WATER RECYCLING FOR CLIMATE RESILIENCE THROUGH ENHANCED AQUIFER RECHARGE AND AQUIFER STORAGE AND RECOVERY

EPA

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Preface and Intended Audience

On February 27, 2020, the U.S. Environmental Protection Agency (EPA) released the National Water Reuse Action Plan: Collaborative Implementation (WRAP, Version 1). Through this initiative, EPA seeks to advance water reuse across the water sector through a series of actions taken by EPA, other federal agencies, industry associations, and relevant stakeholders. WRAP Action 7.4 (Increase Understanding of Current Aquifer Storage and Recovery Practices) was developed to promote the understanding of aquifer storage and recovery (ASR) practices by summarizing the current state of practice and detailing the different factors that should be considered when developing such projects.

As part of Action 7.4, this report focuses on enhanced aquifer recharge (EAR) and ASR in the context of water reuse, providing state- and local-level decision-makers information on using recycled water in EAR and ASR applications. It explores the key considerations to evaluate when planning EAR and ASR as part of integrated water resources management and climate resilience planning. More specifically, it describes:

- The drivers for EAR and ASR.
- The extent of practice of EAR and ASR in the United States.
- Sources of recycled water for these projects.
- Subsurface water quality changes and technical considerations.
- Treatment needs.
- Methods of recharge.
- The regulatory environment.
- Potential costs and benefits.

While decision-makers must account for site-specific conditions when evaluating EAR and ASR projects, this report provides a general overview of current projects using recycled water and identifies the types of issues to address before implementation. Two companion reports from other EPA programs that address other aspects of ASR and EAR are described in Section 2.

The information herein draws from existing EPA resources such as the 2012 Water Reuse Guidelines and the 2017 Potable Reuse Compendium, as well as a search of available literature. EPA also held virtual meetings with staff from the United States Department of Agriculture (USDA), the Ground Water Protection Council (GWPC), and the American Water Works Association (AWWA) to solicit perspectives on major issues related to the use of recycled water in EAR and ASR applications. While not intended to be a comprehensive scientific literature review, this report provides a robust introduction to topics with references to additional resources to empower state and local communities considering an EAR or ASR project using recycled water to build climate resilience and support other local water management priorities.

1. Background

Enhanced aquifer recharge (EAR) is a practice in which groundwater aquifers are recharged by artificial means, including injection wells and infiltration practices such as constructed basins or trenches. Aquifer storage and recovery (ASR) is a sub-category of EAR, in which an aquifer is replenished, and the recharge water is explicitly intended for later extraction and use. EAR differs from natural aquifer recharge by including practices that intentionally recharge aquifers beyond naturally occurring processes. Both EAR and ASR methods can store water for many beneficial uses and to address various hydrologic and water quality issues affecting water supplies or environmental flows. Understanding these benefits more fully is becoming increasingly important as communities seek to build resilience to more frequent and severe drought events now exacerbated by climate change.

This document focuses on the intentional recharge of aquifers with recycled water. It mainly addresses ASR, but it also considers broader applications including EAR, as both share many of the same operational practices and issues. Although EAR and ASR can be practiced with many different sources of water, including surface water diversions, this report focuses exclusively on the use of recycled water.

Currently, ASR and other forms of EAR are most often implemented using treated drinking water and surface water. However, treated municipal wastewater, stormwater,[1] agricultural drainage and return flows, and other sources of recycled water have great potential for increased use in EAR and ASR applications. Recharging aquifers with recycled water can create an alternative wastewater management strategy, and while aquifer recharge with recycled water is practiced in some regions of the country, in many others it represents a new—and largely underutilized—contribution to local water supplies. Although it requires specific considerations for water quality and treatment, recycled water can be a valuable source of water, especially in areas where water quantity is a major concern.

Applications of EAR and ASR with recycled water can address various needs, such as storage and treatment for potable reuse, storage for use in irrigation, land subsidence mitigation, reducing or eliminating surface discharges of wastewater, and protection against saltwater intrusion. Differing regional drivers and potential benefits have resulted in a variety of operational and proposed EAR and ASR projects around the United States, all with unique challenges and solutions that can help inform future projects and integrated water management strategies to enhance resilience to the impacts of climate change.

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[1] Recharge with stormwater is explored more fully in the EPA companion report *Enhanced Aquifer Recharge of Stormwater in the United States: State of the Science Review* (EPA, 2021; see Section 2.1 for more details).

2. Companion Reports and Terminology

2.1 Report on EAR with Stormwater

In July 2021, EPA published a review and summary of the scientific and technical literature on the use of urban stormwater for EAR: *Enhanced Aquifer Recharge of Stormwater in the United States: State of the Science Review*, referred to in this document as the "Stormwater EAR Report." The report discusses technical aspects of capturing and using urban stormwater, such as site selection, fate and transport of pathogens and organic compounds, mobilization of subsurface contaminants, and pretreatment of water prior to recharge operations. Therefore, this current report does not include detail on urban stormwater capture in EAR or ASR, aside from scenarios where stormwater may be incorporated into wastewater reuse applications.

2.2 Report on UIC Aquifer Recharge and ASR Applications

EPA is preparing a report on aquifer recharge (AR) and ASR that focuses on the current state of injection practices within the Underground Injection Control (UIC) Program: *Review of Aquifer Recharge and Aquifer Storage and Recovery via Underground Injection*, referred to in this document as the "UIC AR/ASR Report." It includes an overview of the regulations of AR and ASR via injection wells, a summary of relevant state and federal regulations, an inventory of AR and ASR injection wells within the United States, and a discussion of technical and operational challenges associated with AR and ASR via injection wells. Therefore, this current report does not present details on the UIC program.

Description of Terms for Aquifer Recharge

Several terms are used to describe the replenishment of aquifers, some of them largely synonymous. The descriptions below are included for the purposes of this report only and are not intended to represent official definitions.

- **Aquifer recharge (AR):** The movement of water from the surface or unsaturated zone into the saturated zone (e.g., an aquifer). Recharge is a natural process, but in the context of this report, it refers to the intentional resupply of water to an aquifer.
- **Enhanced aquifer recharge (EAR):** A suite of recharge practices with various goals, site requirements, recharge water types, and infrastructure. A project is considered an EAR project if it results in more recharge than would otherwise be expected through just natural processes. This document uses "EAR" interchangeably with "managed aquifer recharge" (MAR), a term used extensively in the literature.
- **Aquifer storage and recovery (ASR):** The recharge of water for later recovery and use. It is a type of EAR practice. ASR systems that recharge via injection can use the same well for both injection and withdrawal or use separate wells (in close proximity) to inject and withdraw water. ASR systems can also use other EAR practices such as infiltration basins to recharge the aquifer for later recovery and use. ASR is a subset of EAR. For instance, a project to replenish an aquifer to protect the aquifer against seawater intrusion and ground surface subsidence would be considered an EAR project, but not an ASR project, because there are no associated plans to recover the water used to replenish the aquifer.

