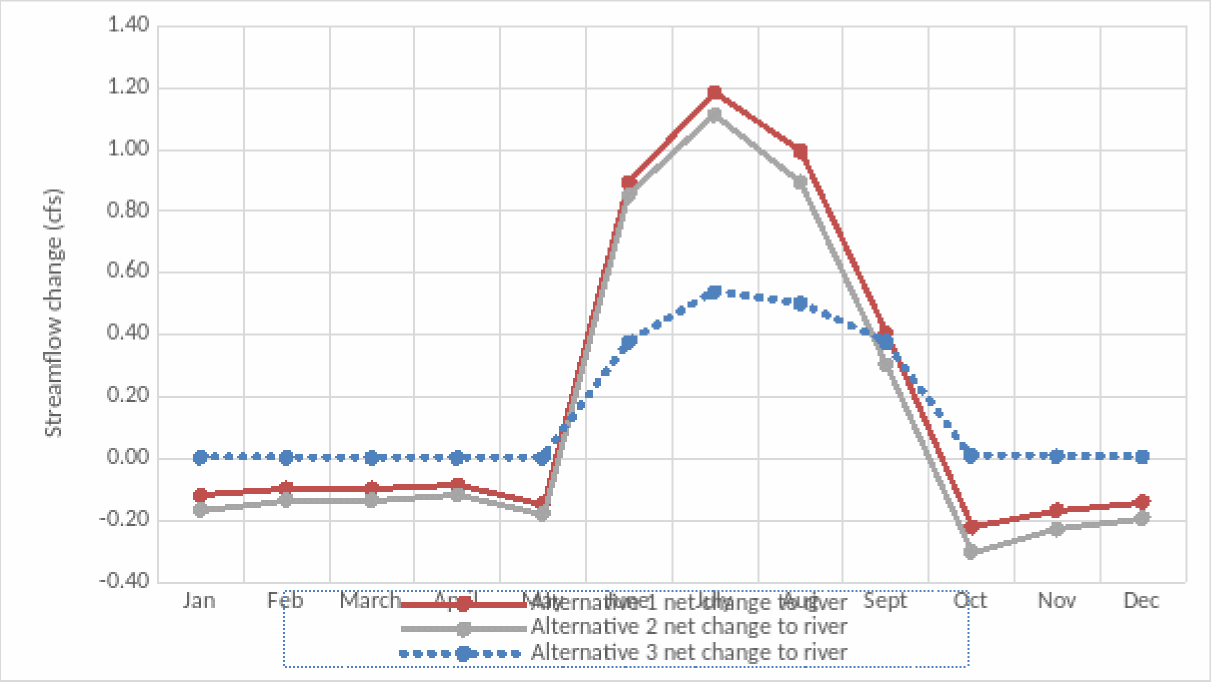


Figure 2. Modeled net change in streamflow under each alternative.

Depletion from loss of agricultural return flow is shown in Figure 2. Similar to Alternative 1, depletion from changes in agricultural return flow are mitigated during June through September by leaving currently applied irrigation water in stream (Figure 3). Changes in agricultural return flows are not mitigated from October through March again because of the limitation of using a seasonal irrigation water right to mitigate a year-round reduction in agricultural return flow. Like Alternative 1, Alternative 2 fails to meet legal requirements to protect existing water rights, demonstrating that a different mitigation plan is needed.

Under Alternative 3, the water formerly applied to the retired acreage is discharged to groundwater via a large drainfield, similar to a septic system. A drainfield is a practical method of performing MAR because it does not require the high-pressure pumping apparatus and energy needed for injection wells. Additionally, infiltrating water underground eliminates the evaporation loss that exists in a surface infiltration basin. The drainfield can both have lower long-term costs and be more water-efficient than these other MAR techniques.

Recharge from the drainfield joins the natural groundwater flow toward the Clark Fork River. The location, timing, and intensity of recharge is analyzed using the model so that streamflow depletion is mitigated using the minimum amount of MAR necessary.

The model allows fine-tuning of the recharge timing and rate using the minimum amount of recharge water necessary (see Figure 3). The fine-tuning that is possible with the model increases water efficiency and lowers costs associated with MAR. As required under law, the entire historic agricultural return flow under flood irrigation is mitigated, even though much of the historic flood agricultural return flow was eliminated in the 1990s when the field was converted to center-pivot irrigation.

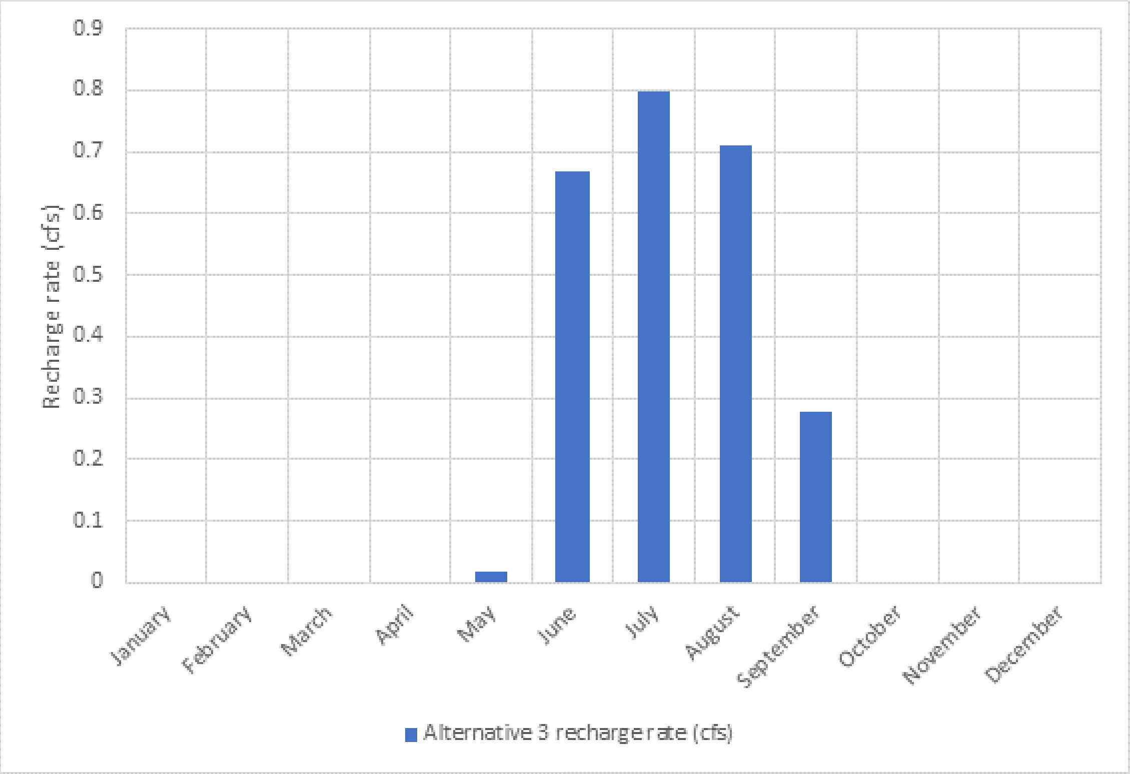


Figure 3. The MAR rate uses the most efficient application of water to meet both project goals and regulatory requirements.

Modeling also demonstrates that the drainfield location affects how efficiently MAR mitigation works. With the drainfield located at the upper end of the field farther from the river, mitigation during summer months is inadequate even when the entire water right allowance for June is infiltrated through the drainfield. With the drainfield located at the upper end of the field, mitigation of agricultural return flow changes would require additional irrigation water to be infiltrated during July and August, which in turn reduces water available to less than the 0.5 cfs in-stream flow target for August. The model shows that locating the drainfield in the middle of the retired field results in adequate mitigation while minimizing the amount of irrigation water that needs to be recharged and maximizing water available for in-stream flow.

Discussion

Modeling demonstrates that MAR proposed in Alternative 3 provides the only viable solution of the three alternatives to meet a specific target for protectable in-stream flow. Figure 3 shows that while increases to Clark Fork River streamflow from Alternatives 1 and 2 are greater than Alternative 3 during summer, Alternatives 1 and 2, which do not employ MAR, fail to mitigate all agricultural return flow loss during October to March and cannot be permitted by DNRC because it would adversely affect other water rights. Modeling the project alternatives with AWAS provides a simple yet effective method to assess and quantify how MAR can offset changes to irrigation agricultural return flow magnitude and timing. The model also allows the water planner to develop a plan to meet a targeted in-stream flow augmentation that maximizes water efficiency and minimizes costs associated with MAR.

