Surface Infiltration Best Suggested Practice

Disclaimers

There are many detailed technical resources on Managed Aquifer Recharge (MAR) methods and practices. These Best Suggested Practices are neither intended to replace the use of industry standard practices, nor to substitute for the services of consulting hydrogeologists and engineers. Local regulations may in fact require the oversight of a qualified professional.

These Best Suggested Practices are provided for general informational purposes and are not intended to constitute engineering, hydrogeological, legal, regulatory, or other professional advice. Users are responsible for determining and complying with all laws, regulations, permits, standards, and other requirements applicable to their particular project and location.

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DEDICATION of this Best Suggested Practice for Surface Infiltration to GARY BURCHARD: This National Ground Water Association Best Suggested Practice for Surface Infiltration is dedicated to Gary Burchard who passed away suddenly in 2025 after an illness. Gary was an enthusiastic participant in NGWA. He actively contributed to and drafted significant sections of this BSP in the best professional manner just prior to his death. We thank him for his example of perseverance and willingness to promote wise groundwater use and protection right up to the end of his life.

1.0 Introduction

Managed aquifer recharge (MAR) is the purposeful recharge of water to aquifers for subsequent recovery or for environmental benefit (NGWA 2025). MAR is an effective water management strategy when compared to water storage in surface reservoirs because it can be implemented in stages, reduces evaporative losses, often has a smaller area affected, provides a level of water quality treatment, rejuvenates aquifer supplies, and can support streamflow and riparian habitat.

The term surface infiltration (surface MAR) as used in this document encompasses a broad range of surface and near-surface MAR approaches. Included among these are recharge basins, ponds, pits, trenches, constructed wetlands, bank filtration, and surface MAR enhancement methods such as drywells. This document serves as the NGWA Best Suggested Practices (BSPs) for these approaches. NGWA has prepared a separate BSP for Aquifer Storage and Recovery using wells (NGWA 2024).

Surface MAR constitutes the majority of managed aquifer recharge, by volume, that occurs in the USA, and the majority of surface MAR occurs in unconsolidated sedimentary basin aquifers. Surface MAR consists of infiltrating water into the unsaturated (vadose) zone. The water percolates downward under the force of gravity

and recharges unconfined aquifer systems that are commonly comprised of unconsolidated basin fill deposits. Bedrock aquifers are not typically considered for surface MAR; however, localized areas where bedrock outcrops at the surface may act as natural recharge zones if the bedrock is highly fractured or porous and thus directing surface water to these areas will enhance recharge rates. The successful application of surface MAR depends on identifying high permeability sediments or fracture zones, with sufficient vadose zone storage, to achieve project objectives.

1.1 Purpose/ Objectives of Surface MAR

Surface MAR objectives and needs can be broadly classified into:

- **Water Supply.** In the more arid western USA, MAR supplements surface water storage and provides water supply reliability during times of drought, reduction of surface water supplies, or meeting water rights requirements. In the eastern USA, MAR typically supports summer peak demands.
- **Aquifer Augmentation/Restoration.** MAR goals may reduce or prevent declining water levels, reduce subsidence, and/or improve water quality (e.g., saltwater intrusion prevention or dilution).
- **Stormwater Capture and Control.** Stormwater basins and use of drywells can reduce flooding impacts, while recharging local groundwater systems.
- **Habitat Support.** Surface MAR can raise groundwater levels and increase baseflow to sustain stream-flows and augment wetland or riparian habitat systems, including cooler summer temperatures for aquatic life.
- **Recreation.** Surface MAR systems may provide basins and water features supporting recreation (i.e., fishing) and urban park systems.

1.2 Overview of Surface MAR Methods

Surface MAR methods reviewed in this BSP include:

- Surface spreading basins
- Stormwater capture and recharge systems
- Riverbed/riverbank filtration (induced recharge)
- Flood-MAR/On-farm recharge
- Surface MAR enhancement methods: gravity drains, drywells, reverse tile drains, infiltration galleries, wick drains.

Bouwer (2002) includes a comprehensive review of managed aquifer recharge and pertinent issues related to its design and implementation. In most sedimentary basins, the vadose zone consists of inter-bedded layers of sand, silts, and clays that are the result of the basin's depositional history. The lateral extent and vertical inter-connectivity of the various sedimentary layers ultimately determine the hydraulic characteristics of the vadose zone.

Successful surface MAR facilities require sufficiently permeable surface sediments and interconnected vadose zone sediments, with sufficient available vadose zone storage without confining lithologic units. Saturated sediments must also be sufficiently transmissive such that infiltrated water can flow laterally away from the recharge area and the sediments should also be free of contaminants that could degrade the water quality in the receiving aquifer. If these conditions do not exist, or where land acquisition is cost prohibitive, recharge wells completed in an underlying aquifer may be a better alternative.

Surface Spreading Basins

The use of surface spreading basins to infiltrate water is the most common surface MAR approach (see Figure 1). Characteristics and conditions for this approach include:

- Near-surface soils sufficiently permeable to permit percolation of surface water
- Sources may be treated or untreated water from streams, stormwater, or treated wastewater

- Design requires careful consideration of water quality, sediment and supply, soil permeability and water table depth
- Shallow low-permeability soils may be excavated for more favorable recharge
- Appropriately designed basin infiltration rates can exceed 2 feet/day with minimal evaporative loss.

As with all MAR methods, excessive clogging of surface soils can be minimized by using high quality water or pre-treating to remove excess suspended solids, nutrients, and organic carbon. Conditions contributing to clogging include:

- Deposition of suspended sediments in the water
- By growth of algae or biofilms at the soil surface
- By entrapment of gases within the soil pores limiting the downward movement of water (Bouwer 2002).