3. Drivers and Business Case for EAR and ASR

EAR and ASR are relevant to a wide range of water management settings and scenarios. However, the implementation of EAR and ASR has generally been prompted by several factors associated with the overuse of groundwater due to increased demand over the last half of the 20th century (Dillon et al., 2019). These factors relate to the reliability of water supplies, the environmental and ecological impacts of overexploitation, economic considerations, and the need for a suite of options for integrated water resource management (Asano, 2006).

Increased groundwater demand has been driven by societal shifts that include population growth and increased energy consumption in urban areas, along with increased irrigation for food production and other agricultural products (Jakeman et al., 2016). Technologically, increased withdrawal has been facilitated by the availability of electric power and submersible pumps (Dillon et al., 2019). Approximately 4,500 km^3 (over 3.5 billion acre-feet) of groundwater depletion occurred globally between 1900 and 2008. Within that period, depletion rates significantly increased starting in 1950, with the highest rates occurring from 2000 to 2008—the most recent year with available data (Konikow, 2011). Water quantity concerns are especially acute in arid regions where water supplies are already scarce and natural aquifer recharge is limited. Demand for water is also particularly high in coastal areas, where high population densities result in heavy water usage.

3.1 Hydrologic Demands and Impacts from Climate Change

From a hydrogeologic standpoint, overexploitation of an aquifer occurs because natural recharge is slower than the rate of groundwater withdrawals. This is often exacerbated by the fact that groundwater residence times in an aquifer can be extremely long (Asano, 2006). For example, the High Plains Aquifer, which underlies eight states and provides a third of the groundwater extracted in the United States, has water older than 13,000 years in some areas (Fienen and Arshad, 2016). Therefore, even if withdrawals were reduced or stopped in an overexploited aquifer, recovery would be slow, and water levels would remain lower than before widespread extraction (Casanova et al., 2016; Angelakis and Paranychianakis, 2003).

Increased groundwater demands are occurring in the context of climate change, with the associated uncertainties and changing weather patterns (Miller et al., 2021). Generally, climate impacts include increased drought, which further stresses water supplies, while higher rainfall intensity can exceed the rate at which water infiltrates into soils, causing flooding and reducing the amount of water that recharges groundwater (Bekele et al., 2018; Dahlke et al., 2018). The Fourth National Climate Assessment (Lall et al., 2018) specifically cites climate change as a major driver in the frequency, duration, and distribution of drought, especially in the Southwest. The Assessment also cites groundwater depletion as exacerbating drought risk. This is further reinforced by the most recent report from the Intergovernmental Panel on Climate Change (IPCC, 2022), which concluded with high confidence that climate change will result in increases in frequency, intensity, and severity of droughts.

Concerns about uncertain water availability and increased demand fall under the broad umbrella of water security, a common driver for water reuse. Using recycled water for various applications helps mitigate this insecurity by turning a waste product into a valuable resource (Dillon et al., 2019). Recycled water in an aquifer recharge setting can provide a steady supply with relatively predictable volume during drought or other conditions where the natural supply of water is uncertain or subject to variability (Angelakis and Paranychianakis, 2003). It is an especially attractive option where water from traditional sources, such as surface water or other aquifers, is not readily available in sufficient quantities to support all drinking water supply needs. In this context, the aquifer used for storage is effectively a bridge between wastewater treatment facilities and drinking water infrastructure (Dillon et al., 2019).

Case Study: Orange County Water District

The Orange County Water District's Groundwater Replenishment System in Southern California is an advanced wastewater treatment facility that recharges the Orange County Groundwater Basin. Its current capacity is 100 MGD; of this amount, approximately 35 MGD is used for a seawater intrusion barrier, with the rest recharged through infiltration basins (Kiparsky et al., 2021). This allows for the aquifer to be recharged while ensuring it is also protected from future seawater intrusion. A project like this one could be implemented with several different sources of water, but using treated municipal wastewater is an increasingly common practice due to consistent availability. By using recycled water, the region has become less reliant on imported sources of water while protecting their existing groundwater supplies.

3.2 Environmental, Ecological, and Social Considerations

Environmental and ecological concerns prompting interest in EAR and ASR relate to the interactions between groundwater and surface water and the need to protect surface water quality and quantity for overall ecosystem health. Reductions in groundwater discharge due to lowered groundwater levels can damage groundwater-dependent ecosystems such as wetlands, riparian forests, and springs fed by baseflow from underlying aquifers (Dillon et al., 2009). In California, excessive groundwater pumping has reduced baseflow to the point that flow in some rivers and streams has slowed or dried up (Fleckenstein et al., 2004). EAR and ASR can be implemented to address these impacts of overdraft, thereby indirectly protecting surface water resources.

EAR and ASR practices using recycled water can also protect surface water quality by reducing effluent discharges and associated nutrient loadings (Page et al., 2018). For example, the Hampton Roads Sanitation District (HRSD) in southeastern Virginia is in the early stages of implementing its Sustainable Water Initiative for Tomorrow (SWIFT), which will use a series of groundwater injection facilities using treated municipal wastewater. While water supply augmentation will be a benefit of this initiative, the primary driver is to manage nutrient discharges in accordance with the Chesapeake Bay Total Maximum Daily Load. Because HRSD can achieve nutrient reductions at a lower cost than neighboring jurisdictions investing in improvements to comply with permit requirements, it is estimated that the implementation of SWIFT may result in up to $2 billion in cost savings through nutrient credit trading (Green Nylen, 2021). A case study in this report provides more information on HRSD's SWIFT project (see page 28).

Excessive groundwater withdrawal causes other environmental and social impacts related to declining water quantity. The loss of hydraulic pressure in an aquifer due to heavy withdrawal can cause land subsidence and endanger buildings and other surface infrastructure in addition to decreasing the existing and future storage capacity of the aquifer. Land subsides when groundwater pumping opens pore space, which then collapses. Porosity within the aquifer is then sometimes permanently lost, along with storage capacity for water. Seawater intrusion can also occur in near-ocean groundwater basins with active groundwater production wells. These wells can often draw down the groundwater within the basin such that seawater begins to flow through the aquifer toward the well. As this happens, the seawater mixes with the previously fresh water within the aquifer, often significantly degrading the groundwater quality. In many cases, groundwater from the aquifer can no longer be used for its intended purpose without expensive treatment and may take decades to recover to its previous freshwater quality.

Recharge of coastal aquifers with the injection of water can provide additional hydraulic pressure to prevent or mitigate the inward migration of saltwater and protect the water quality of inland freshwater aquifers (Bekele et al., 2018). Saltwater intrusion has been a serious enough concern to prompt the installation of injection wells for saltwater intrusion barriers in California and Florida. The use of recycled water helps address these issues, while providing greater certainty for future water supplies. It also gives communities more confidence in their water supplies, since recycled water is a steadier, more climate-resilient water source than many natural supplies.