The DNRC publications are available at the following website under the pull-down menu for Surface Water Reports: Clark Fork Kootenai (mt.gov).

Look for the following titles:

- Clark Fork Water Supply Report Series I—Water Supply and Mitigation Options
- Clark Fork Water Supply Report Series I—Attachment 1 Modeling Report

In addition to the Deer Lodge scenario described here, the reports examine an application of MAR to provide water for a hypothetical residential development in the Bitterroot Valley of Montana.

5.11 Army Post Road ASR Well

Location: Des Moines, Iowa

Operator: Des Moines Water Works

Permitting Agencies: Iowa Department of Natural Resources (IDNR); U.S. Environmental Protection Agency (USEPA); Federal Aviation Administration (FAA); Polk County Public Works Department; City of Des Moines, Iowa

Current MAR Status: In operation

Year Constructed: 2015–2018

Costs: $6.1M

Project Contact Information:

Vern Rash, P.E., L.S. Engineering Project Manager
Des Moines Water Works 2201 George Flagg Parkway
Des Moines, Iowa 50321-1190
Email: rash@dmww.com
Phone: 515-283-8733

Purpose of MAR:

- Water supply resilience

Source Water:

- Rivers/streams/lakes/reservoirs

Water Quality:

- Pretreatment required
- Post-treatment required

Recharge Technology(s):

- ASR well

Project Description

The Army Post Road ASR well facility is a joint project constructed by Des Moines Water Works (DMWW) under an agreement between DMWW, the City of West Des Moines, and the West Des Moines Water Works. The agreement follows the provisions of Chapter 28E of the Iowa Code and was executed in 2015.

The Chapter 28E Agreement states that the purpose for this project is to upgrade the capacity of the water supply infrastructure needed to support future development anticipated for West Des Moines. Included in the anticipated future development is a specific project for Microsoft Corporation, which requires a very high peak demand that could not be met without upgrading the capacity of the water supply system in the area. Construction of the Army Post Road ASR well facility is one of the upgrades needed to meet Microsoft Corporation's water needs. It also will benefit other future water users in this portion of the DMWW service area.

DMWW owns and operates similar ASR well facilities at the L. P. Moon ground storage facility in Dallas County and at the McMullen Water Treatment Plant in southwestern Polk County. As with the L. P. Moon and McMullen ASR well facilities, the Army Post Road ASR well facility injects finished/treated drinking water into a well completed in the Cambrian-Ordovician Aquifer. The drinking water injected into the wells during this "injection mode" is stored in the aquifer for later use during periods of high-water demand in the distribution system.

During high periods of demand, the injected drinking water is withdrawn from the aquifer and returned to the distribution system. This mode of operation is called the "recovery mode" and generally occurs during late spring and early summer. Recovery mode can also be used, however, during other periods that would benefit DMWW's operations. An example of such a period would be when the quality of DMWW's surface water sources is poor due to high nitrate concentrations.

Receiving Aquifer

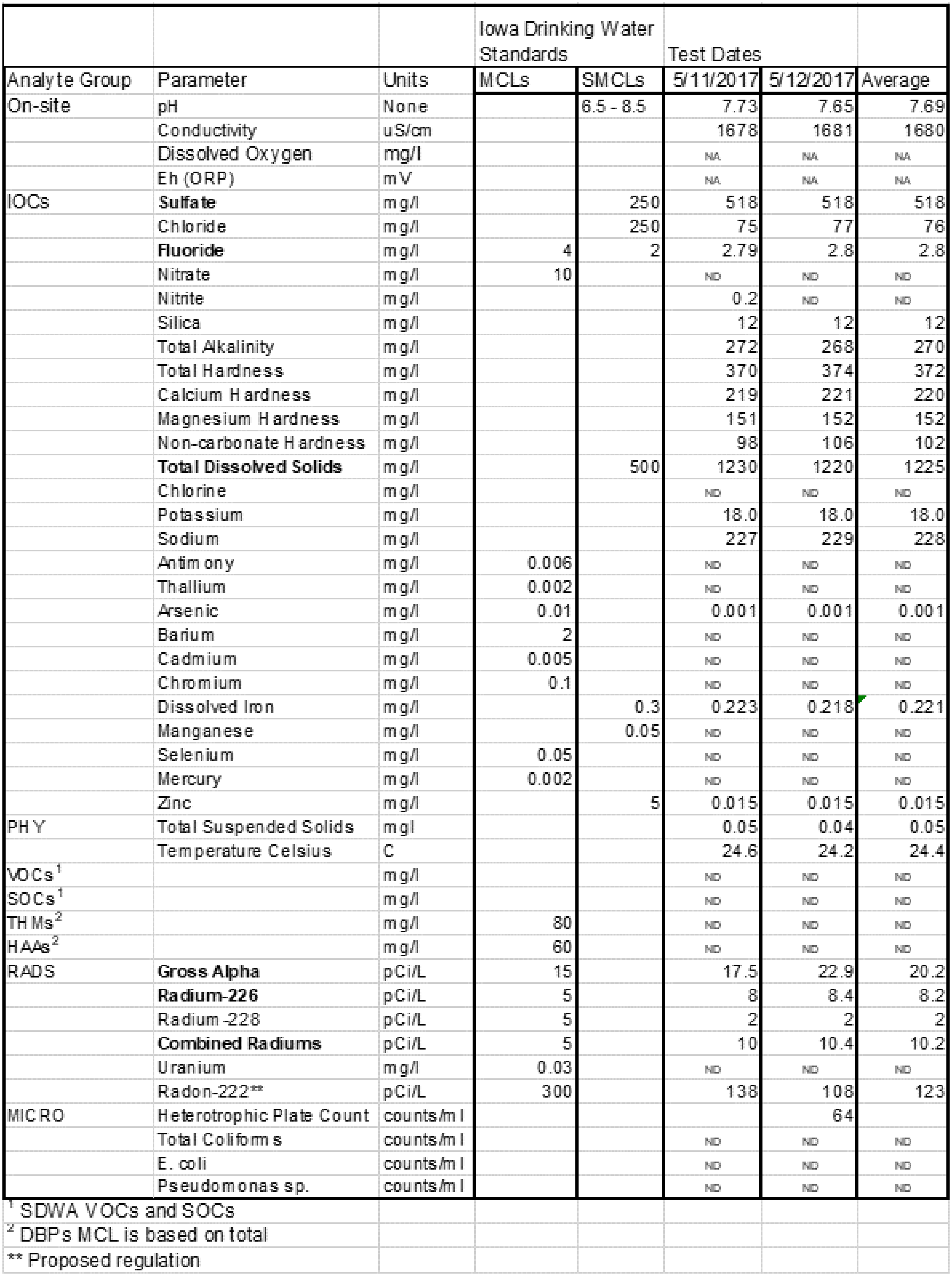
The Jordan Aquifer is the receiving aquifer for the Army Post Road ASR well. What is locally called the "Jordan Aquifer" in the Des Moines area is actually a grouping of three formations: the Root Valley and Oneota Members of the Ordovician Prairie du Chien Formation and the Cambrian Jordan Sandstone (Young 1992; Young and Siegel 1992).

- The Root Valley Member is dolomitic, fine- to medium-grained sandstone with chert. It is 80–90 feet thick in this area.
- The Oneota Dolomite is a cherty, fine- to coarse-crystalline porous dolomite about 200 feet thick. The Oneota Dolomite is characterized regionally as fractured to highly fractured with some crevices producing most of the water in wells screened in the Jordan Aquifer (Horick, P. J. and Steinhilber 1978). Karst features such as fractures, vugs, and caverns form secondary porosity within the dolomite and are common in the Oneota Dolomite in Iowa.
- The Jordan Sandstone is a fine-grained sandstone with some medium- to coarse-grained sections. The sandstone mineralogy is quartz with potassium feldspar, and the sandstone is weakly cemented by dolomite, quartz, or feldspar (personal communication with Tom Miller, Iowa Department of Natural Resources Geological Service Bureau). The Jordan Sandstone is about 50 feet thick.