Approaches to respond to clogging are:

- If considerable suspended solids are present in the source water, pre-sedimentation basins can remove sediment.
- Riverbank or Riverbed Filtration (RBF) systems can also be a viable pre-treatment option prior to recharge in spreading basins (Hutchinson et al. 2017; Keller et al. 2019).
- A review of clogging phenomena and methods to control clogging in off-channel systems are provided in Hutchinson et al. (2013).

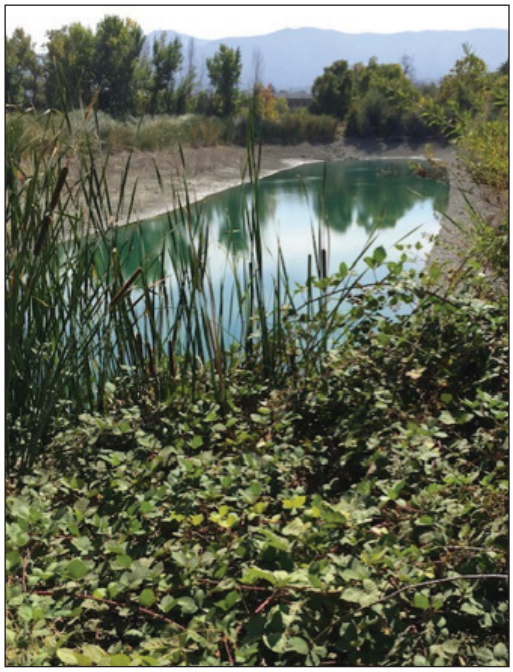


Figure 1. Surface infiltration pond, Santa Clara, California.

Stormwater Capture and Recharge Systems

The use of small detention and check dams and flood control structures in streambeds, with subsequent release of captured stormwater to increase natural recharge rates, has a long history in many regions (Dillon et al. 2018). Projects for stormwater used in aquifer recharge in the western USA and stormwater infiltration disposal to protect surface water quality in the eastern USA use the same engineering and design approaches.

Surface water capture and recharge systems can be divided into both in-channel and off-channel systems.

In-channel systems consist of weirs, dams, and levees that:

- Slow down the movement of water and increase the wetted area
- Increase infiltration into streambeds or floodplains
- Off-channel stormwater systems
- Capture and recharge systems that divert surface water into surface spreading basins or to recharge enhancement features (i.e., drywells)
- Were shown in a recent review of streambed structures to have infiltration rates one to two orders of magnitude greater than for in-channel structures as off-channel systems can control water quality and flow (Dillon et al. 2018)
- Are exemplified by the approximately 150,000 acre-feet/year of surface water diverted from the Santa Ana River to recharge into Orange County Water Districts MAR basins (Hutchinson et al. 2017).

Urban Enhanced Runoff

Urban enhanced runoff (UER) refers to increased stormwater runoff from impervious surfaces such as rooftops and paved areas and can be captured for recharge using a variety of approaches. Implementation of UER should include consideration of:

- The amount of UER-based recharge depends on the local climate and the proximity to the impervious surface.
- Local stormwater capture from rooftop rainwater harvesting systems can recharge significantly higher proportions of UER than local or regional detention basins that capture runoff from larger watershed areas (Pima County 2009).
- UER capture and subsequent MAR have been predicted to increase recharge rates in semi-arid areas by an order of magnitude or greater, i.e., less than 1% to 10% of average annual precipitation (Su et al. 2025; Milczarek et al. 2005; Stephens et al. 2011).

Riverbank/Riverbed Filtration

Riverbank and Riverbed Filtration (RBF) is a method to improve surface water quality through soil-aquifer treatment (SAT) via percolation through sediments in streambeds and riverbanks and subsequent groundwater extraction (Ray et al. 2003). RBF occurs when a downward gradient exists between the surface water level and groundwater extraction location. RBF has been used extensively in Europe since the 1800s (Dillon et al. 2018) and after World War II in the USA (Ray 2003). Factors include that RBF:

- Can be a natural process, such as in lowland rivers or during high river stages
- Can be an induced process, caused by lowering of the groundwater table by nearby groundwater extraction
- Is a useful method for replenishing groundwater, because it results in removal/reduction of suspended and colloidal solids, and reduces bacteria, viruses, and organic and inorganic compounds (Dillon et al. 2018; Ray 2008; Hiscock and Grischek 2002; Tufenkji et al. 2002)
- Is commonly used for pre-treatment of surface water prior to pumping and recovery for public water supplies.

As an example, the Orange County Water District (CA) has conducted pilot and demonstration projects to evaluate RBF as a method to remove sediment and nutrients prior to surface MAR via basins (Hutchinson et al. 2017; OCWD 2024). A system of shallow drains was constructed below a riverbed channel adjacent to the Santa Ana River to induce and capture infiltration. The system is highly effective for removal of suspended solids and nutrients and inducing channel recharge rates of up to 2.5 feet per day (Hutchinson et al. 2017). Other investigations are testing whether RBF can be used to pre-treat water prior to aquifer storage and recovery (ASR) well injection (i.e., Keller et al. 2019).

Flood-MAR

Flood-MAR is the practice of diverting floodwater resulting from snowmelt or rainfall for managed aquifer recharge on agricultural and other landscapes such as refuges, floodplains, and flood bypasses. The State of California is currently encouraging the implementation of Flood-MAR on multiple scales, from individual landowners utilizing existing infrastructure to flood agricultural fields, to modernizing flood protection infrastructure and operations to use extensive detention/recharge areas (State of CA 2018). Fallow farm fields or certain permanent crops are flooded when water supply is abundant to increase groundwater recharge and replenish aquifers. To date, crops that have been evaluated and appear to tolerate long-term submergence of floodwaters (up to three months) include grapes, almonds, and pistachios (Bachand et al. 2016). It is likely that walnut and pecan groves are also candidates for Flood-MAR.

