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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 fluids into 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 waters are 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.

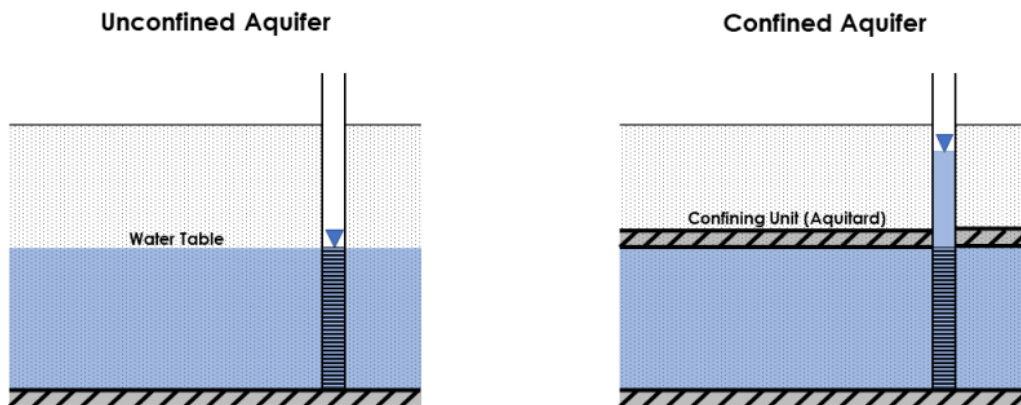


Figure 3-1. Conceptual illustration of unconfined and confined aquifers.