Regional transmissivity of the Jordan Aquifer ranges from 2,000 to more than 4,000 feet per day, with some of the higher values estimated in Polk County where the Army Post Road ASR well is located (CH2M Hill 1996).

Table 1 is a summary of the native Jordan Aquifer water quality. The native water exceeds primary drinking water Maximum Contaminant Levels (MCLs) for several regulated radionuclides (gross alpha, radium-226, and combined radium), as well as several Secondary Maximum Contaminant Levels (SMCL) (sulfates, TDS, fluoride) highlighted in bold in Table 1. The native water is highly mineralized, making it unpalatable as a source of drinking water for most customers. The environment is slightly reducing with measurable concentrations of dissolved iron that will precipitate when in contact with oxidants. Calcium concentrations are also elevated (220 mg/L as CaCO3) but stable at native water pH (7.7).

Table 1—Native Jordan Aquifer water quality at Army Post Road ASR site



			Iowa Drinking Water Standards		Test Dates		
Analyte Group	Parameter	Units	MCLs	SMCLs	5/11/2017	5/12/2017	Average
On-site	pH	None		6.5 - 8.5	7.73	7.65	7.69
	Conductivity	uS/cm			1678	1681	1680
	Dissolved Oxygen	mg/l			NA	NA	NA
	Eh (ORP)	mV			NA	NA	NA
IOCs	**Sulfate**	mg/l		250	518	518	518
	Chloride	mg/l		250	75	77	76
	Fluoride	mg/l	4	2	2.79	2.8	2.8
	Nitrate	mg/l	10		ND	ND	ND
	Nitrite	mg/l			0.2	ND	ND
	Silica	mg/l			12	12	12
	Total Alkalinity	mg/l			272	268	270
	Total Hardness	mg/l			370	374	372
	Calcium Hardness	mg/l			219	221	220
	Magnesium Hardness	mg/l			151	152	152
	Non-carbonate Hardness	mg/l			98	106	102
	Total Dissolved Solids	mg/l		500	1230	1220	1225
	Chlorine	mg/l			ND	ND	ND
	Potassium	mg/l			18.0	18.0	18.0
	Sodium	mg/l			227	229	228
	Antimony	mg/l	0.006		ND	ND	ND
	Thallium	mg/l	0.002		ND	ND	ND
	Arsenic	mg/l	0.01		0.001	0.001	0.001
	Barium	mg/l	2		ND	ND	ND
	Cadmium	mg/l	0.005		ND	ND	ND
	Chromium	mg/l	0.1		ND	ND	ND
	Dissolved Iron	mg/l		0.3	0.223	0.218	0.221
	Manganese	mg/l		0.05	ND	ND	ND
	Selenium	mg/l	0.05		ND	ND	ND
	Mercury	mg/l	0.002		ND	ND	ND
	Zinc	mg/l		5	0.015	0.015	0.015
PHY	Total Suspended Solids	mgl			0.05	0.04	0.05
	Temperature Celsius	C			24.6	24.2	24.4
VOCs[1]		mg/l			ND	ND	ND
SOCs[1]		mg/l			ND	ND	ND
THMs[2]		mg/l	80		ND	ND	ND
HAAs[2]		mg/l	60		ND	ND	ND
RADS	**Gross Alpha**	pCi/L	15		17.5	22.9	20.2
	Radium-226	pCi/L	5		8	8.4	8.2
	Radium-228	pCi/L	5		2	2	2
	Combined Radiums	pCi/L	5		10	10.4	10.2
	Uranium	mg/l	0.03		ND	ND	ND
	Radon-222**	pCi/L	300		138	108	123
MICRO	Heterotrophic Plate Count	counts/ml				64	
	Total Coliforms	counts/ml			ND	ND	ND
	E. coli	counts/ml			ND	ND	ND
	Pseudomonas sp.	counts/ml			ND	ND	ND

[1] SDWA VOCs and SOCs

[2] DBPs MCL is based on total

** Proposed regulation

Water Quality

Water quality considerations at the Army Post Road ASR well include:

- Geochemical compatibility of source water and receiving aquifer water. Lime-softened finished water is considerably different from native Jordan Aquifer water. The source water is strongly oxidizing (400mV ORP) and has an elevated pH (9.5). Oxidation of ferrous iron and precipitation of calcium would therefore be expected at the recharge front. The extent to which these reactions occur with continued operation of the ASR well is monitored by DMWW because these reactions could impact aquifer integrity and water quality. Bacteria counts in the source water are very low due to disinfection. The source water can, however, support bacterial growth should the disinfectant be neutralized. Table 2 is a summary of source water quality during pilot testing.

Table 2—Source water quality at Army Post Road ASR site

			Standards		Shakedown			Cycle 1			Cycle 2			Cycle 3			Cycle 4		
Analyte Group	Parameter	Units	MCLs	SMCLs	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
On-site*	pH	None		6.5 - 8.5	9.50	9.77	9.66	9.51	9.77	9.69	9.51	9.77	9.59	9.30	9.40	9.34	8.93	9.36	9.16
	Conductivity	uS/cm			262	330	301	205	344	279	298	337	313	304	338	322.8	252	373	334
IOCs	Sulfate	mg/l		250	28.83	30.12	29.475	26.26	26.27	26.265	28.24	30.07	29.155	31.39	37.16	34.275	40.25	75.41	53.18333
	Chloride	mg/l		250	29.08	29.41	29.245	27.56	27.59	27.575	28.69	30.56	29.625	30.55	31.1	30.825	29.58	33.15	31.50667
	Fluoride	mg/l	4	2	0.7	0.8	0.75	0.74	0.74	0.74	0.31	0.56	0.435	0.73	0.78	0.755	0.74	0.79	0.773333
	Nitrate	mg/l	10		7.74	7.79	7.765	8.34	8.87	8.605	7.46	8.37	7.915	7.46	8.35	7.905	0.25	4.06	1.576667
	Nitrite	mg/l			ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Silica	mg/l			6.7	6.7	6.7	11	11	11	6.7	8.4	7.55	6.9	8.4	7.65	7	7.7	7.35
	Total Alkalinity	mg/l			44	61	52.5	67	69	68	44	46	45	46	58	52	56	60	58
	Total Hardness	mg/l			114	134	124	143	145	144	123	127	125	128	129	128	92	122	114
	Calcium Hardness	mg/l			62	101	82	84	101	93	69	85	77	73	91	82	31	88	63
	Magnesium Hardness	mg/l			33	52	42	41	61	51	42	54	48	39	54	46	30	49	38
	Non-carbonate Hardness	mg/l			70	73	71	74	78	76	77	84	80	71	82	76	32	62	47
	Total Dissolved Solids	mg/l		500	176	209	192.5	209	211	210	176	186	181	197	209	203	203	278.5	240.75
	Free Chlorine	mg/l			1.09	1.14	1.108	0.93	1.28	1.024	0.99	1.09	1.056	1.12	1.42	1.312	0.95	1.46	1.145
	Sodium	mg/l			11.02	11.79	11.405	10	10.12	10.06	11.45	12.17	11.81	12.57	13.72	13.145	15.22	27.21	19.46
	Antimony	mg/l	0.006		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Thallium	mg/l	0.002		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Arsenic	mg/l	0.01		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Barium	mg/l	2		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Cadmium	mg/l	0.005		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Chromium	mg/l	0.1		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Copper	mg/l	TT		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Lead	mg/l	TT		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Dissolved Iron	mg/l		0.3	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Manganese	mg/l		0.05	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Selenium	mg/l	0.05		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Mercury	mg/l	0.002		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Zinc	mg/l		5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PHY	TDS	mgl			176	209	192.5	209	211	210	176	186	181	197	209	203	203	278.5	240.75
	Total Suspended Solids	mgl																	
	Temperature Celsius	C			15.8	15.9	15.84	15.8	15.9	15.84	15.4	20.16	16.992	19.2	20.1	19.72	20.4	23.4	21.91667
VOCs[1]		mg/l			ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
SOCs[1]		mg/l			ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
THMs[2]	Total Trihalomethanes	mg/l	0.08		0.019	0.0212	0.0201	0.0242	0.0242	0.0242	0.0234	0.0234	0.0234	0.028	0.0293	0.02865	0.0286	0.029	0.0288
HAAs[2]	Total Haloacetic Acids	mg/l	0.06		ND	0.007	0.0035	0.007	0.008	0.0075	ND	0.008	0.004	ND	ND	ND	ND	ND	ND
RADS[3]		pCi/L			ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MICRO	Heterotrophic Plate Count	counts/ml			0	8	3	0	26	13	24	152	80	1	36	14	4	6	5
	Total Coliforms	counts/ml			ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	E.coli	counts/ml			ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Pseudomonas sp.	counts/ml			ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