3.3 Integrated Management of Water Supplies

There is an increasing awareness of the need for the integrated management of water resources that addresses local and regional needs, and EAR and ASR can play a valuable role. As noted above, EAR and ASR are useful complements to surface water storage, as these approaches can help protect the water supply against surface influences such as evaporative loss, algal blooms, atmospheric deposition of contaminants, etc. (Hartog and Stuyfzand, 2017; Zheng et al., 2021). With greater seasonal variations in water availability due to climate change (Casanova et al., 2016), EAR and ASR also provides a way to remedy mismatches between water availability and demand (Hartog and Stuyfzand, 2017).

By developing a local water supply that includes alternative sources through water reuse, some communities will also become less reliant on imported water. This is especially important for communities in western states that rely on water from the Colorado River Storage Project or the Central Arizona Project, which require water to be transported large distances with allocations that can fluctuate based on availability. EAR and ASR provide water storage options in areas where there is a lack of suitable sites or land area for surface reservoirs (Asano, 2006). As urbanization, population growth, and water demand continue to exert stress on water availability and quality, the ability to bolster existing aquifers and to store and retrieve previously underused water resources, such as recycled water, holds promise in resilient water management planning (Dillon et al., 2019; Casanova et al., 2016; Hartog and Stuyfzand, 2017). Climate change further stresses these demands and makes it critical that communities diversify their water supply portfolio rather than relying on a single source of drinking water. Through a diverse supply portfolio with recycled water, a community’s supply is more resilient to climate stresses and able to withstand more common and persistent drought events.

3.4 Economic Drivers

In addition to environmental and social drivers, there are also economic drivers for pursuing aquifer recharge using recycled water. In some cases, using recycled water for aquifer recharge to supplement groundwater supplies is less expensive and energy intensive than other drinking water supply options, such as desalination. In addition, storage in an aquifer can preclude the need for infrastructure such as pipelines or canals and reduce loss by evapotranspiration (Asano, 2006; Jimenez-Cisneros, 2014). For example, in Southern California, reliability concerns and the high costs of importing water have long prompted interest in use of recycled water for EAR/ASR and other water reuse applications (Dahlke et al., 2018). EAR can also be a lower-cost option for treated wastewater disposal than other methods (Asano, 2006). More information about costs and benefits of EAR and ASR approaches is provided in Section 10 of this report.

West Basin Municipal Water District's Edward C. Little Water Recycling Facility in El Segundo, California, produces five different types of recycled water for different uses including groundwater recharge.

4. Current Practice of EAR and ASR in the United States

EAR and ASR practices have emerged as water stress has increased in many communities, driven by increasing demand for water and a decline in natural sources (including groundwater). Before the evolution of intentional EAR and ASR practices, recharge occurred passively in many places via drainage wells for flood management, septic systems, and infiltration and percolation during irrigation. These incidental routes of recharge were unmanaged with respect to water quality or other health and environmental considerations (Dillon et al., 2019). Over time, unintentional recharge of aquifers began to be managed, resulting in improvements in water quantity and quality. Progress in the use of EAR is largely due to significant developments in technologies and management practices over the past 60 years (Dillon et al., 2019).

Common sources of recharge water have typically been surface water diversions and water from other aquifers, generally recharged via infiltration basins (Casanova et al., 2016). However, recycled water has been used to some degree for decades, including in projects in the western and southwestern United States. Early EAR practices in the United States evolved from irrigation with the implementation of recharge basins for spreading—particularly in Arizona, which saw several pilot projects in in the 1960s and 1970s (Dillon et al., 2019). The Flushing Meadows pilot project (Salt River Valley, Arizona) and the 23rd Avenue recharge project (Phoenix, Arizona) both used several infiltration basins and recharged the aquifers with treated municipal wastewater. The passage of the treated municipal wastewater through soil that these infiltration-based projects employed, and the associated water quality improvements, eventually become known as soil aquifer treatment (SAT). Additionally, some entities began using injection wells due to limited available land area.[2]

When treated to an appropriate level, wastewater effluent has become an acceptable source of water for EAR and ASR. Advancements in treatment technologies, such as the development of membranes suitable for membrane bioreactors in the early 1990s, played an important role in the advancement of both EAR and ASR (Dillon et al., 2019). In addition, some aquifers previously considered to be too brackish for beneficial use have been transformed into productive water resources through infiltration or injection of higher-quality water and the resulting dilution of the brackish water (Dillon et al., 2019).

Case Study: Central Arizona Water Conservation District

Under authority provided in 1993 by the Arizona State Legislature, the Central Arizona Water Conservation District (CAWCD) seeks to give landowners and water providers a mechanism to demonstrate that they have an assured water supply. As part of a first-of-its-kind public/private agreement in 2014 between CAWCD and Liberty Utilities, the Liberty Aquifer Replenishment Facility began construction in 2016 and began operation in February 2017. Located in Goodyear, Arizona, this 51.77-acre facility was constructed to receive water that is not sold for irrigation from Liberty's Palm Valley Water Reclamation Facility for recharge into the regional aquifer in an area where water levels are currently declining at a historic rate (Liberty Utilities, 2017).

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[2] See EPA's Underground Injection Control program and the UIC AR/ASR Report (in preparation) for additional information on aquifer recharge and ASR injection wells.

In the United States, general growth of EAR and ASR over the last few decades has been estimated at 5 percent per year (by volume) but may in fact be underreported due to incomplete data availability (Dillon et al., 2019; Zhang et al., 2020). The average volume of water used for EAR grew from 302 million m^3 (about 250,000 acre-feet) per year in 1960–1970 to 2,569 million m^3 (about 2.1 million acre-feet) per year in 2011–2015 (Dillon et al., 2019). This follows similar trends in 33 other countries, where EAR volumes have increased from 1,029 million m^3 (about 835,000 acre-feet) per year to 9,945 million m^3 (about 8.1 million acre-feet) per year during the same timeframe (Dillon et al., 2019). Though data were not available to indicate how much of this volume represented use of recycled water, as population increases and water supplies in some regions continue to be strained, treated wastewater will likely be considered as a consistent resource for use in EAR and ASR projects.

4.1 Geographic Scope and Distribution of Technologies

EAR and ASR are also increasingly common outside the United States as a water management strategy, as seen in the map of EAR projects which includes ASR, throughout the world (Figure 1, Stefan and Ansems, 2018). The map shows a broad mix of project types in Europe, the United States, China, and elsewhere. (The database used to produce Figures 1 and 2 can be found at https://ggis.un-igrac.org/view/marportal.)