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

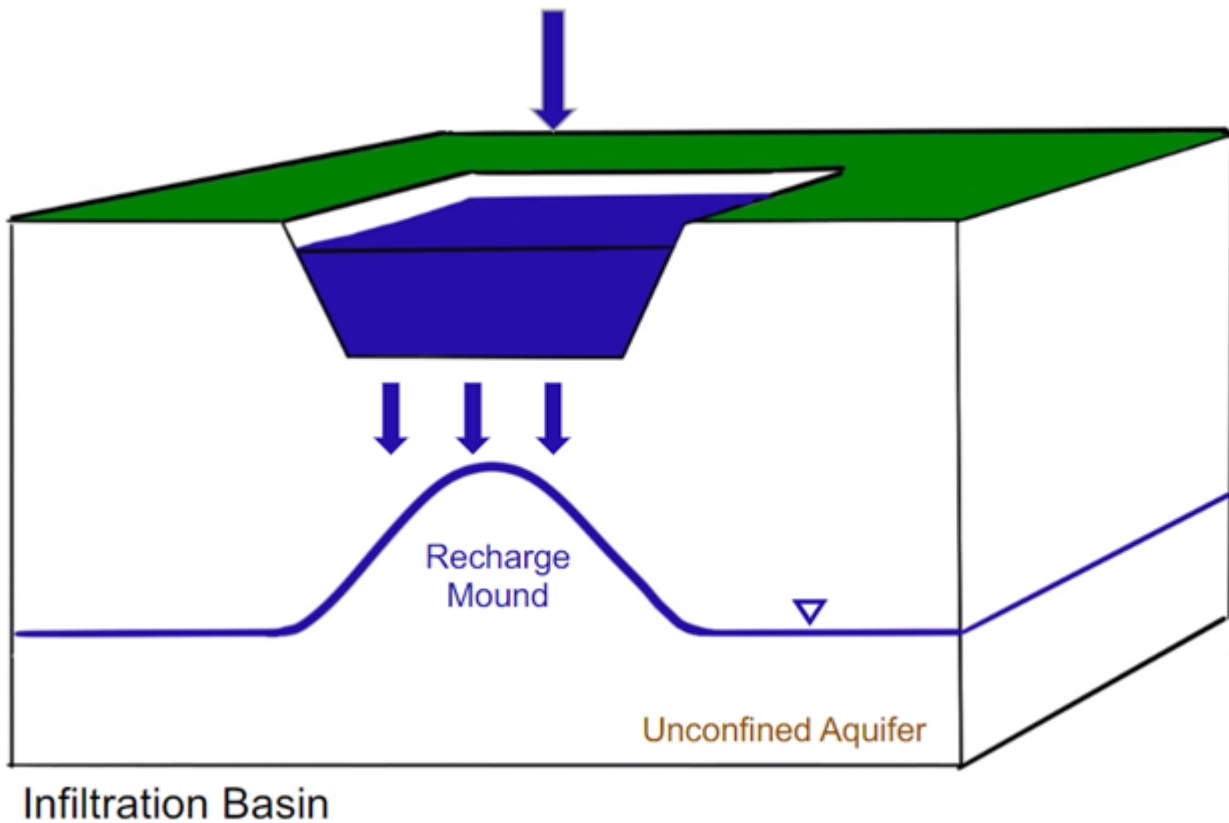
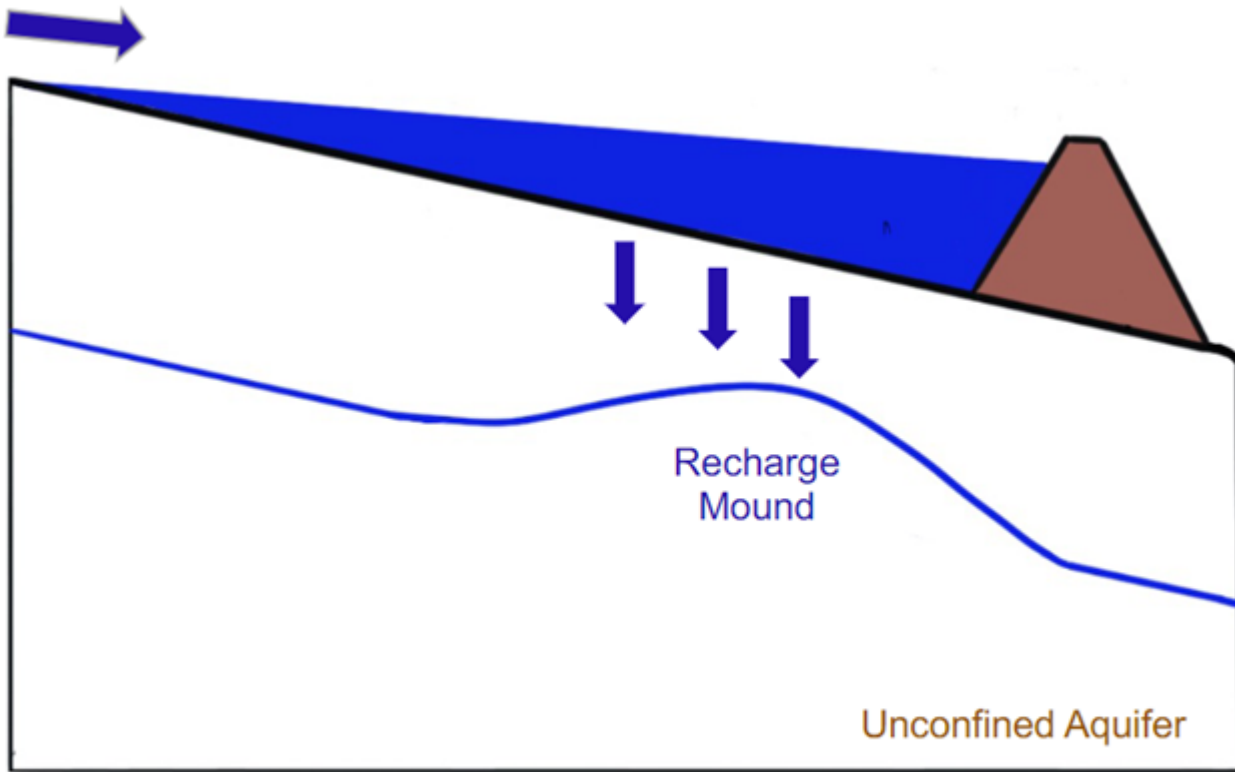