Successful conjunctive use projects currently underway in California include the McMullin On-Farm Flood Capture and Recharge Project in Kings Basin (20,000 acres of on-farm flood capacity; Bachand et al. 2015, 2016). Recent surveys in California estimate that up to 500,000 acre-feet were recharged using Flood-MAR methods in 2023 (PPIC 2024).

Surface MAR Enhancement Methods

If surface soils are not permeable enough to infiltrate suitable quantities of water, or insufficient land is available for infiltration basins, then recharge enhancement features can be utilized to direct water to highly permeable layers within the vadose zone.

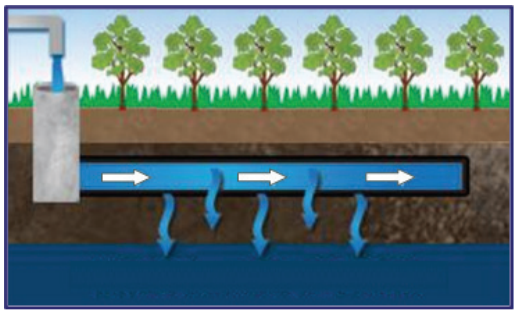


Figure 2. Infiltration gallery diagram.

Drywells. Drywells are a common urban solution for capturing and infiltrating stormwater into highly permeable subsurface layers within the vadose zone. Each state has its own set of requirements and design standards, but in practice, drywells are generally limited to be no closer than 10 feet above the groundwater table and are prohibited in areas that store potential groundwater contaminants (i.e., gas stations, industrial areas) unless secondary containment is provided for those facilities. Towns in the eastern USA typically use less land for stormwater management and may utilize a system of drywells for stormwater capture and infiltration. If this approach is taken, an Underground

Injection Control (UIC) Class V shallow well permit may be required.

Typical drywell dimensions are up to 4 feet in diameter and 20 to 50 feet deep. Dual-chamber drywell designs include a primary settling chamber or pre-treatment device with injection piping routed into a secondary drywell chamber to reduce the sediment load and extend drywell lifetime (Graf 2010). Pre-treatment methods in urban environments include petrochemical sponges to sorb pavement oils and interceptors to trap debris. Most work to date (i.e., Edwards et al. 2016) and indicates that the vadose zone effectively treats contaminants recharged by drywells, although limited data exists on emerging contaminants (Geosyntec 2020).

Infiltration Galleries. At locations where restrictive low permeability soils are shallow (i.e., less than 15 feet deep), infiltration galleries, or trenches, can also be constructed by excavating a trench, typically less than about 1 meter wide and 5 meters deep. Trenches are backfilled with sand or gravel to promote rapid downward movement of water to the infiltrating layer. Infiltration galleries can be constructed with a perforated pipeline to apply water on the surface, or placed in a channel or conveyance to capture water as it flows along the soil surface (Bouwer 2002). (See Figure 2.) A UIC Class V permit may be required in some states.

Reverse Tile Drains. Reverse tile drains are a form of infiltration galleries; tile drain trenchers are used to trench and place perforated pipe at depths of 8 to 12 feet with subsequent backfill with gravel around the pipe followed by trenched soils. As of 2024, at least 20 reverse tile drain systems had been installed in California (LIDCO 2024).

Vadose Zone Injection Wells. Vadose zone injection wells are a low-cost alternative to ASR wells in areas with sufficiently deep vadose zones and have been demonstrated to function for long operational periods. Similar in design to drywells (i.e., large-diameter boreholes), vadose zone injection wells work via gravity infiltration. As an example, since 1996 the City of Scottsdale (AZ) has recharged approximately 5,000 acre-feet/year of advanced treated wastewater into 180-foot-deep vadose zone recharge wells which are screened from 90 to 170 ft bgs. Over time, losses in well performance have occurred, but can be controlled by periodic shutdown and reducing injection rates (Gastelum et al. 2009).

The use of vadose zone injection wells is appropriate for highly treated water in areas with extensive low permeability sediments at the surface, or where land costs are prohibitive. States may require a UIC Class V permit for installation of vadose zone injection wells.

Surface infiltration MAR enhancement technologies are advantageous because they are relatively inexpensive; however, as with all recharge projects, clogging is an issue. Ideally, water should be pre-treated prior to use for recharge, as infiltration galleries and most drywells cannot be pumped or flushed to remove a clogging layer. Infiltration galleries should be designed with geotextile filter fabric, or sand filters above the backfill, but these

need maintenance to maintain infiltration capacity at the surface. Likewise, surface water should be pre-treated with sand filtration prior to recharge into reverse tile drains. Ultimately, it is an economic decision between pre-treating water, screening out sediment to extend the life of the recharge feature, or constructing new ones once clogging occurs (Bouwer 2002).

Benefits of Soil-Aquifer Treatment. Water recharged by all of these methods may benefit from soil-aquifer treatment (SAT). The SAT process results in nutrient and pathogen reduction as recharged water is percolated through the unsaturated zone and to a lesser extent as it travels through the aquifer, prior to well recovery (NGWA 2025). SAT is a cost-effective, sustainable means of removing pathogens and reducing nitrogen, dissolved organic matter, and many organic micropollutants while recharging groundwater. Efficiency of contaminant removal is subject to source water quality, subsurface properties, and management measures used. Appropriate site selection and design and pre-treatment of source water can improve performance of SAT to support MAR for future use (Sharma and Kennedy 2016).

2.0 Planning, Phased Implementation, and Project Scaling

As with many complex projects, planning and phased implementation of MAR investigations and design work is the best approach to achieving a successful project. The planning phase should include an initial screening study to identify project objectives, recharge water availability and quality, potential MAR sites and site suitability, potential environmental impacts, and infrastructure requirements. The planning phase should also include consultation with regulatory agencies and review of nearby MAR facilities, if present. States may require issuance of UIC Class V permits for drywells, vadose zone injection wells, and infiltration galleries.