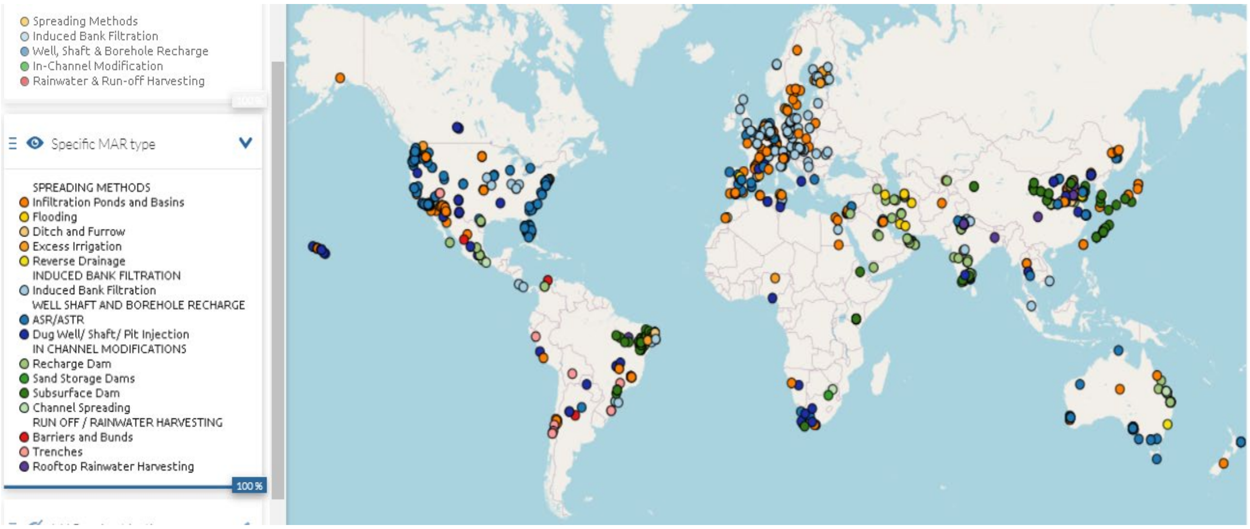

Figure 1: EAR projects throughout the world (Stefan and Ansems, 2018)

Figure 2 is a map from a database of EAR projects in the United States (Stefan and Ansems, 2018). In general, this map suggests these projects are located in more populous areas. In the map:

- Dark blue locations are those using wells for injection.[3]
- Orange locations represent infiltration ponds and basins (spreading methods), used in EAR projects in California, Utah, Arizona, Washington, Oregon, North Dakota, Kansas, New York, New Jersey, and Florida. (There are also spreading projects in Alaska and Hawaii, not shown in the map.)

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[3] See the UIC AR/ASR report (in preparation) for a more comprehensive inventory of AR and ASR wells in the United States.

- Light gray locations represent induced bank filtration projects in Washington, Nebraska, Kansas, Texas, Indiana, Kentucky, New Jersey, and Ohio. (This report does not cover such projects in detail.)

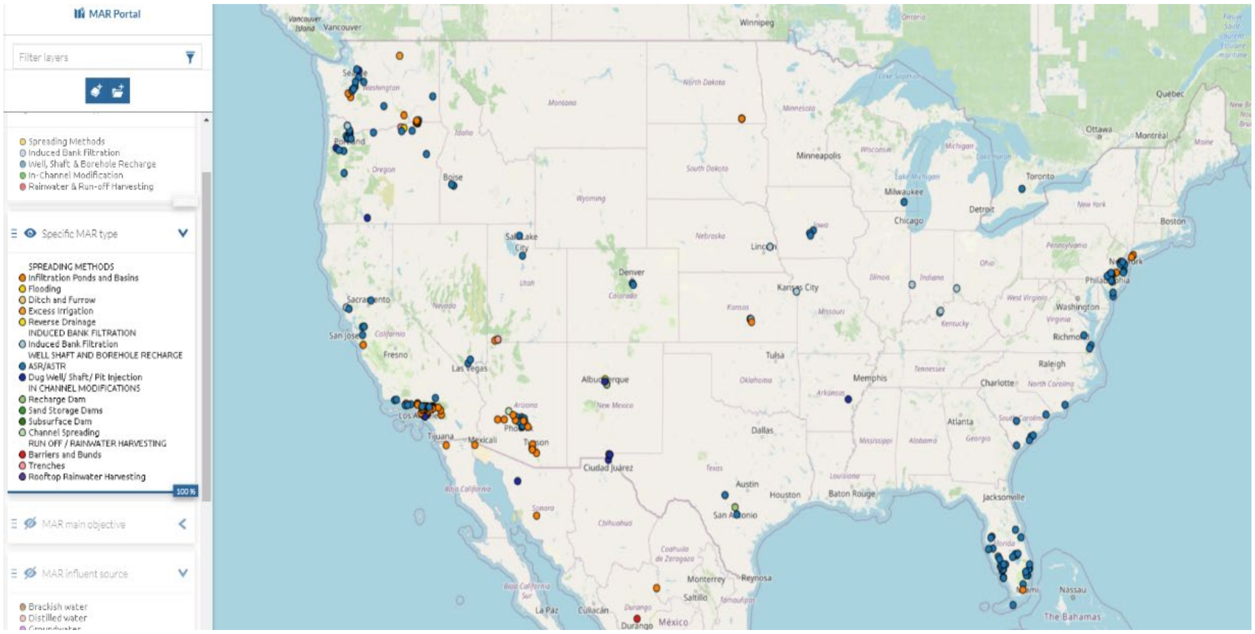

Figure 2: EAR projects in the continental United States (Stefan and Ansems, 2018)

Although Figures 1 and 2 do not distinguish which aquifer recharge projects use recycled water, they illustrate where recharge is currently implemented as a viable and valued part of water management. Additionally, they demonstrate that EAR is not a practice limited to water-stressed regions. Rather, these projects represent examples of methods, siting considerations, and other aspects of recharge projects that have commonalities with situations where recycled water is used for recharge. As of 2018, injection wells appeared to be used more often than infiltration in Florida and the northwest states of Oregon and Washington. On the other hand, infiltration projects are more common in the arid Southwest (Utah, Arizona, and California), as shown in Figure 2’s orange locations. This region receives relatively sparse rainfall, resulting in fewer perennial streams or rivers, with higher temperatures and lower humidity leading to higher evapotranspiration rates (Gelt et al., 1999). Accordingly, depth to water in this region is typically greater, allowing for seepage of recharge water to depths below the reach of most plants. These factors make recharge of shallow groundwater by infiltration more attractive, allowing for underground storage of water from spring snowmelt and storm events and reducing the potential for evapotranspiration.

5. Sources of Recycled Water for EAR and ASR

EAR and ASR projects use a variety of sources of water for recharge including surface water (diversions from lakes, streams, rivers), stormwater, treated municipal and industrial wastewater, treated drinking water, groundwater from another aquifer, and agricultural return flows and drainage. The source of water being used for recharge depends on factors such as availability, quality of the source of water, the required quality of the recharge water to ensure compatibility with the native groundwater, and eventual end-uses. Some projects use more than one source of water (e.g., stormwater and treated wastewater), which can represent a more integrated approach to water resource management, further diversifying water supply. Historically, surface water has been a primary source of recharge water, especially given its abundance in temperate humid climates (Casanova et al., 2016).