Figure 3-2. Infiltration Basin

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



Retention Structure

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

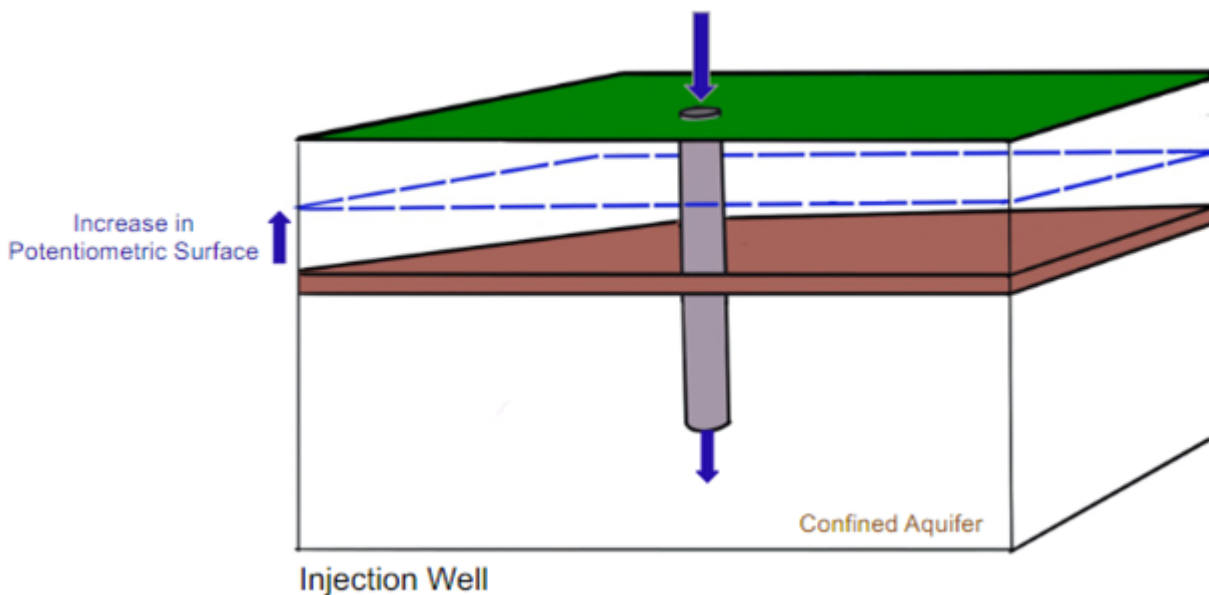


Figure 3-4. Injection Well

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