The next step is to conduct a feasibility study at the site or sites being considered based on the screening study results. The feasibility study usually involves field investigations. These may include characterizing the near-surface infiltration rates and hydrogeology of the target recharge zones, evaluating chemical interactions between recharge water and native groundwater, estimates of groundwater mounding, and conceptual-level design of the MAR infrastructure.

The screening- and feasibility-level studies both require data to be collected and analyzed, with more detailed data needed for the feasibility-level study. Information gained from these studies is used in the design of the MAR system. The following sections describe these project components. More detail on the planning phase of surface MAR projects is provided in ASCE (2020) and in McCurry and Pyne (2022).

2.1 Screening Study

Screening studies usually consist of developing project objectives and assembling existing information, but do not involve field investigations. Improving water supply is a common objective for surface MAR projects, but project objectives can include diverse items such as providing additional water treatment, increasing baseflow to streams, protecting and enhancing groundwater-dependent ecosystems, or managing seawater intrusion or other salinity-related issues. The project objectives should define the data quality objectives, data collection activities, and evaluation of potential recharge sites. Examples of screening level study approaches include McCurry and Pyne (2022), Kazakis (2018), Russo et al. (2014), and O'Geen et al. (2015).

Screening-levels studies should compile and analyze available data to assess:

1) Quantity and temporal availability of water to be recharged to gain a general understanding of the infrastructure needed
2) Land availability proximal to the source location
3) Site hydrogeology suitability
4) Potential water quality interactions and treatment requirements 5) Engineering and implementation constraints.

Water availability includes when and how much water will be available, both physically and legally. The legal availability of water is a significant issue in the arid western USA where each state has specific water rights law. If

other MAR systems sites are proximal to the area, their design, operations, and performance should be evaluated closely to determine aspects that have worked well and aspects that could provide valuable insights for improvement.

During the MAR screening phase it is helpful to follow a multi-criteria decision-making (MCDM) process to determine if a given site or project should move into the feasibility study phase. The screening phase can be thought of as a fatal flaw analysis or viability assessment (NRMMC 2009). In most cases this would include whether sufficient water is available and reasonably close to the potential recharge site; whether site conditions are suitable for infiltration, storage, and recovery of the recharged water; and whether there are water quality or regulatory limitations. A negative answer to any of these might eliminate a potential site.

Screening-level criteria such as basin recharge rates, aquifer storage capacity, likely treatment requirements, ease of site access, and cost to implement can be defined in numeric terms as part of a site scoring process to determine how well a potential recharge site meets a given criterion, with the higher score meaning a better match (i.e., McCurry and Pyne 2022). Each of the criteria is assigned a score for each potential project site, with the total score being an objective measure of how well a site meets the objectives of the project. A MCDM approach like this is helpful in comparing potential sites and more easily conveying the results to managers, regulators, and the public. Examples of site scoring are presented in McCurry and Pyne (2022), Kazakis (2018), and Russo et al. (2014).

Additionally, the 2020 Supreme Court decision in *County of Maui, Hawaii v. Hawaii Wildlife Fund* (No. 18-260) held that certain discharges of pollutants through groundwater may require a Clean Water Act permit when the discharge is the functional equivalent of a direct discharge from a point source to navigable waters. Accordingly, where a surface MAR project involves recharge water containing pollutants and there is a potential hydrologic connection to jurisdictional surface waters, project proponents should evaluate whether the Clean Water Act or other federal, state, or local requirements may apply. Such evaluation may include consideration of aquifer transport and other site-specific factors relevant to the movement of pollutants from the MAR site.

The screening study reduces the number of potential recharge sites down to a smaller number and helps to identify data gaps and issues that warrant further evaluation. The data compiled during the screening phase and the process used to evaluate and eliminate potential sites should be combined with the feasibility study phase.

2.2 Feasibility Study

Surface MAR feasibility studies should include field investigations to address data gaps identified in the screening study to meet project objectives and may need to be undertaken at multiple sites if they all pass the screening phase. The purpose of the field investigations is to collect site-specific data that will help address criteria such as: the likely infiltration rates; the depth to groundwater; the storage volume in the vadose zone; the potential for water perching above shallow lower-permeability layers; the rate of groundwater mounding and recharge water movement away from the site; and potential geochemical reactions between recharged water, the vadose zone, and native groundwater.

Site-specific investigations to addressing these issues is best accomplished through a two-phased approach: a Phase 1 near-surface investigation to identify limitations to infiltration and a Phase 2 deeper subsurface investigation to identify deeper low permeability layers that could impede recharge or recovery (Milczarek et al. 2003).

The first phase typically consists of excavating test pits and conducting geologic logging and infiltration testing to classify sediment layering and potential infiltration rates at the near-surface. This phase is used to remove sites from consideration that have low permeability layers that cannot be economically removed, prior to spending money on deeper, more costly investigations. If the near-surface infiltration rates meet the project objectives and depending on the size of the project, the second phase may require borehole drilling and geologic logging and collection of samples for physical, hydraulic, and geochemical testing. This second phase is used to characterize the vadose zone and identify any deeper subsurface layers that could impede recharge. Monitor wells may be installed at selected locations to allow groundwater level monitoring and aquifer testing. In addition, vadose

zone wells and hydraulic properties can be tested if there are concerns about thick low permeability layers (Milczarek et al. 2003).

Field data should be used to estimate the vadose zone and aquifer hydraulic properties; predict potential mounding of the recharged water; and identify operational constraints such as the potential for clogging from the source water and geochemical compatibility between the source water, vadose zone, and native groundwater. These analyses are needed to predict the potential recharge rates and storage capacity of the recharge project, potential operational limitations to clogging and/or unwanted geochemical interactions, and the potential for groundwater mounding to adversely affect operations or nearby groundwater users (i.e., domestic wells or groundwater remediation operations). Ultimately some level of either analytical or numerical groundwater modeling will be needed to assess the regional groundwater elevation rise and localized groundwater mounding that may affect nearby stakeholders.