Considerations for undertaking EAR and ASR with recycled water include the availability of the water to be recycled in terms of volume, timing, and proximity. Additionally, annual cycles in agricultural settings affect how much recycled water is available for irrigation versus recharge. Water rights in the western states may also influence whether treated municipal wastewater is required to be discharged instead of being reused (see the text box on page 26 for more details on this topic) (EPA, 2012).

5.1 Treated Municipal Wastewater

Treated wastewater from municipal wastewater treatment plants is commonly used for EAR and ASR in regions with limited water resources. Industrial wastewater is less common for recharge outside of its contribution to municipal wastewater flows, as it can contain reactive and recalcitrant organic compounds and heavy metals. However, it can be used for recharge if the water is of adequate quality.

According to Rauch-Williams et al. (2018), about 32 billion gallons per day (BGD) of municipal wastewater is treated in the United States each year, with about 2.5 BGD currently recovered for some form of reuse after treatment. Of this 2.5 BGD, just over half is used for landscape and agricultural irrigation, and the rest is used for a variety of other end-use applications. In California, 18.4 percent of treated municipal wastewater is reused, with about 69 percent of that amount used for non-agricultural purposes, including groundwater recharge (Borch et al., 2021). While reuse is practiced in many different settings, treated municipal wastewater has the advantage of being relatively consistent in volumes throughout the year in locations where there is a robust wastewater supply in relative proportion to water demand. The consistent availability of treated municipal wastewater is especially important for communities looking to build resilience to climate change, since they can assure that part of their water supply portfolio will be available even in times of drought. However, water quality considerations for municipal wastewater must be resolved as sufficient treatment is needed prior to reuse and recharge (Page et al., 2018).

5.1.1 Pathogen Risks

For potable reuse applications, including recharge of drinking water aquifers, pathogens are generally considered to be the primary acute risk to public health. Pathogens of greatest concern are typically bacteria (e.g., *Campylobacter*), enteric viruses (adenoviruses and noroviruses), and enteric protozoa (*Giardia* and *Cryptosporidium*) (Nappier et al., 2018). Pathogen concentrations in raw wastewater can vary by location, but estimates can be derived for common reference pathogens to develop treatment benchmarks for potable reuse (EPA, 2017; Soller et al., 2018). Treatment processes such as ozone, high-dose UV, membrane processes, and other disinfection processes are implemented to reduce pathogen concentrations in wastewater effluent to an acceptable level as determined by the relevant regulations (see Sections 6 and 9 for more detail). In general, the risk benchmark for pathogens in potable reuse is to achieve a less than 1 in 10,000 annual risk of infection which is the generally accepted level of risk for conventional drinking water (Regli et al., 1991). Some states are now developing regulations and treatment requirements for specific pathogen groups for both indirect and direct potable reuse.

5.1.2 Chemicals and Compounds of Emerging Concern

If not treated appropriately, chemicals and other compounds of emerging concern can be a chronic risk for public health in water reuse applications. The Chemical Abstract Service of the American Chemical Society lists over 394,000 chemicals, many of which are found in different types of wastewater. Furthermore, identifying such chemicals in wastewater can be difficult. Although many are removed via different mechanisms during conventional wastewater treatment, some will persist (Prasse et al., 2015) and advanced treatment may be needed for some reuse applications, especially potable reuse. Aside from limits on select chemicals from federal and state regulations, a common strategy for monitoring chemical removal in water reuse is through performance-based surrogates used as proxies for different classes of chemicals. California has taken such an approach for health- and performance-based indicators and surrogates as part of a monitoring strategy for compounds of emerging concern in recycled water (Drewes et al., 2018).

5.1.3 Other Water Quality Parameters

For other parameters related to water quality, treated effluent may contain higher concentrations of organic carbon, but lower concentrations of suspended solids compared to other sources of water such as stormwater (Page et al., 2018). The higher organic carbon content has implications for the redox status in the aquifer and vadose zone, affecting the overall geochemical environment. Microbial consumption of organic matter consumes oxygen, and if organic matter concentrations are high enough, this depletion can drive the system towards anoxic (oxygen-free) conditions. In anoxic subsurface environments, iron oxides can dissolve, releasing associated contaminants into the water (see Sections 6.3 through 6.5 for more detail). Dissolved organic carbon can also contribute to the formation of disinfection byproducts when water is chlorinated for disinfection. Characterization of the types of organic carbon present in effluent that will be used for recharge will help in anticipating subsurface processes and any potential treatment issues to be addressed.[4]

Recycled municipal wastewater may also pose concerns due to elevated salinity and other elements such as boron (EPA, 2012). The salinity in treated municipal wastewater depends on the original content in the raw wastewater, such as human activity including the use of water softeners, types of waste being discharged, and other factors (EPA, 2012). Higher salinity in recycled water relative to surface water presents management challenges for EAR and ASR, particularly in agricultural settings.

For nutrients, loadings often vary seasonally because of effects on microbial treatment processes (Page et al., 2018). Nitrogen species in secondary treated wastewater effluent include ammonia, nitrate,

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[4] EPA's *2012 Guidelines for Water Reuse* includes further discussion on the components of organic carbon in wastewater.

nitrite, and organic nitrogen (Goren et al., 2014). In some facilities, the nitrogen is present as nitrate, while in others, nitrogen is primarily present as ammonium (Goren et al., 2014). Recycled water that has not been nitrified or denitrified can contain over 20 mg/L of ammonia (EPA, 2012), and some states require nitrogen removal for some classes of recycled water. For example, California requires total nitrogen of less than 10 mg/L for groundwater recharge to protect public health (California Code of Regulations, Title 22, §60320.110). The significance of nutrients in the recharge water depends on the intended use upon withdrawal (Dillon et al., 2009). For aquifers used as a drinking water supply, nitrate is a significant issue and care should be taken to ensure that recharge does not endanger groundwater quality. This is especially true in communities that are dependent on private wells without centralized drinking water treatment.

If an aquifer is in hydraulic connection to groundwater-dependent ecosystems, the potential loading of nutrients needs to be acceptable for the species present (Dillon et al., 2009). In addition, if the groundwater may be used as a potable supply in the future or if recharge may affect private wells, human health effects need to be considered (EPA, 2012). In a system using SAT, some of the nutrient concerns can be mitigated, but performance for nutrient removal will be variable and system-specific (e.g., anaerobic conditions favor the reduction of nitrate) (Bekele et al., 2011; Page et al., 2018). However, in cases where an aquifer is used for irrigation, and not for drinking water purposes, the nutrients present in the recharge water may be beneficial if the overall water quality is sufficient.