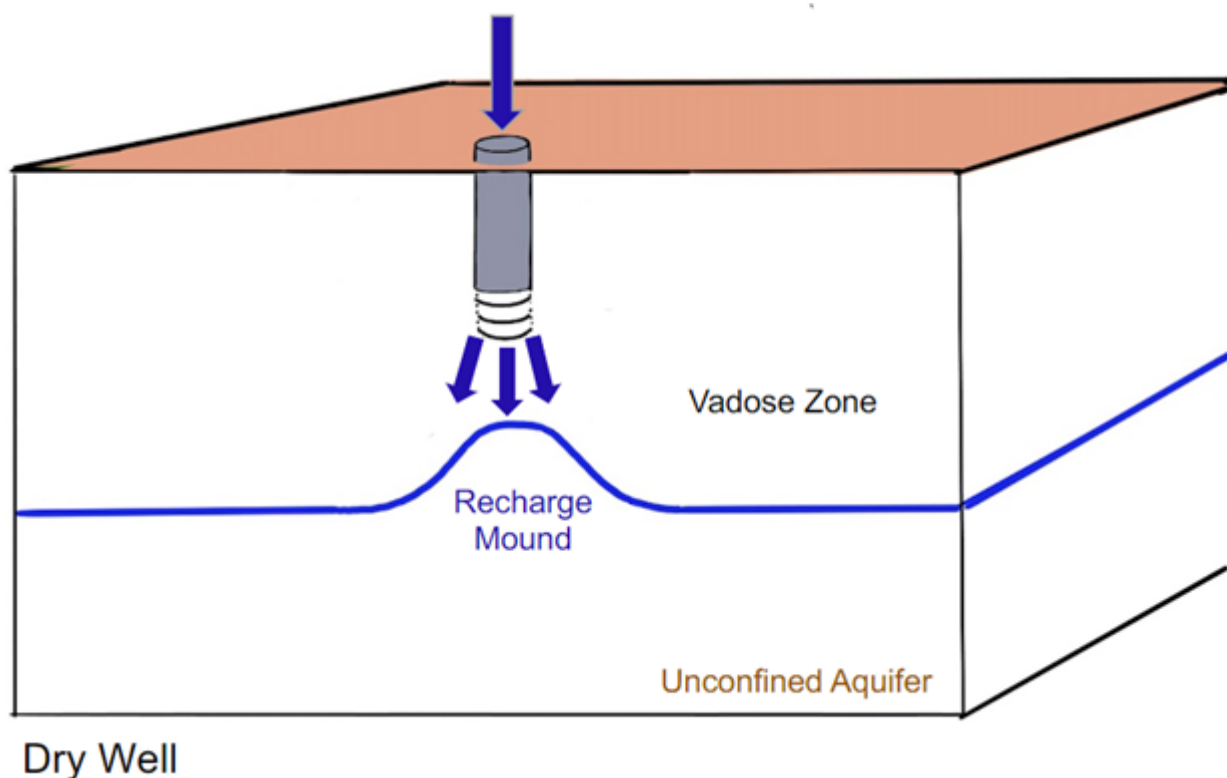


Figure 3-5. Dry Well

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

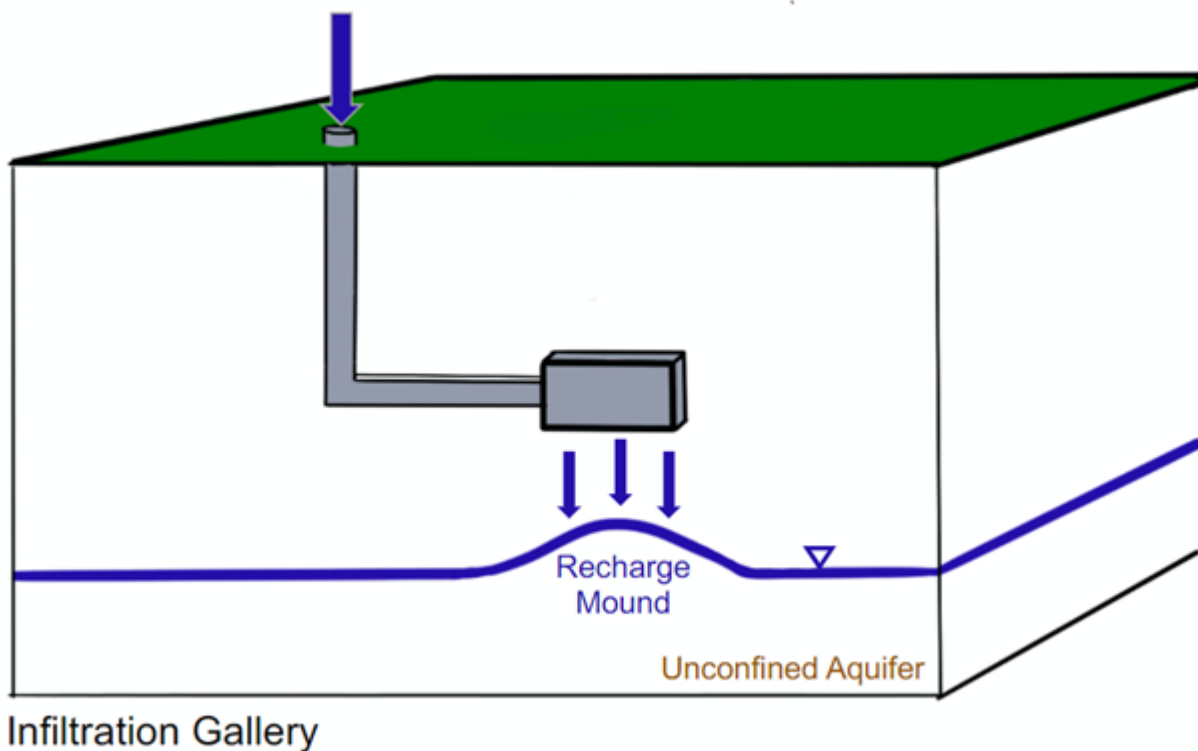


Figure 3-6. Infiltration Gallery

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:

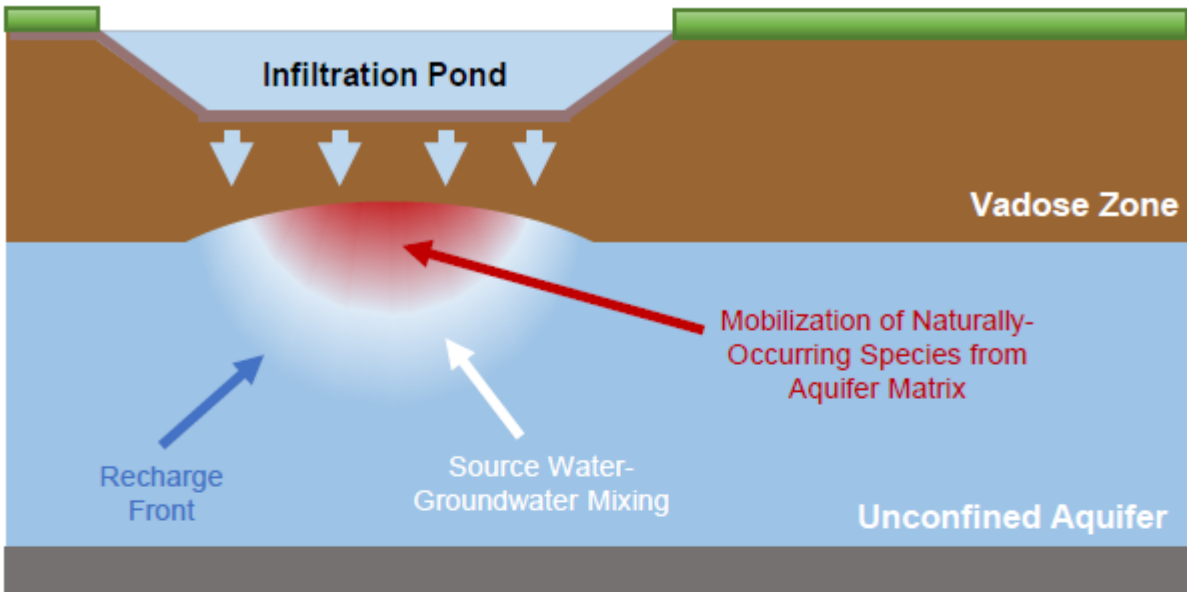
- The types of geochemical reactions that may occur during MAR are discussed in [Section 3.5.2.1](#). These geochemical reactions may include processes such as biodegradation, ion exchange, formation of complex ions, redox reactions, acid-base reactions, sorption, and/or mineral precipitation and dissolution ([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.