[1] SDWA VOCs and SOCs

[2] DBPs MCL is based on total

[3] RADS (Gross Alpha, Radium-226, Radium-228, Combined Radiums, Uranium, Radon)

** Proposed regulation

TT Treatment technology, action levels of 1.3 and 0.015 mg/l for Copper and lead respectively

- Quality of recovered water. Water quality deteriorates during recovery as native groundwater mixes with the injected water. During pilot testing of the Army Post Road ASR well, recovered water quality did not exceed MCLs for regulated substances until 100% recovery by volume during shakedown and cycle 1, where treated water contributed only 30% and 40% of the recovered water, respectively. The proportion of finished to recovered water increases with each successive injection cycle, so no primary drinking water standards will be exceeded when recovering injected water through 100% recovery by volume. However, the highly mineralized native groundwater caused exceedances of secondary drinking water standards for sulfate and TDS during pilot testing. In operation, DMWW monitors the TDS of the recovered water and halts recovery when the TDS approaches the secondary MCL of 500 mg/L.
- Disinfection. Approximately 680 feet of 30-inch diameter water main was installed from the ASR well house to the connection point to the water distribution system. A 30-inch diameter pipe was required to provide sufficient time for the water recovered from the ASR well to be in contact with the disinfectant and meet the required contact time value for 4-log inactivation of viruses by free chlorine before entering the distribution system. Carbon dioxide is added to the recovered water to adjust the pH downward to just below 9. This allows for a lower detention time and contact time value for the disinfection portion of the recovery process prior to the recovered water returning to the distribution system.
- Well clogging. It is possible that physical, mechanical, or biogeochemical processes will result in clogging of the ASR well such that reconditioning will eventually become necessary to maintain yield. DMWW continuously monitors the performance of its ASR wells and has not yet encountered any clogging issues after many years of operation.

Regulatory Considerations/Issues

Provisions of the underground injection control (UIC) permit issued by the USEPA include the following:

- Injection rate shall not exceed 2.5 million gallons per day (1,736 gallons per minute) nor shall the total storage volume during injection operations exceed 450 million gallons.
- Injection pressure, measured at the surface, shall not exceed 85 pounds per square inch gauge (psig).

- Monitoring provisions state that samples of the recovered water must be analyzed to determine whether any metals, such as arsenic, or radionuclides were mobilized by the injected water during storage in the aquifer. This requirement was based on the results of sampling and testing conducted during well development and pilot testing that showed concentrations of antimony and arsenic above their respective MCLs in the recovered water. There have been no detections of antimony or arsenic in testing of the recovered water conducted since the ASR system became operational.

Summary of permits required for the Army Post Road ASR well:

- Iowa Department of Natural Resources—Well Site Survey
- Iowa Department of Natural Resources—Limited Registration
- Iowa Department of Natural Resources—Construction Permit
- Iowa Department of Natural Resources—Water Use Permit
- Iowa Department of Natural Resources—General Permit No. 6 Well Discharge
- Iowa Department of Natural Resources—National Pollutant Discharge Elimination System (NPDES) General Permit No. 2
- City of Des Moines, Iowa Site Plan Approval

- USEPA Underground Injection Control Permit
- Federal Aviation Administration 7460-1 Permit

5.12 South Metro Water Supply Authority Regional ASR Groundwater Model Scope of Work

Author: Lisa Darling and Linda Bowling

Site Name: South Metro Water Supply Authority Regional ASR Groundwater Model Scope of Work (August 17, 2022)

Location: Aurora, Colorodo

Operator: South Metro Water Supply Authority (SMWSA)

Permitting Agency: USEPA, Region 8, 1595 Wynkoop Street, Denver, Colorado 80202

Current MAR Status: Planning

Year Constructed: N/A

Costs: Project costs for Phase I estimated to be $184,035

Project Contact Information:

Lisa Darling, executive director, South Metro Water Supply Authority, 8400 East Prentice Ave. Suite 315, Greenwood Village, CO 80111, (720) 216-5158, LisaDarling@southmetrowater.org

Project Website/Publication Links: N/A

Purpose of MAR:

- Sustainable water supply

Source Water:

- Rivers/streams/lakes/reservoirs

Water Quality:

- Pretreatment required

Recharge Technology(s):

- Aquifer storage and recovery well

Project Description

South Metro Water Supply Authority (SMWSA) is a partnership of 14 water providers in the South Metro region of Denver, Colorado. SMWSA members and other regional providers (for example, Denver Water and Aurora Water) have had numerous conversations on the value of a South Metro ASR Regional Model. Such a model will support informed decision-making, particularly on the use of ASR to store Water Infrastructure and Supply Efficiency (WISE) Partnership deliveries and other renewable surplus supplies when deliveries exceed demands, and then to draw upon the stored reserves when needed. The model could serve as a tool to evaluate ASR operational scenarios; better understand ASR-related infrastructure needs; and address geologic, operational, and accounting questions. A South Metro ASR Regional Model will be an asset for water providers throughout the region. As a result of these conversations, a scope of work document has been prepared and is presented below.

East Cherry Creek Valley Water and Sanitation District (ECCV), Centennial Water and Sanitation District (Centennial), and the Town of Castle Rock (Castle Rock) have been identified as ASR “hubs” for incorporation into the South Metro Regional ASR Model. Centennial has an operational ASR program, and Castle Rock has initiated their ASR program. ECCV has developed a local ASR model to evaluate ECCV-specific ASR operational scenarios. These providers are geographically well positioned to serve most of the South Metro region, with ECCV serving as an “eastern hub,” Centennial serving as a “western hub,” and Castle Rock serving as a “southern hub.” They also have access to key conveyance infrastructure necessary for transporting water throughout the South Metro region.

The South Metro ASR Regional Model will be designed to assist in investigating the feasibility, opportunities, and limitations of an integrated three-hub regional ASR system. This entails the following suite of critical questions identified by SMWSA members and regional providers:

- How conducive are the three hubs in meeting regional demand and storage needs?
- What sort of peak and optimum injection and extraction rates could we anticipate with an integrated multi-hub ASR system?
- What are the dynamics related to groundwater mounding resulting from ASR? This is related to anticipated

groundwater levels and gradients during and post injection/extraction periods, lateral extent of the mounding effect, and duration of the mounding effect in relation to extractions and injections.

- How many wells and what other accompanying infrastructure are necessary for a multi-hub ASR system and what are the costs?
- How can the individual hubs be integrated to operate on a systemwide level?
- Are there critical limitations in injections and extractions (bottlenecks) that need to be addressed before a regional ASR system could be optimized?
- What sort of interactions with nearby wells outside of the hub water providers' service area should be anticipated?
- How do systemwide regional ASR operational scenarios influence groundwater levels and are there favorable ways ASR could be managed to mitigate groundwater level declines?
- Could a South Metro Regional ASR Model be the initial steppingstone for a suite of tools needed to operate and integrate a multi-hub South Metro regional ASR system?

Project Planning/Implementation

The South Metro Regional ASR Model includes two phases:

- Phase 1: Development of a conceptual model—The South Metro conceptual model will include the compilation of a broad spectrum of technical data. Such data will entail groundwater levels; aquifer properties, including transmissivity, hydraulic conductivity, pumping/slug tests, and well yields; location of wells and neighboring wells (as feasible); operational capacity; delivery limitations; and any water quality concerns. These data will form the technical platform necessary to develop and calibrate a numerical South Metro Regional ASR Model (to be developed in Phase 2).
- Phase 2: Development of the numerical South Metro Regional ASR Model—The numerical model will be constructed to simulate ASR operations in the three designated hubs. Modeling scenarios will be developed to address the questions listed above, empowering stakeholder participants to assess how ASR may be integrated at a multi-hub regional level within the South Metro area.

Project Objectives

Specific objectives for Phase 1 of this project include:

- Develop a comprehensive compilation of available data specifically pertaining to the application of ASR in the three identified hubs (ECCV, Centennial, and Castle Rock).