The results of the initial data analyses may lead to more field investigations and analyses to address specific data gaps. Other investigations that might be undertaken during the feasibility study phase include developing a better understanding of infrastructure, such as piping, re-grading and basin design, and both pre- and post-treatment requirements to identify cost estimates.

Results of the feasibility study should be documented to provide details on the field investigation methods, the data analyses, and their results and identify items necessary for permitting. Those involved in the feasibility study should interact with the design team to provide guidance to the project design.

2.3 Early Consultation with Regulatory Agencies

Early consultation with state and local regulatory agencies will provide direction on the critical objectives needed for design, construction, and operational permit approvals. Each state's requirements must be checked as they vary from state to state. Nearly all aspects of proposed MAR projects have a regulated component, including water rights and source, design, construction, pre-treatment, storage, recovery, and subsequent treatment, if needed. These consultations can also answer key questions about location, MAR system design, water source and quality, timing of activities, required information for permits, and changes made in any regulatory conditions.

Regulatory guidance provides focus for design, improves the efficiency of project development, and contributes to minimizing cost by providing objectives that receive public review. Such regulatory agency consultation may occur prior to, during, or following preparation of a conceptual project and the screening or feasibility studies. State-specific MAR regulations continue to evolve, largely due to continuously changing water quality requirements, and are different in each state.

If drywells are part of the infiltration system, achieving an early understanding of current regulatory procedures, requirements, and preferences pertaining to surface infiltration basin implementation is important. However, in some cases it may be more effective to complete all or most of the feasibility study prior to the initial regulatory agency meeting in anticipation of questions from the regulatory agency.

2.4 Recharge Project Design Considerations

Early in the design process the design objectives of the MAR facility as well as the design criteria and constraints should be identified. The MAR guidelines published by the American Society of Civil Engineers (2020) state that the primary design objective of MAR facilities is to optimize the cost per unit volume of recharge, storage, and recovery over time. Design criteria, which are the capabilities the system should achieve once operating, will differ for each project. Likely criteria include those related to the performance of the surface infiltration method such as the system's ability to increase or maintain water stored in aquifers while meeting regulatory requirements. The area available for the surface MAR system may be a design constraint. Other design constraints may relate to the location of the source of recharge water, and subsequent pipeline costs/feasibility, or the quality of the water. Recharge water high in suspended solids, such as stormwater, may require pre-treatment prior

to recharge.

As in any infrastructure design, the design process for surface MAR systems progresses through phases of conceptual, preliminary, and final design, concluding with a set of Issued for Construction plans and specifications that will be used to bid the project for construction. Typical components of the MAR system that need to be addressed in the design include berm configuration, spillways, pipelines, pre-treatment systems, electrical power lines, flow measurement devices, erosion protection for flow inlet structures and basin's berms, basin elevation monitoring, and groundwater monitoring systems.



Figure 3. Surface infiltration pond near Palm Springs, California.

Groundwater monitoring is a critical component of the operation of a MAR system and is the most direct means to assess an aquifer's response to recharge. The American Society of Civil Engineers (2020) discusses the need for nested monitoring wells located near recharge basins for gradient evaluation and for measurement of rising water tables in sensitive areas. In particular, the development of a groundwater mound that rises to the bottom of a basin will reduce recharge rates and basin performance. Monitoring wells are also required for groundwater quality assessment in response to aquifer recharge. ASTM Standard D5092 provides detailed guidelines for groundwater monitoring design as well as installation.

If there is a high level of uncertainty in design variables such as long-term recharge rates and groundwater response, a pilot project may be warranted. The decision to conduct a pilot test should be made early in the design process. Bouwer (2002) provides reasons such as seasonal changes in infiltration rates due to slower drying and infiltration recovery during winter periods, and bio-clogging in the summer months. ASCE (2020) provides further discussion on the scale and duration of pilot testing. Construction of a pilot test should be as large as possible to understand heterogeneities in subsurface properties, uncertainties in geochemical response to recharged water, and water table response (ASCE 2020).

However, if other MAR systems are operating in the general area of the planned system or there is a high level of subsurface characterization and uncertainty in the design parameters is minimal, a pilot study may not be necessary.

Irrespective of the project scale, grading sites for surface infiltration is one of the more costly aspects of a surface infiltration MAR project. Therefore, in the early phases of the design, consideration should be given to the siting and layout of surface infiltration basins to reduce the grading requirement, resulting in cost savings. Decisions on basin layout should also account for the possible need for service roads and for storage areas for scraped materials produced during basin maintenance. Finally, if deeper low permeability lithologic units are a concern for groundwater mounding, long and narrow basins can be designed to minimize the influence of mounding on adjacent basins (Bouwer 2002).

2.5 Regulatory and Permit Requirements

Federal Permit Requirements

Federal permitting requirements applicable to MAR projects may vary depending on the source of the recharge water, the design and operation of the facility, the location of the project, and other project-specific circumstances.

i. Water Source – No specific requirements for federal permits for water sources to recharge surface infiltration basins exist.
ii. Water Quality – Treated wastewater sent to a MAR facility is not addressed under the NPDES permit process for wastewater discharge.

Sinkholes and drywells used for recharge may be required to have an Underground Injection Control (UIC) permit if the recharge does not meet regulatory requirements.