A. Surface Recharge



B. Subsurface Recharge

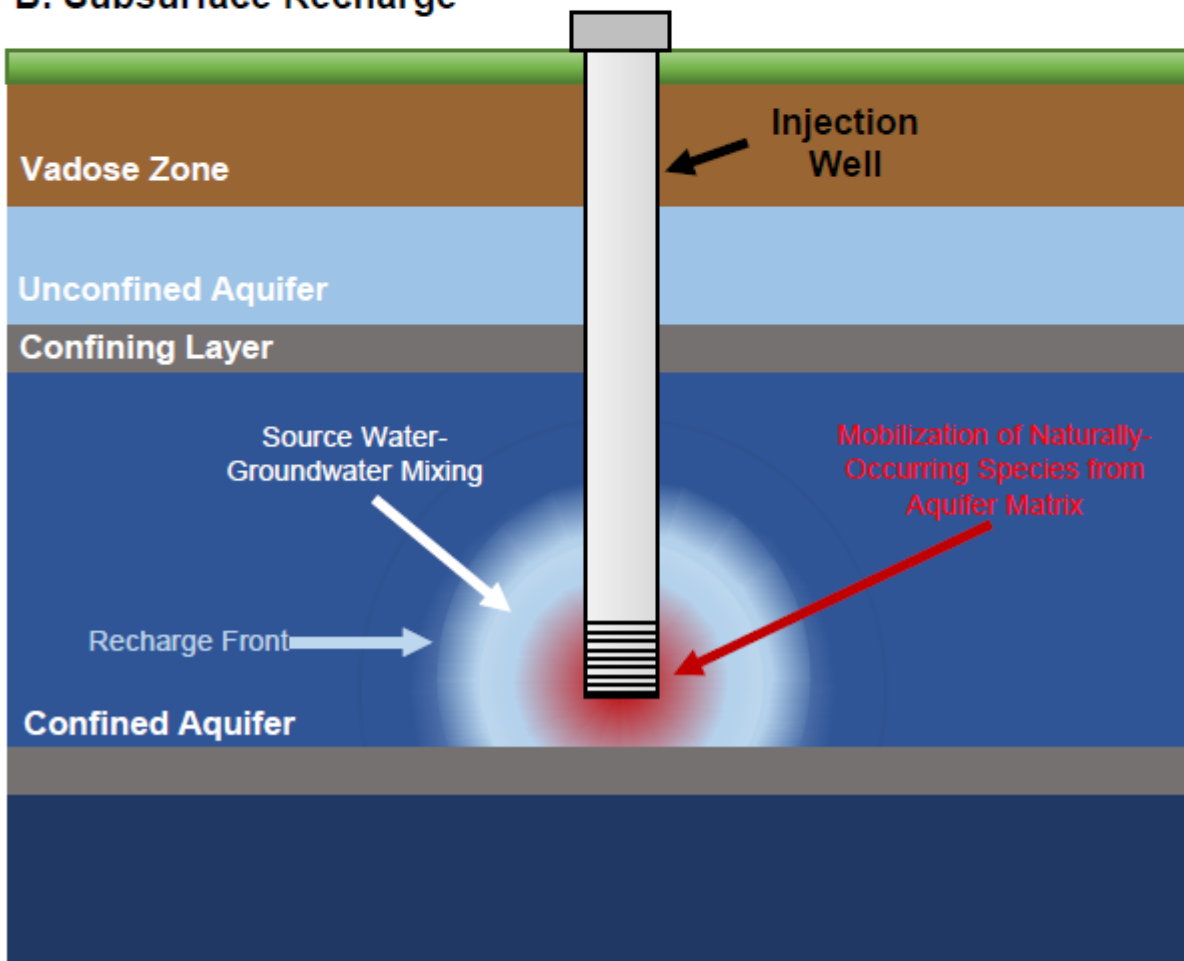


Figure 3-7. Geochemical reactions and recharge fronts.

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).