5.2 Agricultural Return Flows and Drainage

Agricultural return flows and drainage typically refer to excess irrigation water or natural precipitation that generally flows to surface water. While there are opportunities to reuse return flows and drainage for recharge, there are significant incentives to limit return flows through more efficient practices or to directly reuse return flows for irrigation. The primary reason fields are drained is to lower the water table. This is often accomplished through tile drainage systems to drain excess water that may otherwise affect root health in crops.

Case Study: Arvin-Edison Water Storage District

Located in California's Central Valley, the Arvin-Edison Water Storage District has been practicing aquifer recharge to support agricultural irrigation since the 1960s. During wet years, excess surface water is infiltrated through 1,500 acres of spreading ponds that can be withdrawn later during dry years. Before aquifer recharge was introduced, overdraft was up to 113,000 acre-feet per year and threatened the long-term sustainability of agriculture in the region. However, between 1966 and 1999, 4.2 million acre-feet of water was stored in the aquifer (National Research Council, 2008). While this is not a direct example of EAR or ASR implemented with recycled water, it is a specific example of ASR being practiced to support agricultural irrigation.

Based on the 2017 Census of Agriculture (USDA, 2019), nearly 100 million acres of farmland use either tile drainage or artificial surface drainage. Much of this land area is concentrated in the Midwest, with significant amounts in the West as well (USDA, 2019). Drainage is usually managed by allowing water levels to remain closer to the surface in the spring when root depth is shallow and rainfall is high, then slowly lowering the water table in front of the growing roots (Skaggs et al., 1994). Although the drained water is often transported away from the location on the surface, it can be captured for recharge. An estimate of the potential drainage volume in the United States (based on the fraction of farmland drained by tile but not counting precipitation) suggests that about 220 billion gallons of water per year may be available for reuse. Of that amount, 65 percent is attributed to western states. However, to utilize this available water, infrastructure such as storage, pumping, distribution, and potentially treatment would be needed (Hejase et al., 2022).

5.2.1 Water Quality and Regional Considerations

Constituents of concern in agricultural drainage used for EAR and ASR include nitrate, phosphate, salts, and other chemicals such as fertilizers and pesticides (Borch et al., 2021). Trace elements can also be present—arsenic, molybdenum, and selenium, among others—and mobilized during irrigation (Tanji and Kielen, 2002). Water quality will vary from location to location, but there are some general trends. Compared to applied irrigation water, subsurface drainage generally has higher salinity with more nitrogen and potentially more pesticides and phosphorus. This change in water quality depends on a variety of factors including irrigation method, soil characteristics, the use of fertilizers and other chemicals, the drainage system, climate, and site operations (Tanji and Kielen, 2002). While it is more of an operational consideration, sediment contained in agricultural drainage can result in clogging and impede infiltration.

There are also regional differences in drainage water quality. In eastern states, nutrients in agricultural drainage are considered valuable for reuse, and treatment may not be needed. In the West, drainage can be highly saline; in the San Joaquin Valley in central California, for example, total dissolved solids can reach 5,000–20,000 mg/L. Such highly concentrated drainage poses greater water quality concerns, and treatment is more likely to be needed before the water can be used for recharge (Hejase et al., 2022).

While the quality of agricultural drainage has been an issue for its impacts on wildlife and ecosystem health in the western states for quite some time (USGS, 2003), there are still research needs for the application of agricultural drainage in EAR and ASR. Many of the same compounds and trace elements of concern for surface water contamination would also be of concern for EAR or ASR, but more information is needed on the influence of SAT and other subsurface processes on water quality and treatment needs. Once contaminated, aquifers are difficult, expensive, and time-consuming to remediate, making evaluations of water quality and treatment needs crucial.

Recharge on Agricultural Land

There is interest in California and other states with irrigated agriculture in investigating the potential for aquifer recharge using agricultural land. This concept would apply water on agricultural land in excess of crop needs when water is in sufficient supply and demand is low (Bachand et al., 2012). The practice would not convert existing agricultural land into spreading grounds or infiltration basins as land would be kept in production during growing seasons. Using recycled water in the same way would take this concept further by using a water source that would likely be in consistent supply even in times of low precipitation. However, it would introduce additional considerations such as the quality of the recycled water and the efficacy of SAT, impacts on groundwater quality, as well as the effects on agricultural production. In addition, there are some existing regulatory constraints: for example, some states require that recycled water for irrigation be applied at the agronomic rate to prevent over-irrigation and protect groundwater quality. A complete compilation of state-level regulations for water reuse is being developed through EPA's REUSExplorer, found at http://www.epa.gov/reusexplorer. More discussion on this topic is found in Richardson et al. (2018).

5.3 Stormwater

Stormwater runoff from rain and snowmelt events that flow over land or impervious surfaces is often viewed as a nuisance or a drainage problem for communities to manage. As some communities face water stress, stormwater is increasingly being viewed as a resource that can be captured, treated, and used for different purposes. Among these end-uses is aquifer recharge through EAR or ASR. While the availability of stormwater is intermittent and dependent on climatic conditions, it can significantly contribute to a local water supply. For example, in California it has been estimated that up to 3 million acre-feet per year of stormwater is available for capture in the urban areas of California, depending on the amount of rainfall, in a given year. This is roughly on par with the potential for enhanced urban water efficiency and wastewater reuse (Cooley et al., 2022). With climate change projected to increase the frequency and severity of rain events as well as drought (Lall et al., 2018), capturing stormwater when it is available may become more crucial to supporting sustainable groundwater supplies. Much like municipal wastewater, stormwater has different chemical and microbial constituents that can pose risks to groundwater quality through EAR or ASR applications. Details on treatment needs and other considerations are largely dependent on site-specific conditions and more detail on the use of stormwater in EAR can be found in EPA's Stormwater EAR Report.

The Pure Water Monterey project in Central California uses municipal wastewater, stormwater, agricultural drainage, and agricultural wash water in its potable reuse facility to replenish the Seaside Groundwater Basin.

6. Subsurface Water Quality Changes and Technical Considerations

EAR and ASR systems can change the chemistry of the recharge water and the water in the aquifer through chemical and biogeochemical processes that depend on the properties of the recharge water as influenced by treatment before recharge occurs, the chemistry of the groundwater in the aquifer, the mineralogy of the aquifer, and the properties of the vadose zone (e.g., if the system is infiltration-based and provides SAT). For example, the groundwater may have achieved equilibrium with the aquifer matrix, and the addition of new water can be expected to trigger geochemical reactions (Page et al., 2018). While these subsurface processes are often quite complex, there is a long history of projects successfully navigating challenges to implement EAR and ASR projects using recycled water. An initial understanding of these processes and a site-specific investigation are needed, but there are typically feasible solutions (including treatment, detailed in Section 8) to the different issues that might arise.