- Develop a robust South Metro conceptual model that will inform development of the South Metro numerical model in Phase 2.
- Work closely with the stakeholder technical committee in collecting data and input on key project components as the project progresses.
- Develop an easily digestible technical report summarizing the available data; conceptual model development approach; key findings; and constructive recommendations for Phase 2.

Phase 1 will involve three tasks:

Task 1: Project and Grant Administration. Task 1 includes routine calls/meetings every 6 weeks with the technical committee to convey results and receive feedback, coordination with SMWSA to implement the project, project invoicing by INTERA to SMWSA, and activities necessary for Colorado Water Conservation Board (CWCB) grant administration.

Task 2: Data Collection and Identification of Data Gaps. The purpose of Task 2 is to collect the data necessary to develop a comprehensive common understanding of the hydrogeology within each hub and a suite of hydrogeologic data necessary to conduct the ASR modeling. Most relevant are the hub-specific data that have been collected by each hub. Such data entails: groundwater levels; stream and lake locations; aquifer properties and tests, including transmissivity, hydraulic conductivity, pumping/slug tests, well yields; lithology logs, geophysical logs from boreholes; location of wells and neighboring wells (as feasible); operational capacity and delivery limitations; any water quality concerns; and data gaps. Data from the USGS, state, well driller logs, and local studies will also be assessed. In addition, data collected as part of the USGS Denver Basin Aquifer System Model (DBASM) development will be included. The DBASM model will serve an important role during the development of the numerical South Metro ASR Regional Model in Phase 2, where the model will be converted into a MODFLOW 6 to allow for the numerical integration of the three proposed local hubs.

Task 3: Develop Conceptual Model. The purpose of Task 3 is to develop a conceptual model that establishes the system framework and the range of parameters required to construct a numerical model. It is foundational in identifying sources, sinks, and pathways associated with an aquifer. The conceptual model also defines unknowns and uncertainties in a system and identifies gaps in data. A well-constructed conceptual model identifies additional data needs, supports site quantifications, and generates preliminary answers to complex questions. It focuses on the stratigraphic and physical position as well as the characteristics of the aquifers.

The conceptual model developed for this task will provide the foundational information and input data necessary to develop the numerical model in Phase 2. Such information will include a regional and local hub-specific overview on the following: geologic and hydrogeologic maps and cross sections and description of key geologic and hydrogeologic features, including key aquifers; regional relationships between surface water, recharge, and groundwater; subsurface formations that influence groundwater movement and storage; visuals showing seasonal groundwater contour maps and regional and local groundwater flow depictions; well extractions; hydrographs depicting changes in groundwater levels over time; general characterization of groundwater quality; and parameters that will be included in the numerical model (for example, local hub transmissivities, and aquifer boundaries). Data collected in Task 2 will be used to inform the conceptual model, primarily focusing on the three local hubs. Information collected from the recent previously conducted ECCV conceptual and numerical modeling effort will provide the basis for the conceptual modeling of the ECCV Hub.

Task 3.1: Castle Rock Hub and Task 3.2: Centennial Hub. These tasks include the evaluation of geologic and geophysical data from the producing aquifers within the Castle Rock Hub boundary and the Centennial Hub boundary. As described above, a variety of geologic and groundwater data will be assessed to provide a conceptual model of the underlying subsurface. This includes key numerical modeling parameters, such as aquifer transmissivity, hydraulic conductivity, and storage, that will be directly incorporated into the Phase 2 numerical modeling effort. Core data results from the drilling of wells will also be examined to determine appropriate specific yields of the aquifers for numerical modeling purposes. Additionally, hydrographs showing groundwater level fluctuations and available potentiometric data will be evaluated to inform the numerical modeling calibration in Phase 2. It is assumed that Castle Rock and Continental will provide the data necessary to inform the hub conceptual model along with additional data sources cited in Task 2. Data from neighboring provider wells may also be incorporated where readily available.

Regional data from the DBASM study/USGS model will also be collected and compared with the local hub-specific data to ensure data compatibility. This is an important step in preparing the conceptual model for numerical development because, as mentioned in Task 2, it is anticipated that the regional USGS model from the DBASM study will be converted into MODFLOW 6 as a component of the Phase 2 numerical modeling effort. This conversion will be critical in integrating the three local hubs from a regional perspective and will further offer the ability to add additional local hubs if desired in the future. (Essentially the three local hub numerical models will be “insets” in the newly developed regional MODFLOW 6 model). Since the DBASM study/USGS model will inform the converted MODFLOW 6 regional model, data evaluated for the Castle Rock Hub and Continental Hub conceptual models in this task will be compared with data from the DBASM study/USGS model. Comparison of the Castle Rock Hub–specific data and Continental Hub–specific data and DBASM data will focus on the hub boundaries where the coarser scale MODFLOW 6 regional model will “connect” with the refined smaller scale local Castle Rock Hub numerical model inset.

Task 3.3: ECCV Hub. INTERA developed a conceptual and numerical model of the Arapahoe Aquifer within the ECCV service area as part of ECCV’s previously conducted ASR numerical modeling efforts. While the focus of that effort was on the Arapahoe Aquifer, additional data were collected and reviewed for the Denver and Laramie Fox-Hills Aquifers to assess the hydraulic connectivity between these two aquifers and the Arapahoe Aquifer. This task includes further refinement of the ECCV conceptual model for the ECCV Hub to characterize and enhance the additional aquifers. It also includes the addition of ECCV’s Willows Wellfield (pending ECCV’s approval).

Task 3.4 Consolidation of Data and Synthesis of Results. A critical factor to the success of this project is developing materials and data that are easily digestible and useful to the South Metro regional providers. INTERA will work with the technical committee in organizing the conceptual model into a comprehensive set of materials that 1) informs the numerical model and 2) can be utilized by stakeholders for additional studies and/or decision-making purposes. Such materials will consist of spreadsheet database(s) of collected data and informative visual aids, including maps of key geologic formations, groundwater-level contours, and well locations. INTERA will receive feedback from stakeholders on these draft materials as they are being presented during the technical committee meetings.

Task 4: Documentation. This task entails the development of a report documenting the data synthesis and evaluation conducted in Tasks 1–3. The report will focus on the conceptual model, providing detailed narratives on the regional and local hub geologic and groundwater characteristics discussed in Task 3. The main goals of the report are to: (1) provide a foundational understanding of the groundwater dynamics regionally and within each hub, (2) inform the Phase 2 numerical groundwater modeling effort, and (3) serve as a reference to stakeholders when developing modeling scenarios and interpreting model results during the Phase 2 numerical modeling effort. The initial draft report will be developed for review by SMWSA followed by a second draft reviewed by the technical committee. The final draft will be provided to the Colorado Water Conservation Board and be available to the public.

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Appendix A: MAR Team State Survey

Survey Purpose:

ITRC's Managed Aquifer Recharge Team is developing guidance and training on the range of innovative aquifer recharge options. The guidance will define the appropriate geologic settings and tools needed for characterization and design. We will use the results of this survey to identify and guide the development of the Team products, including the technical and regulatory guidance document.

Project Introduction:

Managed Aquifer Recharge (MAR) is a form of aquifer management that focuses on groundwater availability and quality. MAR includes Aquifer Recharge used to replenish aquifers and Aquifer Storage and Recovery to store water for beneficial purposes in the future. Augmenting groundwater storage through MAR represents a cost-effective way to:

- Increase the availability of groundwater for potable, non-potable, irrigation, or fishery uses.
- Improve groundwater sustainability by acting as a barrier to saltwater intrusion or aquifer subsidence.
- Improve water quality through aquifer filtration.
- Address groundwater dependent eco-systems (wetlands).
- Provide enhanced baseflow for downstream users and minimal instream flows.

To help support the growing practice of MAR, ITRC is working to produce a technical guidance document and training that will evaluate:

- The potential uses of MAR,
- Innovative characterization approaches, and
- Modeling tools (GIS, groundwater modeling, water balance) that:
- Support development and placement of MAR infrastructure and
- Evaluate the factors for safe and successful implementation.

In this survey, the first set of questions (4 to 8) are not specific to MAR but are more general to aquifer management activities. The Team expects that most states have some aquifer management activities (such as UIC programs) and have a general understanding of aquifer management issues and input about states' approaches would be important to focusing our products. Questions 10 to 15 are specific to MAR projects and may be skipped if the state does not have such projects.