State Permit Requirements

Some states may require multiple permits to operate an underground storage facility. Local requirements for MAR facilities may be site-specific.

i. Water Rights/Quantity/Source – Regardless of the water source (treated wastewater, recycled water, stormwater, or other water source), rights to the water source should be clear and documented. The state may require that rights to use the water for recharge are clear and other claims on the water cannot be made. For recovery of the water in storage, water users should have a clear and documented right to use the water stored in the ground when it is recovered. Working with the state early in the process of establishing a MAR facility to ensure that the source and use rights are approved, clear, and documented is essential.
ii. Water Quality – Underground Injection Control (UIC) regulations address the quality of fluid emplacement underground. These regulations may apply if the infiltration facility is: a hole whose depth is greater than the largest surface dimension; an improved sinkhole; or a subsurface fluid distribution system. Checking to see if the state has UIC program primacy is an important first step. If the state has primacy, it may include specific requirements and conditions for sinkholes and drywells in the UIC permit, including monitoring and reporting to be done on a continuing basis. The entity responsible for the MAR facility should contact their state on specific requirements. If the state does not have primacy, the UIC permit program is managed by the U.S. Environmental Protection Agency through the regional office for that state.

3. Water Quality Considerations

As discussed in previous sections, recharge water may be derived from a variety of sources. While the quality of water used in surface recharge applications may not be as critical as that used in ASR applications (see ASR guidance document), there are still important considerations for successful operation and recovery of recharged water. Water quality considerations that may be important include physical, chemical, and biological parameters or constituents and geochemical interactions that may occur between the recharge water and aquifer material.

For example, water with high total suspended solids (TSS) or sediment load may result in physical clogging of infiltration basins. Recharged water that is high in nutrients may promote near-surface biological growth resulting in bio-clogging and additional maintenance activities and costs. Additionally, recharged water can positively influence the water quality of a degraded aquifer (i.e., affected by historical agriculture), or could result in flushing of antecedent salts (i.e., nitrate) or the dissolution of oxyanions such as arsenic, selenium, and uranium from the aquifer material.

These potential considerations are by no means an exhaustive list related to recharged and recovered water quality concerns. Comprehensive review of water quality concerns and characterization and testing of recharge water/aquifer material interactions should be undertaken ensuring that the preliminary design investigation provides sufficient data for the subsequent phases of design and that appropriate measures are taken to address water quality for all managed aquifer recharge projects.

4. Operations and Maintenance

4.1 Operations

Surface MAR system performance is evaluated by monitoring water quality, basin water levels and ground-

water elevations, flow rates, and volumes during both the pilot phase and once the system is fully in use. Data obtained during pilot and/or operational phases will indicate how the system performs with respect to design, operational goals, and regulatory compliance. It also provides test-proven benchmarks to evaluate future operational performance.

Surface MAR systems should be evaluated continually as a whole and individual basins/components. Performance and changes in performance may inform the sequencing of basin usage (prioritizing better-performing basins) and degree and frequency of maintenance (see Section 4.2). Finally, information about groundwater elevation increases will reveal whether increased storage in the aquifer is affecting the MAR system performance or has negatively impacted any neighboring land or water users.

4.2 Maintenance

Surface MAR facility performance and conditions should be continually monitored. Performance and condition observations will dictate when maintenance is needed. Hutchinson et al. (2013) suggest that basins should be taken off-line for maintenance when the basin's infiltration rate has declined to approximately 30 percent of its initial rate. When planning maintenance activities, basins should be considered individually as variability in the soils and geology underlying the basins result in variable performance, and maintenance schedules and activities are resultingly customized.



The following are some of the more common basin-maintenance activities.

Drying

The most common activity, and always first activity, is the drying of the basin undergoing maintenance. Desiccation and cracking of the surficial clogging layer may be sufficient to restore infiltration rates. Additionally, if further activities are contemplated, then basins must be dried sufficiently for safe access and operation of equipment. Furthermore, thorough drying helps minimize compaction that may be caused by equipment operations.

Raking/Harrowing

At some point, simply drying the basins will not sufficiently restore infiltration rates and the surficial clogging layer must be physically broken up or removed. A spring-tooth harrow can be used to break up the surficial clogging layer without incorporating the clogging material deeper into the soil. Low-bearing pressure equipment should always be used (i.e., light tractor, small wide-tracked dozer) to minimize subsurface compaction.

Scraping and Ripping

Periodically, raking/harrowing will not sufficiently restore infiltration rates, and the entire clogging layer must be removed. Field inspection of the soil profile will indicate the thickness of the surficial layer that must be removed. Care must be taken to observe whether previous harrowing has penetrated finer material deeper into the profile. Scraping using dozers, graders, or scrapers may require the use of heavy equipment, and ripping to an adequate depth (i.e., 2-3 feet) should be completed afterwards to mitigate compaction of the surficial soil caused by the heavy equipment. Frequency of basin scraping will be driven by site-specific conditions. Many operators find that scraping and ripping on a five-year cycle is sufficient. If surface infiltration rates are not restored, deep ripping (5-6 feet) may be useful.

Vegetation Control

Vegetation that grows on the berms of basins may be allowed because it anchors finer-grained soils that may otherwise erode into the basins and add clogging potential. Vegetation, however, growing on the floor of basins may trap clogging material and hinder maintenance activities and should be periodically removed.

Sand Replenishment

If a sand filter is an integral part of the basin floor design, then its thickness should be monitored and the sand periodically replaced as needed.

Waste Disposal

Facility owners/operators should remember to make plans for disposal of soil and vegetation waste that is generated as part of perpetual, periodic maintenance activities.

Berm Repair

Integrity of basin berms should be periodically inspected and repaired as needed. Berm repairs should follow design specifications.

Maintenance of Measurement Devices

To provide accurate measurements of inflow into the basins, weirs and flumes should be periodically cleaned and flowmeters should be calibrated. Likewise, for the measurement of basin water levels, transducers should be periodically calibrated and staff gauges cleaned as needed.

Security

To reduce risk of contamination and vandalism, security measures such as fencing, gates, and locks should be periodically inspected and repaired as needed. Vegetation should be kept trimmed back from fences.