Percolation of recharge water through the vadose zone during SAT can also prompt geochemical and biogeochemical processes that provide treatment of the recharge water (Page et al., 2018). Processes affecting the composition of the recharge water as it flows through the vadose zone (also known as the unsaturated zone) and saturated zone (Figure 3) include biodegradation of dissolved and particulate organic matter, nitrification and denitrification, adsorption of ammonium, adsorption of trace elements, adsorption of organic compounds, cation exchange, and precipitation of phosphates (Goren et al., 2014). Pathogen removal also occurs during this time through attenuation as well as inactivation depending on the soil characteristics and travel time. Additional pathogen removal is achieved based on residence in the aquifer with greater removal correlated with longer residence times (EPA, 2017).

The sections below briefly describe several types of subsurface changes and processes.

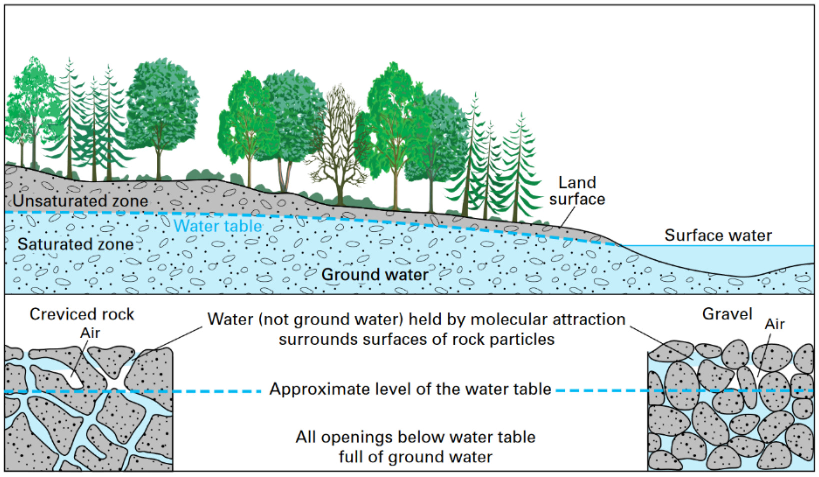

Figure 3: Unsaturated and saturated zones in soil (Source: United States Geological Survey).

6.1 Mixing Effects in the Aquifer

Where recharge waters and native groundwater mix, the water chemistry will be the result of any dilution effects from the physical blending, along with geochemical or biogeochemical reactions. Recharge water and ambient groundwater may differ in salinity, and salinity can be higher in treated wastewater than other recharge water sources, such as surface waters or stormwater. Once the recharge waters mix with the ambient groundwater, the salinity of the recovered water will likely differ from that of the recharge water (Page at al., 2018). For this reason, it is helpful if recharge water salinity is lower than or similar to groundwater salinity. If the aquifer contains high-quality groundwater, the additional salinity could be detrimental to crops if the recovered water is used for irrigation and other applications such as potable reuse. To remediate this, treatment processes, such as reverse osmosis may be needed to ensure that salinity is at an appropriate level.

When the recharge water is less saline than the groundwater (e.g., a brackish or saline aquifer) and the aquifer matrix contains fine clay particles, certain types of clay minerals (e.g., montmorillonite) will expand. The swelling clogs pore spaces but is reversible if the salinity increases again (Maliva, 2020). The influx of fresh water can also mobilize (disperse) clays from the aquifer matrix. They will then be transported in the water and can reduce aquifer permeability when they become trapped in pore spaces. This type of clogging is not reversible. Whether and how much clay will swell and disperse is site-specific, depending on aquifer mineralogy and the water chemistry changes occurring when the recharge water mixes with the native groundwater (Maliva, 2020).

Mixing of waters may also alter the geochemical conditions in the aquifer such that minerals can dissolve (e.g., calcite) or precipitate (e.g., iron [hydr]oxides), which can affect the permeability and porosity of the aquifer (EPA, 2021; Page et al., 2018; Bekele et al., 2011). Other changes, such as decreases in calcium and magnesium in groundwater from dilution, can cause clays to swell and disperse; this can cause clogging, lowering hydraulic conductivity (EPA, 2021). Such changes will affect project operations factors such as injectivity, stability of well infrastructure, and transport of contaminants.

6.2 Soil Aquifer Treatment and Changes in the Unsaturated Zone

SAT is generally considered part of the overall treatment process for treated municipal wastewater being used for recharge through infiltration. Depending on conditions, passage through the vadose zone during SAT can result in the partial attenuation or removal of several types of pollutants often found in treated municipal wastewater. These include pathogens, nitrate and ammonium, protein-based organic matter, disinfection byproducts (e.g., N-nitrosodimethylamine [NDMA], haloacetic acids [HAAs], and total trihalomethanes [TTHMs]), and pharmaceuticals and other emerging contaminants (Trussell et al., 2018; Hartog and Stuyfzand, 2017).

As an example of treatment during SAT, a field trial of infiltration of secondary treated wastewater through a 9-meter-thick calcareous vadose zone achieved the following reductions: 30 percent for phosphorus, 66 percent for fluoride, 62 percent for iron, and 51 percent for total organic carbon (TOC) with a residence time of four days in the vadose zone and less than two days in aquifer. This treatment also achieved partial reductions in pharmaceuticals (oxazepam and temazepam), and pathogens (Bekele et al., 2011). There was no reduction in total nitrogen, but there was a reduction in total organic nitrogen and ammonia and an increase in nitrate due to aerobic conditions in the vadose zone. These reductions illustrate that the benefits of SAT vary by constituent and can change over time. For example, phosphorus removal may decline as adsorption sites eventually become saturated (Bekele et al., 2011). More specific to pathogens, several studies on the attenuation of microorganisms suggest significant removal for a variety of different pathogens including up to 8 $\log_{10}$ removal of MS-2 virus and 9.5 $\log_{10}$ *Cryptosporidium* depending on travel time (EPA, 2017; Trussell et al., 2015).

Several factors control the geochemical and biogeochemical processes that treat water during SAT. For example, travel time is significant, with the desired time depending on the soil characteristics, the depth to groundwater, and the desired level of pollutant removal and attenuation. In addition, a pH between 5 and 8 is best for degrading organic contaminants and minimizing trace metal mobility (Casanova et al., 2016). The mineralogy of the vadose zone can also exert significant control on the removal of metals and organics through the sorption sites on iron and manganese (hydr)oxides and clay minerals (Casanova et al., 2016). These processes are complex and site-specific.

Like pH, reduction/oxidation (redox) conditions exert significant control on subsurface geochemistry and biogeochemistry in both the vadose and saturated zones. The effects of redox changes can be beneficial (e.g., managing nutrients) or problematic (e.g., mobilization of metals or other contaminants). An approach to managing recharge water treatment during SAT is to promote different redox conditions via flooding and drying cycles to achieve treatment goals such as the removal of trace organic compounds or nitrogen (Bekele et al., 2011). The ability to optimize an SAT system to promote these redox-dependent transformations is valuable for managing the water quality concerns associated with EAR and ASR using recycled water.