MAR Survey 2022

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Appendix B: Water Quality Parameters

Parameter Group	**Relevance**	**Relevant Case Study**
Physical Parameters		
Dissolved Oxygen	Dissolved oxygen is a measure of oxygen in the water. Dissolved oxygen can affect geochemistry in aquifers, resulting in decreasing or increasing levels of arsenic. The sediment composition in the aquifer can affect release potential (Fakhreddine et al. 2020).	Orange County, CA (Fakhreddine et al. 2020).
Temperature	Temperature differentials might play a role in bacterial growth and clogging. Temperature gradients can also be used as tracer for analysis of water movement (Caligaris, Agostini, and Rossetto 2022). Temperature can also change water viscosity (AWWA 2015).	
Turbidity	Turbidity is a way to measure particles in the water. The units are nephelometric turbidity units (NTU), a measure of light scatter.	Salisbury, South Australia (Page et al. 2015)
Total Dissolved Solids (TDS)	The sum of all substances dissolved in water, including organic and inorganic substances. A high number of dissolved solids can hinder water use (USGS Water Resources 2019). Dissolved solids could leach into the receiving aquifer if the source water is high in TDS (Waterhouse et al. 2020).	Perth, Western Australia (Johnston, Martin, and Higginson 2013)
Total Suspended Solids (TSS)	The sum of solids suspended in the water, greater than 2 microns in size.	Perth, Western Australia (Johnston, Martin, and Higginson 2013)
Chemical Parameters		
Disinfection By-products	Adding chlorine or other disinfecting substances, such as chlorine dioxide or ozone, to water for disinfection can result in reactions that produce chemicals that pose human or environmental risks. Examples are chloroform, bromoform, bromate, chlorodibromomethane, and N-nitrosodimethylamine (NDMA). Conditions within the aquifer may determine whether disinfection by-products degrade or remain (Imig et al. 2022; Landmeyer, Bradley, and Thomas 2007; Liu et al. 2018).	

Emerging Contaminants PFAS Pharmaceuticals Microplastics	There are currently several contaminants in drinking water that are not regulated. These are often called emerging contaminants or unregulated contaminants. The USEPA has an unregulated contaminant monitoring rule and has set some proposed MCLs for some contaminants, such as six PFAS contaminants as PFOA and PFOS, though these proposed values are not enforced by USEPA. There are also health advisories for some contaminants that are not enforced. More information can be found at USEPA's page called Monitoring Unregulated Contaminants in Drinking Water (https://www.epa.gov/dwucmr). Potential risks of PFAS in MAR, for example, are outlined in Page et al. (2019).	City of Tucson, AZ (Cáñez et al. 2021)
Inorganic Chemicals	Inorganic chemicals are natural elements, such as arsenic, manganese, iron, or compounds such as sodium chloride or hydrogen peroxide. Inorganic chemicals may affect aquifer water quality. Sometimes inorganic chemicals are mobilized from the surrounding geologic structures through interaction with the source water chemistry.	Green Bay, WI (Bilotta et al. 2021)
Nutrients	Nutrients such as nitrogen or phosphorus can encourage the growth of microbes such as bacteria and algae. There are water quality parameters in place in some states to ensure nutrient levels are kept low. Nitrate and nitrite can also affect potability of drinking water, as it can cause health conditions like blue baby syndrome.	(Waterhouse et al. 2020)
Pesticides	Pesticides are chemical formulations that are intended to manage populations of pests such as insects, rodents, and weeds. Pesticides can be found in stormwater or irrigation runoff, particularly in agricultural or developed areas, including residential areas. Infiltration into an aquifer could affect possible end uses of the water, such as drinking water, without further treatment.	A potential concern in agricultural MAR. (Levintal et al. 2023)
pH	pH is a measure of how acidic or basic the water is, based on the number of hydrogen atoms. pH can influence geochemical reactions that release minerals into the water.	Perth, Western Australia (pH buffering) (Seibert et al. 2016)
Salinity	Salinity is a measure of salts in the water—often sodium chloride—but other salts can be measured as well. Water that has high salinity is unsuitable for humans or animals to drink and often unsuitable for other purposes, such as irrigation (USGS Water School of Science 2018) In certain areas, salt water might intrude into freshwater aquifers.	Southwestern U.S. (Zektser, Loaiciga, and Wolf 2005)
Sodicity	High sodium can cause swelling of clays, followed by possible mobilization of metals (AWWA 2015).	
Total Organic Carbon (TOC)	Total organic carbon is how much organic carbon is in water. This is a measure of how many organic contaminants (plant material, animal material, microbes, and synthetic organic chemicals) that a water body contains. High TOC can result in low oxygen levels if materials start to decompose, and low oxygen levels can have geochemical effects.	Finland (Jokela et al. 2017)

Volatile Organic Compounds	Volatile organic compounds (VOCs) might be present in receiving aquifers because of previous contamination, such as from improper disposal practices. Source waters may also be contaminated. There are state and federal limits on VOCs.	Copenhagen, DK and Gothenburg, SE (Kuster et al. 2010)
Biological Parameters		
Algae/Cyanobacteria	Cyanobacteria blooms (also called algae blooms) can emit cyanotoxins into the water that can be very toxic to humans and animals if ingested and cause skin irritation on contact. USEPA has an MCL for microcystin, one type of cyanotoxin, and health advisories for others, such as anatoxin and cylindrospermopsin (USEPA 2022e). Some states also have their own requirements or guidelines. MAR via bank infiltration might be a good means to remove cyanotoxins.	Lagoa do Peri, Brazil (Brookes et al. 2021)
Bacteria	Bacteria such as *Escherichia coli (E. coli*), *Salmonella, Campylobacter,* or other pathogens with animal or human sources may cause human illness if the water is ingested or contacted.	Salisbury, South Australia (Page et al. 2015) Llobregat MAR system, Spain (Barba et al. 2019)
Protozoa	Protozoa are parasites often shed into the water from ill animals or humans. When ingested by humans, they can cause illness. Many states have specific requirements for MAR water quality.	Shafdan, Israel; Nardò, Italy; Bolivar, Australia; and Sabadell, Spain (Ayuso-Gabella et al. 2011)
Viruses	Viruses such as norovirus or enterovirus, often from human sources, can cause human illnesses in others when the water is ingested or contacted.	Parafield, Australia (Sasidharan et al. 2017)
Radiological Parameters		
Naturally Occurring Radioactive Materials (NORM)	Naturally occurring radioactive elements can be found in the aquifer water when it is extracted. Radioactive particulates, called radionuclides, can be harmful to human health. Many states use the federal MCL or their own water quality measures to determine whether water is safe for drinking purposes ((USEPA 2022f), (USEPA 2022g)).	

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Appendix C. State, Territory, and Tribal Contacts for Managed Aquifer Recharge (USEPA, 2022)

State, Territory, or Tribe	***Agency Contact***
Alabama	Alabama Department of Environmental Management
Alaska	USEPA
Arizona	Arizona Department of Environmental Quality Groundwater Protection Program
Arkansas	Arkansas Department of Environmental Quality
California	State Water Resources Control Board
Colorado	USEPA
Connecticut	Connecticut Dept. of Energy and Environmental Protection, Water Permitting and Enforcement Division
Delaware	Ground Water Discharges Section, New Hampshire Department of Environmental Services, Drinking Water Source Protection Program
Florida	Florida Department of Environmental Protection
Georgia	Georgia Environmental Protection Department
Hawaii	Department of Health, Safe Drinking Water Branch Safe Drinking Water Branch
Idaho	Idaho Department of Water Resources UIC Program
Illinois	IL USEPA UIC Program, Illinois Environmental Protection Agency
Indiana	USEPA
Iowa	USEPA
Kansas	Kansas Department of Health and Environment
Kentucky	USEPA