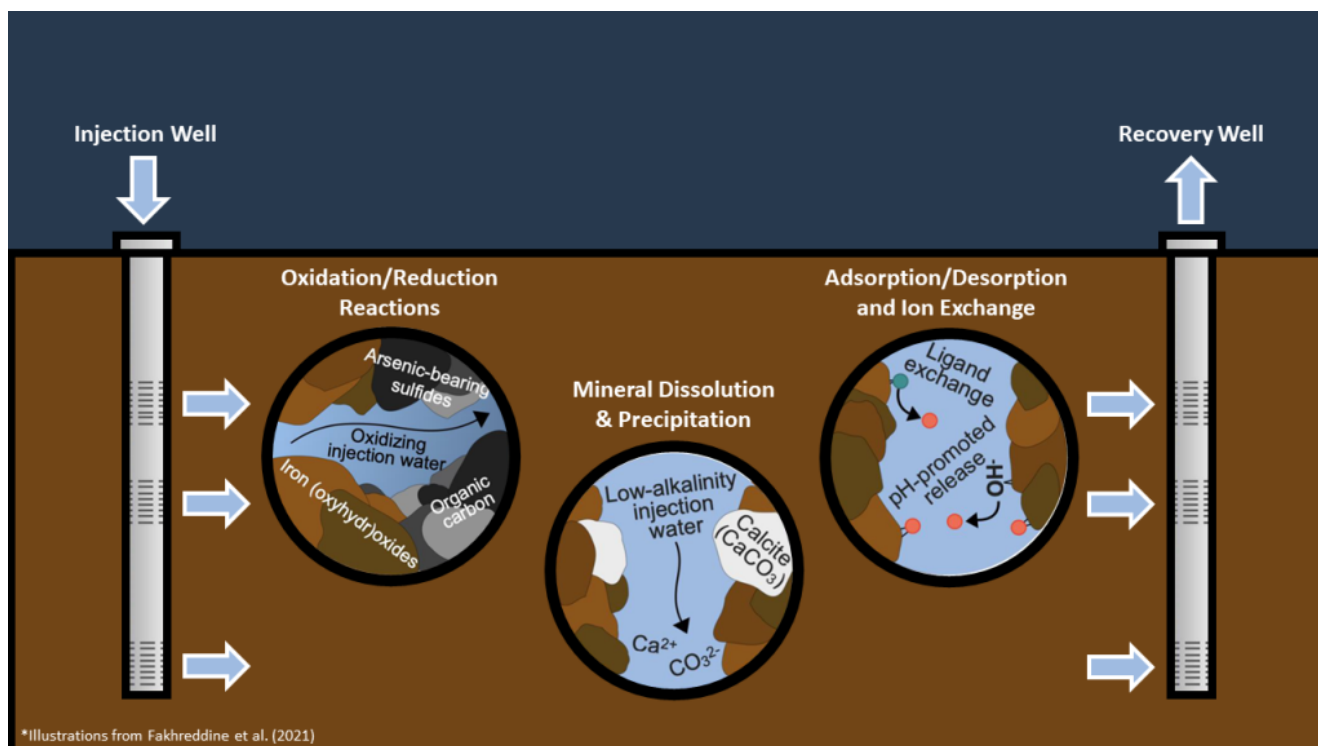


Figure 3-8. Geochemical reactions that may occur during MAR.

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.

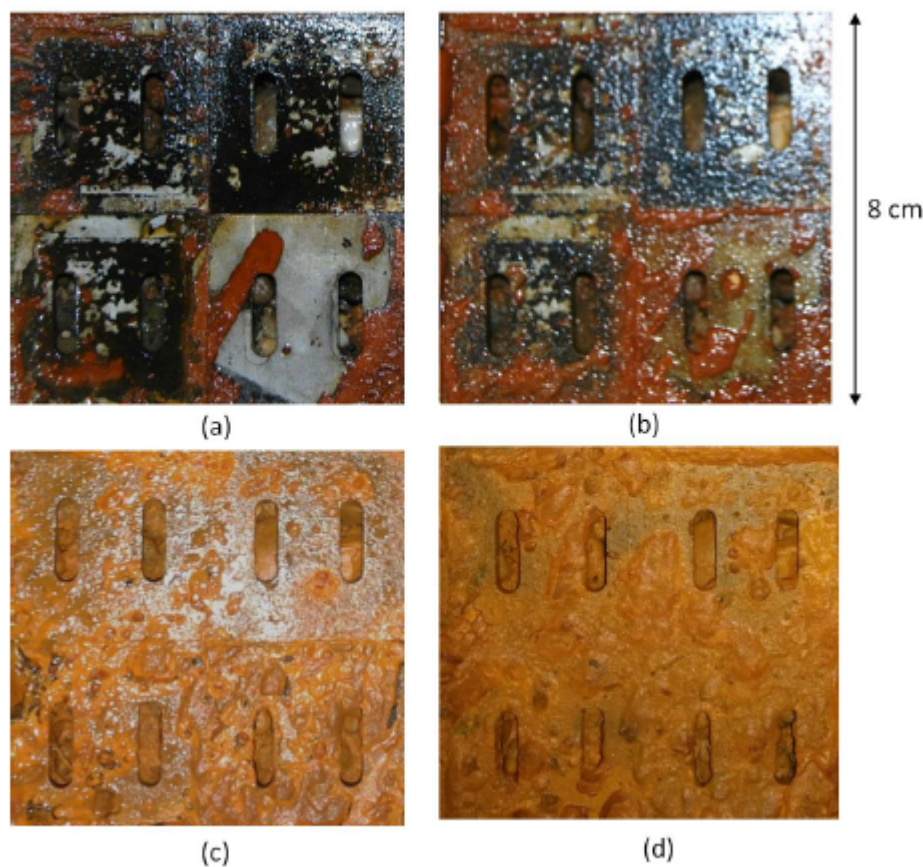


Figure 3-9. Example of well screen clogging after (a) 1, (b) 20, (c) 29, and (d) 73 days.

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 mineralogy	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.