5. Monitoring

5.1. Background and Purposes of Monitoring

Monitoring is a key component of a surface MAR system and should focus on basin performance, water quality, and groundwater elevations. Monitoring programs should be based upon project-specific considerations, including the data for evaluating system performance, compliance with regulatory requirements, and maintenance needs. Typically, these evaluations focus to a large degree on demonstrating that a project is not endangering aquifer water quality or impacting springs, seeps, nearby wells, or neighboring land uses such as sand and gravel quarries or groundwater remediation sites. A dedicated monitor well and/or piezometer network should be designed to monitor the recharge operations to minimize potential impacts to other stakeholders.

For most MAR facilities in the United States, monitoring programs are determined or approved by the state regulatory programs. The objectives of a monitoring program are typically guided by compliance requirements to protect human health and the environment and prevent adverse effects as described above. To do this, monitoring should be designed to track quality of source water, recharged water, receiving groundwater, recovered water, and recovered water after treatment as appropriate. The monitoring plan also needs to identify potential water quality threats, such as existing and potential contaminant sources, changes in water quality due to geochemical processes, or seawater intrusion.

Monitoring is also a key tool to sustainably manage the groundwater basin. Planners need to identify their objectives regarding operational or storage goals, performance goals, and management, control, and recovery of recharged water. Typically, associated monitoring includes instantaneous and cumulative inflows into the facility and into individual basins, water levels in the basins, and groundwater elevations. These monitoring data are used to track the operational performance and help to establish the appropriate intervals for maintenance tasks. These measurements, along with those of precipitation and evaporation, also allow for the calculation of a water balance for the basin and estimation of infiltration rates.

Using a Supervisory Control and Data Acquisition (SCADA) system at available locations remains the most reliable method for real-time operations management. Such systems record and store data, with a data collection frequency typically 15 minutes to one hour, which provides the opportunity for real-time monitoring and management of recharge operations. This option has become more affordable because of availability of cellular network-based telemetry systems. Many surface MAR facilities are also equipped with SCADA logic control for automated operations.

TABLE 1. Monitoring Types, Locations, Frequency, and Needs

Type	Location	Purpose	Equipment Needed	Frequency	Need
Flow Rates	Inlet andoutlet structures as needed	Determine rate of water flow into basin	Weir, flume, or pipe-based flowmeter	Continuous operation	Critical for water balance
Basin Elevation	Stilling well in each basin/ facility	Determine water volume in basin and fill/ infiltration rates	Pressure transducer with datalogger. Staff gauge for manual readings.	5-minute with automation. Service quarterly, calibrate yearly.	Critical for water balance
Groundwater Monitor Wells	Upgradient and downgradient wells to assess groundwater gradients, placement relative to sources of drinking water or other sensitive receptors	Measure water level	Pressure transducer with datalogger	Hourly with automation, manual quarterly	Critical for regulatory compliance; requirements vary by jurisdiction and project
		Collect water quality samples	Low-flow sampling pump	Quarterly	Critical for regulatory compliance; requirements vary by jurisdiction and project
		Measure quality parameters	Water quality sondes for electrical conductivity, temperature	Hourly with automation, service quarterly	Useful adjunct for monitoring arrival of infiltration pulses
Vadose Zone Monitor Wells	Completed in perching layers if present; multi-nest piezometers with sensors if needed	Monitor perched water mounding, WQ and vadose zone interactions	Pressure transducer with datalogger, other sensors (see below)	Hourly with automation, manual quarterly, calibrate yearly	Monitor perching that could affect operations or nearby groundwater users
Weather Station	At facility, or nearby station	Monitor meteorological conditions. Estimate evaporation rate.	Temperature and relative humidity sensor	Hourly with automation, service quarterly, calibrate yearly	Important for calculating the water balance, making operational decisions
			Wind sensor		
			Solar radiometer		
		Measure rainfall	Tipping bucket		
		Measure direct evaporation rate	Class A evaporation pan	Hourly with automation, service weekly	
Suction Lysimeter	Under area of infiltration, can install at various depths in boreholes (dual chamber lysimeters up to 150 meters)	Monitor recharge water quality in vadose zone	Suction-style lysimeter	Sample quarterly or after infiltration events	Use for sampling recharge water from vadose zone if water quality is a concern
Soil Sensor	Under area of infiltration, install at various depths in boreholes	Track infiltration wetting fronts and drying, soil salinity	Soil moisture, temperature, and electrical conductivity	Automated datalogging at various time intervals	Use for monitoring wetting and drying, infiltration changes

Monitoring frequency is a function of monitoring methods and objectives of the monitoring program. As such, the design and location of monitoring wells will be dependent upon hydrogeology, composition of aquifer units (such as confined aquifer with multiple zones vs. unconfined aquifers), maximum rate and duration of recharge operation, existing groundwater gradient, and water quality threats. Typically, periodic water level measurements and water quality sampling—including tracer parameters—are used to estimate the fate and transport of recharged water and mixing with native groundwater. Additionally, the monitoring network is instrumental in calibrating groundwater flow and transport models and for measuring responses to aquifer pumping tests to estimate basin and aquifer parameters.

Table 1 provides a summary of the monitoring system types, purposes, and frequency. Monitoring types are also discussed further in Section 5.2.

5.2 Monitoring Type Descriptions

Flow Measuring and Recording

Basin inlet pipes, normally under pressurized flows, should be fitted with flow-measuring devices. Ideally electronic, totalizing flowmeters would be used. These automated devices report cumulative changes in volume and instantaneous flow rate remotely and allow for more informed operations. These should be calibrated and carefully installed, as many have restrictions on placement configurations. Alternately, a manual totalizer checked on a daily basis can be an economical choice but does not allow for SCADA integration.