Louisiana	Louisiana Department of Natural Resources
Maine	Maine Dept. of Environmental Protection, Division of Water Resource Regulation
Maryland	Water and Science Administration, Maryland Department of the Environment
Massachusetts	Massachusetts Dept. of Environmental Protection, UIC Program/Drinking Water Program
Michigan	USEPA
Minnesota	USEPA (Minnesota Department of Health, Minnesota Pollution Control Agency)
Mississippi	Mississippi Department of Environmental Quality
Missouri	Missouri Department of Natural Resources
Montana	USEPA
Nebraska	Nebraska Oil and Gas Conservation Commission
Nevada	Nevada Division of Environmental Protection Underground Injection Control Program (Also Nevada Division of Water Resources for required permits.)
New Hampshire	New Hampshire Department of Environmental Services, Drinking Water Source Protection Program: https://www.des.nh.gov/climate-and-sustainability/conservation-mitigation-and-restoration/source-water-protection
New Jersey	New Jersey Department of Environmental Protection
New Mexico	New Mexico Environment Department
New York	USEPA
North Carolina	North Carolina Department of Environment Quality
North Dakota	North Dakota Department of Environmental Quality
Ohio	Ohio EPA UIC program, Ohio Environmental Protection Agency
Oklahoma	Oklahoma Department of Environmental Quality
Oregon	Oregon Department of Environmental Quality UIC Program
Pennsylvania	USEPA
Rhode Island	Rhode Department of Environmental Management, Office of Water Resources
South Carolina	South Carolina Department of Health and Environmental Control

South Dakota	USEPA
Tennessee	Tennessee Department of Environment and Conservation
Texas	Texas Commission on Environmental Quality
Utah	Utah Department of Environmental Quality, Division of Water Quality
Vermont	Vermont Department of Environmental Conservation, Drinking Water and Groundwater Protection Division
Virginia	USEPA
Washington	Washington Department of Ecology UIC Program
West Virginia	Stormwater & Groundwater/UIC Programs, West Virginia Department of Environmental Protection
Wisconsin	WDNR Underground Injection Wells, Wisconsin Department of Natural Resources
Wyoming	Wyoming Department of Environmental Quality
Territories	
Guam	Guam Environmental Protection Agency Water Resources Program
Northern Marina Islands	CNMI Bureau of Environmental and Coastal Quality
Puerto Rico	CNMI Bureau of Environmental and Coastal Quality
Tribes	
Five Civilized Tribes	Five Civilized Tribes
Navajo Nation	Navajo Nation Environmental Protection Agency Underground Injection Control Program

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Appendix D: Team Contacts

Team Leaders:

Kelsey Bufford
Oklahoma Department of Environmental Quality
kelsey.bufford@deq.ok.gov

Kristopher McCandless
Virginia Department of Environmental Quality
kristopher.mccandless@deq.virginia.gov

Program Advisors:

Jim Rocco
Sage Risk Solutions LLC
jrocco@sagerisk.com

Lesley Hay Wilson
Sage Risk Solutions LLC
lhay_wilson@sagerisk.com

Writing Group Leaders:

Introduction:

John Mitsdarfer
Oklahoma Department of Environmental Quality
john.mitsdarfer@deq.ok.gov

Anthony Daus
GSI Environmental Inc.
addaus@gsi-net.com

Managed Aquifer Recharge Overview; Project Planning:

Nancy Rice
Minnesota Department of Health
nancy.rice@state.mn.us

Adam Janzen
Barr Engineering Company
ajanzen@barr.com

Recharge Technologies:

Robert Hillegas
Colorado Department of Public Health and Environment
robert.hillegas@state.co.us

Patrick O’Connell
United Water Conservation District
patricko@unitedwater.org

Case Studies:

Robert Nail
Texas Commission on Environmental Quality
robert.nail@tceq.texas.gov

Maureen McGraw
Tetra Tech, Inc.
maureen.mcgraw@tetratech.com

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Appendix E: Glossary

A

Adsorption

The mechanism whereby ions or compounds within a liquid or gas adhere to a solid surface upon contact.

Advanced treated water (ATW)

Wastewater that has been thoroughly treated by advanced treatment processes to reduce contaminant concentrations (including virus and pathogen reduction) to meet regulatory limits. This water often contains such low levels of impurities (for example, TDS) that it requires conditioning before it can be recharged.

Advection

The transport of solutes along with flowing groundwater.

Alkalinity

The acid neutralizing capacity of a solution.

Agricultural return flow

The portion of irrigation water that leaves the field, either as surface runoff or as infiltration to the water table.

Anisotropy

The dependence of a property on direction; for example, hydraulic conductivity is commonly different in the horizontal and vertical directions.

Aquifer storage and recovery (ASR)

A water resources management technique for storing water underground during wet periods and recovering that water at a later date, typically facilitated by ASR specific wells. These wells can be used for both the injection of source water and recovery of groundwater.

Aquifer storage transfer and recovery (ASTR)

An ASTR system uses separate injection wells and extraction wells allowing the injected water to migrate or transfer from the injection area prior to extraction occurring.

B

Base flow

The component of river or streamflow between storm flow peaks. Base flow is composed predominately of groundwater that discharges to the stream bed. Enhancing baseflow, particularly during low seasonal flow or during droughts, is a target for MAR.

Biofouling

The unwanted accumulation of microorganisms, plants, or algae on surfaces such as well screens that cause degradation of the surface’s primary function.

C

Clay swelling

The tendency of some clays to increase in volume due to changes in water content or and/or salinity.

Confined aquifer

Aquifers that are bounded above and below by lower permeability confining units. Confined aquifers are pressurized, and therefore the water level in a well completed in a confined aquifer typically rises above the top of the aquifer.

D

Desorption

The opposite of adsorption; the release back into solution of a solute that formerly clung to a solid surface.

Dewatering

The pumping of groundwater to lower the water table below the base of an excavation. Dewatering is frequently used in construction projects and open-pit mining.

Disinfection by-products

Chemicals formed when organic and inorganic matter react during water treatment processes. An example is the formation of chloroform when chlorine reacts with organic matter in the water.

Dispersion

The dilution of a solute along the advancing edge of groundwater flow. Dispersion is caused by the variability in both pore-scale velocities and flow path distances due to the physical characteristics of flow in porous media.

E

Environmental justice

The fair treatment and meaningful involvement of all people, regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies (USEPA 2023b)

F

Flood-managed aquifer recharge (Flood-MAR)

An integrated and voluntary resource management strategy that uses floodwater resulting from, or in anticipation of, rainfall or snow melt for MAR on agricultural lands and working landscapes, including but not limited to refuges, floodplains, and flood bypasses. (Flood-Managed Aquifer Recharge (Flood-MAR) (ca.gov))

H

Hydraulic conductivity

A measure of how easily water flows through the aquifer. Values of hydraulic conductivity typically range over orders of magnitude.

Hydrogeologic conceptual model

A hydrogeologic framework that forms one of the foundational pillars in planning and designing the MAR project. The hydrogeologic conceptual model typically consists of a report that provides the hydrogeologic setting (hydrostratigraphy), receiving aquifer physical characteristics (for example, depth to water, permeability, storage coefficient, degree of confinement), receiving groundwater quality, groundwater flow characteristics (directions, rates, volumes, variability), nearby public and private groundwater users, and groundwater/surface water connections.

Hydrogeologic feasibility

Feasibility of both recharging an aquifer and later recovering the recharged water.

I

Injection well

As used in this document, an injection well, also referred to as a recharge well, is a bored, drilled, or driven shaft or a dug hole where the depth is greater than the largest surface dimension used to directly supply water into the saturated zone or aquifer(s) for the purpose of recharge or replenishment.

Ion exchange

Sorption process in which ions of like charge are exchanged between a solid and a solution surrounding the solid.

L

Liquefaction

When saturated, loosely packed soil near the ground surface liquefies and loses all strength during an earthquake. Liquefaction often results in major structural damage.

M

Managed aquifer recharge (MAR)

The purposeful recharge of water to aquifers for subsequent recovery or for environmental benefit (Dillon et al. 2009).

P

Phreatophyte
Plant with a deep root system that taps the water table aquifer.

Produced water
Oil wells produce both oil and water; this water is commonly known as produced water. Produced water is typically very saline and contains both suspended and dissolved hydrocarbons.

R

Receiving aquifer
Aquifer into which source water is applied. An aquifer can be a porous medium such as sand and gravel, fractured hard rock such as granite, karst, or a combination.

Receiving aquifer lithology and mineralogy
The general physical and chemical characteristics of the solid materials that make up the aquifer matrix. For example, a quartz (mineral) sandstone (lithologic) aquifer.

Recharge front
The interface where source water comes into contact with native groundwater.

Recharge technology
Method used to introduce source waters into an aquifer. Technology can range from relatively passive methods such as farm-flood infiltration to more intensive methods such as injection wells.

Reclaimed water
As used in this document, the term “reclaimed water” has the same meaning as “recycled water.”

Recycled water
Treated wastewater that is reused for a new purpose, such as irrigation, potable water supply, and groundwater supply, among others. Sources of wastewater include but are not limited to municipal, industrial, and agricultural wastewater.

Redox
Redox reactions are chemical reactions that involve the transfer of electrons between two species, where oxidation is the loss of electrons and reduction is the gain of electrons.

Residence time
Length of time recharged water resides in an aquifer before it is extracted. Residence times can be mandated by regulatory agencies to ensure pathogens and other contaminants are filtered from the recharged source water prior to being removed from the subsurface and served as drinking water.

S

Saturation Index
A measure indicating the tendency of water to dissolve or precipitate a particular mineral.

Seismicity
The occurrence or frequency of earthquakes in a region.

Soil aquifer treatment
The filtration of wastewater through the soil matrix to remove wastewater contaminants through physical, chemical, and biological processes.

Source water
Source water intended for use as recharge. This can range from transient sources such as captured available flood flows to more consistent sources such as treated water originating from a wastewater treatment plant. Source water availability and quality are key components in the design and implementation of MAR projects. Source water quality can be highly variable and may require treatment or design constraints to improve water quality prior to use in recharge.

Specific storage
A parameter that quantifies the change in aquifer storage due to compressibility effects of both the water and the aquifer matrix.

Specific yield
The fraction of the total aquifer volume that can be either drained of water or refilled with water. The upper bound on the specific yield is the total porosity of the aquifer, but the specific yield is typically less than the porosity because capillary pressure effects prevent the complete replacement of one fluid in aquifer pore space with a different fluid.

Storm flow

The peak in discharge from a river or basin that is seen after a precipitation event. Storm flow is composed predominately of runoff with some through flow. The water associated with storm flow may contribute to flooding and may be more than demand and thus potentially available for MAR.

Stormwater

Stormwater runoff is generated from rain and snowmelt events that flow over land or impervious surfaces, such as paved streets, parking lots, and building rooftops, and does not soak into the ground (USEPA 2023b).

T

Tracer study

Aquifer studies that are performed to understand groundwater flow pathways and residence times. Tracers can include naturally occurring chemicals and introduced substances such dyes, salts, and isotopes. These are often performed when injecting treated wastewater.

U

Unconfined aquifer

An aquifer whose upper water surface (water table) is at atmospheric pressure and is able to receive direct infiltration/recharge from precipitation or surface water.

V

Vadose zone

The unsaturated to intermittently saturated zone between the ground surface and the water table.

W

Water banking

The purposeful recharge of surface water or treated water with the intent to recover a portion of the water later by the parties that performed the recharge.

Water supply resilience

The ability to recover from disruptive events such as droughts and floods and adapt to future uncertainty.

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Appendix F: Acronyms

ASR	aquifer storage and recovery
ASTR	aquifer storage, transfer, and recovery
ATW	advanced treated water
BLM	Bureau of Land Management
CEC	Contaminant of Emerging Concern
cfs	cubic feet per second
FERC	Federal Energy Regulatory Commission
gpm	gallons per minute
LID	low impact development
MAR	managed aquifer recharge
MCL	Maximum Contaminant Level
mgd	million gallons per day
MIW	mining-influenced waters
NGO	nongovernmental organization
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
OCWD	Orange County Water District
OM&M	operations, maintenance, and monitoring
PFAS	per- and polyfluoroalkyl substances

RI	rapid infiltration
TDS	total dissolved solids
TOC	total organic carbon
TSS	total suspended solids
tTEM	towed transient electromagnetic methods
UIC	underground injection control
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USFWS	United States Fish and Wildlife Service
USDW	underground source of drinking water
USEPA	United States Environmental Protection Agency

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Eric Bennett Idaho Department of Environmental Quality	**John Mitsdarfer** Oklahoma Department of Environmental Quality
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Jamie Mitchell Hampton Roads Sanitation District	

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Doug Bacon USEPA Region 8	**Jon Fields** USEPA

Doug Beak USEPA	**Chris Patterson** Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC)
Linda Bowling USEPA Region 8	

Public and Tribal Stakeholders

Lorrie Council Ground Water Protection Council

Emeritus and Academia Stakeholders

Emre Burcu Özkaraova Ondokuz Mayis Ãœniversity	**Mark Widdowson** Virginia Tech
Guy Sewell ECU Professor Retired	

Industry Affiliates

Brad Bessinger S.S. Papadopulos & Associates, Inc	**Brandon McLean** Brown and Caldwell
Brian Caldwell Ensafe, Inc.	**Michael Mobile** McDonald Morrissey Associates
Bob Cohen Tetra Tech	**Joanna Moreno** WSP Golder
Dayne Crowley Wood Environment & Infrastructure	**Patrick O’Connell** EKI Environment & Water, Inc.
Maria Daugherty EA Engineering, Science, and Technology, Inc.	**Travis Pacheco** Torrent Resources (Oldcastle)
Tony Daus GSI Environmental Inc.	**Sorab Panday** GSI Environmental, Inc.
Jeff Davis Integral Consulting Inc.	**Tim Parker** Ramboll
Emmanuel Fonseca EKI Environment & Water, Inc.	**Scott Payne** WWC Engineering
John Fontana Vista GeoScience, LLC	**Alex Rosenthal** Wood Plc
Beth Hoagland S.S. Papadopulos & Associates, Inc	**Tony Schroer** Barr Engineering Company
Adam Janzen Barr Engineering Company	**Mike Taraszki** Wood Environment & Infrastructure

Gregg Jones Brown and Caldwell	**Chuck Thibault** Tioga Environmental Consultants
Mike Jorgensen Stantec Australia	**Dimitri Vlassopoulos** Anchor QEA
Maureen McGraw Tetra Tech	**Claire Wildman** Geosyntec Consultants, Inc.

ITRC & Environmental Justice – A Commitment to Our Values

Environmental Justice is making its way to the forefront of today's environmental community following decades of documentation detailing the disproportionate burden placed on low-income and minority communities by pollution and environmental hazards. Failure to address EJ concerns has led to grave consequences for low-income or minority communities; without a voice, human health in these communities can suffer greatly as a result of poorly informed environmental decision-making.

Defined by the United States Environmental Protection Agency (EPA) as "…the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies," EJ can only be achieved when everyone has "the same degree of protection from environmental and health hazards, and equal access to the decision-making process to have a healthy environment in which to live, learn, and work." (USEPA, 2020a). Since its inception in the early 1980s, the field of EJ has grown to encompass a broad spectrum of other environmentally inclusive subjects, concerns and, ultimately, legislation; some of the terminology commonly used today includes Social Equity, Social Impact, and Environmental Equity.

Signed on February 16th, 1994, Executive Order 12898 officially recognized EJ on a federal level, directing agencies to focus attention on the environmental and human health effects of federal actions on minority and low-income populations (USEPA 2020b). Further executive action has been seen recently with the signing of Executive Order 13990, on January 20, 2021, which established White House and Inter-Agency Environmental Justice Councils, as well as the Justice40 Initiative for federal identification and investment in disadvantaged communities (Federal Register, 2021). Another milestone was met when New Jersey became the first state in the nation to adopt legislation on permitting requirements based on EJ. Signed on September 18, 2020, Senate Bill 232 requires the New Jersey Department of Environmental Protection "to evaluate the environmental and public health impacts of certain facilities on overburdened communities when reviewing certain permit applications." (O'Connor, 2020).

ITRC will continue to develop reference material for project managers and environmental professionals to consider in the use of current and future ITRC guidance materials in environmental decision-making and project design. ITRC will include the principals of EJ in future environmental products – working towards our mission while paying express attention to our core values of diversity, equity, inclusion and transparency. ITRC is excited to be a part of addressing environmental justice and bringing more voices to addressing the national and local environmental challenges.

ITRC Organizational Diversity, Equity & Inclusion

Diversity, equity, inclusion and transparency are embodied within the core values of ITRC. They are fulfilled in the pursuit of ITRC's mission and vision. ITRC's Membership Code of Conduct requires every member to benefit from team consensus and collaboration. ITRC requires diverse perspectives that provide the knowledge and skills to address all environmental challenges in pursuit of developing innovative products.

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