Basin outlets, where present, are more complex to measure. They are typically designed to run under partially full conditions, essentially open channel flow similar to a stormwater collection system. They can be open pipes or can include a weir or flume, where flow constrictions are used. These systems rely on calculating flow by having a known cross-sectional area and combining that with the measurement of one or more water depths or levels. Equipment to measure the depth can be as simple as a manual, permanently mounted staff gauge. However, pressure transducers or acoustic sensors provide higher quality data collected at 5- to 10-minute intervals. These sensors are essential for systems which change rapidly, such as off-channel reservoirs or stormwater infiltration basins, but are also helpful for remotely monitoring less dynamic systems.

Measurements of Water Level in the Basin

Ongoing, regular basin water level monitoring needs to be conducted during the operational life of the facility. At a minimum, staff gauges should be installed in every basin with the staff gauge zero at the basin invert. For continuous water-level data, transducers and dataloggers may also be installed and integrated into the SCADA system.

Infiltration Rate Monitoring

Volumetric or water balance method

Facility operators may estimate the infiltration rate by calculating the water balance of the basin. This can be as simple as dividing the total inflow volume by the area of the basin after water levels have stabilized, or as complex as taking infiltration (I) as the balance of the other water flow components. This can be computed using the formula:

$$I = Q_{in} + P - Q_{out} - ET - \Delta h/A$$

Where Q_{in} is the inflow rate, P is precipitation, Q_{out} is the outflow rate, E is the evaporation rate, h is the change in basin water level, and A is the area of the basin. The first method only provides reliable results if the time frame is on the order of weeks to months. However, the second method can be used at a 5- to10-minute interval, depending on the instrumentation used.

Falling-head method

At any time after inflow into a basin has stabilized, inflow to the basin may be turned off and the decline in

basin water level may be monitored, either visually or recorded by a transducer and datalogger. This method will yield infiltration rate in terms of length per time [L/T].

Groundwater Level Changes

For small systems only a few acre-feet per year, monitor well systems (i.e., piezometers) may involve two monitor wells (one located near the recharge facility, the other near at some distance from the recharge basin). Very large recharge-basin systems may require numerous monitor wells. These wells help to monitor discharge dynamics, groundwater response, and mound dissipation rates (often important if separation from the basin floor is required). Water levels can be manually measured on a quarterly basis using an e-line or steel tape or collected at one-hour to one-day intervals using a pressure transducer. In the case of the latter, care should be taken to regularly compare the transducer data to a manual water measurement and adjust the calculated water level appropriately.

Source Water Quality Monitoring

Monitoring of source water quality needs to be conducted during the operational life of the facility. In the case of basins infiltrating treated sewage effluent, the monitoring frequency will depend on the plant's operations, but a weekly sampling interval is common. In other settings, like stormwater or off-channel recharge, event- or flow-based sampling may be necessary. Automated water sampler devices can assist in such situations. Analytes are strongly dependent on the source water type and setting; tests like suspended solids, dissolved solids, organic carbon, nutrients, and metals are common, as they contribute to clogging, salinization, and biogeochemical reactions.

Groundwater Quality Changes

For most cases, groundwater quality samples need to be collected from designated monitoring wells for laboratory analyses. In terms of sampling protocols and methods, the site-specific regulatory compliance requirements dictate the method selection and sampling frequencies. Recharge operators typically use a dedicated sample pump and transducer in monitor wells. The sample pump is activated sufficiently in advance of a sampling event to purge the wellbore so that the water produced is representative of the water in the aquifer, not the water in the well casing. Alternately, a low-flow sampling pump and controller can be used with a flow-through cell and sonde to determine when measurements have stabilized, and a sample can be collected.

Water quality sondes can also be permanently deployed to monitoring wells to measure water quality parameters like temperature, electrical conductivity, dissolved oxygen, pH, and oxidation-reduction potential. This method can be very useful in detecting the arrival of the saturation front after an infiltration event (if periodic) or determining the travel time from the surface. Hourly measurement frequencies are typical. These sensors can be permanently deployed, with quarterly visits to perform essential regular maintenance tasks and download data.

6. Summary and General Guidance

Surface infiltration (surface MAR) which involves recharging water at the surface through recharge basins, ponds, pits, trenches, drywells, constructed wetlands, or other systems is currently the predominant method of recharging groundwater. Surface MAR can be used for water supply, aquifer augmentation and restoration, stormwater capture and control, habitat support, and recreation on the impoundments. Through infiltration of water regardless of the source, groundwater must be protected and its water quality not degraded.

In the western United States, ensure that rights to the source water, stored water, and recovered water are known and documented. State requirements frequently play a significant role in regulating surface infiltration projects, and potentially applicable federal requirements may also need to be considered depending on the nature and circumstances of the project. In some cases, local requirements may also apply, particularly with re-

gard to location and relation to local infrastructure.

Early contacts with state and local regulatory agencies will help in identifying needed steps that will likely affect the cost and benefit of the project in a number of aspects: for ensuring rights to the water received and used; for protecting groundwater quality; and for mitigating potential effects on adjacent groundwater users. This contact may occur after completing some initial project feasibility development.

Surface MAR feasibility studies should include field investigations to address site-specific data gaps. Information from nearby MAR projects will be useful in these investigations. Field investigations may include infiltration rates, depth to groundwater, storage volume in the vadose zone, permeability of geologic layers, prospective groundwater mounding, recharge water movement from the site, and potential geochemical reactions. Operation and maintenance activities should be tied to monitoring surface and subsurface conditions. Clogging of the infiltration bed can be addressed by raking and removal of bed sediments. Monitoring wells will provide performance, water quality, and water elevation data.

Critical steps for success:

- Recognize the unique aspects of each site being considered.
- Document the water rights.
- Take a phased approach to site feasibility analysis.
- Initiate early and continuing consultation with regulatory agencies.
- Place priority on protecting groundwater quality.
- Evaluate potential impacts to adjacent groundwater users.
- Monitor to guide operation and maintenance decisions.

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Email ngwa@ngwa.org **Websites** NGWA.org and WellOwner.org