Additionally, recharge water may leach salts and other constituents from the soil during infiltration, adding to the concentrations already in the recycled water used for recharge. This is a particular concern for groundwater quality in agricultural areas because certain ions (boron, chloride, sodium) can accumulate in sensitive crops, damaging them and reducing crop yields (Richardson et al., 2018).

Case Study: Monterey One Water

Located in the central coast of California, the Monterey Peninsula Water Management District and Monterey One Water jointly developed the Pure Water Monterey initiative to replenish the Seaside Groundwater Basin with recycled water. This project also provides recycled water for landscape and agricultural irrigation in the northern Salinas Valley, where agriculture—both growing and processing crops—is a major industry (Kenny et al., 2019; Monterey One Water, 2021). This facility uses a similar treatment program as the Groundwater Replenishment System in Orange County but is unique in using multiple water sources. In addition to municipal wastewater, this project incorporates stormwater runoff, agricultural drainage, and agricultural wash water. This project began operation in 2020 with a design capacity of 5 MGD (Monterey One Water, 2021); since operation began, Monterey has proposed to expand to a capacity of 7.6 MGD and to increase recharge to the Seaside Groundwater Basin from 3,500 to 5,750 acre-feet per year (Duffy and Associates, 2020). While this is a unique facility, it demonstrates that a robust treatment and management program can be put in place to incorporate multiple alterative water sources into a single project.

6.3 Organic Carbon and Nutrients

Organic carbon in recharge water provides a source of energy for microbes, facilitating the degradation of trace organic pollutants and the reduction of nitrate. Organic carbon in the sediments also promotes adsorption of metals, removing them from water as it infiltrates through the vadose zone (Casanova et al., 2016) or moves through an aquifer. In an SAT system, dissolved organic matter is largely removed by microbial activity in the upper two meters of the vadose zone (Goren et al., 2014), and in relatively short travel times often measured in days (Trussell et al., 2018).

As noted in Section 7.1, concerns about nutrients depend on the intended end-use of water in an EAR or ASR system. An awareness of both the incoming concentrations in the recharge water and the anticipated geochemical and biogeochemical processes in the vadose zone and saturated zone is needed to manage system operations and plan for the recovered water quality. A complex set of systems control nutrient dynamics in the subsurface. For example:

- Ammonium removal is controlled by cation exchange and redox conditions in the soil, as are transformations among the nitrogen species. Under oxic conditions, ammonium is converted to nitrate. If nitrate removal is needed, subsurface conditions must be anaerobic; nitrate is converted to nitrogen gas via denitrification under anaerobic conditions and is released from the system (Goren et al., 2014).
- As noted above, nitrogen removal during SAT can be optimized by cycling between oxic and anoxic conditions, although efficiency will vary by system and is not always adequate (Bekele et al. 2011).

6.4 Redox Conditions

Redox conditions play a key role in biogeochemical processes in soils and groundwater, similar to the role they play in settings such as lakes, wetlands, and rivers. Because they are involved in the retention, release, and transformations of constituents in both water and soils/sediments, redox conditions affect the quality of the recovered water in EAR and ASR. This in turn has implications for operational choices and treatment needs before and after recharge.

In an EAR or ASR system, redox conditions depend on the recharge water quality, soil properties, depth to water table, temperature, and choices in operational practices (e.g., alternating between oxic and anoxic conditions) (Goren et al., 2014). As noted above, redox conditions in an infiltration basin (e.g., SAT system) can be controlled by flooding. Prolonged saturation of the vadose zone promotes the development of anoxic conditions, leading to processes such as denitrification and dissolution of iron and manganese minerals and release of any adsorbed contaminants (Goren et al., 2014). The recharging effluent may also be subject to diurnal changes due to daily cycles in sunlight and temperature, with increased dissolved oxygen and pH during the daytime (Goren et al., 2014). In the saturated zone, redox status may be changed by an influx of more oxygenated recharge water, although this effect is often more dramatic where recharge is done via injection wells.

6.5 Arsenic and Metals Mobilization

Mobilization of arsenic and other metals from aquifer materials has been a significant concern in some EAR and ASR systems, especially in Florida (Neil et al., 2014; Fakhreddine et al., 2015; Vanderzalm et al., 2011; Yang et al., 2016). This water quality issue arises when oxygenated recharge water is introduced into an anoxic aquifer containing arsenic-bearing minerals. The ensuing oxidation can release arsenic into the water. The arsenic may either become adsorbed to the surface of secondary iron (hydr)oxide minerals or remain in the groundwater. Should conditions subsequently become anoxic, the dissolution of iron minerals will release any arsenic or other contaminants (e.g., metals, phosphate, organics) adsorbed to the mineral surfaces. This balance between mobilization and retention will be site-specific, depending on the characteristics of the aquifer, groundwater, and recharge water. The potential for arsenic mobilization can be mitigated by matching the recharge water more closely to the native groundwater (e.g., by reducing dissolved oxygen in the water). However, arsenic can also decline during multiple operational cycles (e.g., repeated injection and recovery) as the pool of arsenic-bearing minerals is depleted (Maliva et al., 2018). Additional discussion on arsenic and metals mobilization is found in EPA's *2012 Guidelines for Water Reuse* and in EPA's UIC AR/ASR Report (in preparation).

7. Treatment Needs Associated with Sources of Water and End-Uses

7.1 Treatment before Recharge

Treatment needs before recharging an aquifer with recycled water vary depending on the source and quality of the recharge water, the recharge method, the end-use after recovery, and site-specific characteristics (Asano and Cotruvo, 2004). For example, if the native groundwater is of high quality and the end-use requires high-quality recovered water (e.g., for potable use), treatment will be quite important (Page et al. 2018). Treatment can also ensure water used for recharge is compatible with the subsurface soils, sediments, and groundwater to minimize geochemical reactions such as mineral dissolution, precipitation, and mobilization of contaminants like arsenic (see Section 6.5 for details).

For EAR and ASR with treated municipal wastewater involving injection wells, treatment requirements are often more stringent to address specific pathogens and other pollutants (see Section 9 for details on state regulations). The treatment processes used vary, but generally include a combination of low- and high-pressure membrane treatment, disinfection through chemical treatment, ultraviolet light, oxidation through ozonation, or other advanced oxidation processes, such as the combination of ultraviolet light and hydrogen peroxide (EPA, 2017).

SAT—the process where water passes through the unsaturated zone above a groundwater table, improving water quality through a variety of physical, chemical, and biological processes that retain, transform, or degrade contaminants, nutrients, and pathogens—can also be used in infiltration projects as part of a treatment strategy in place of some engineered treatment systems in locations with the appropriate hydrology and soil conditions (Goren et al., 2014). The specific treatment technologies and approaches selected for a project will vary based on the state regulations, source water quality, and other conditions such as the ability to manage brine concentrate from reverse osmosis.

While treatment can occur after withdrawal, addressing water quality issues in the recharge water is often more effective. For example, for controlling dissolved organic carbon, trace organics, and disinfection byproducts, laboratory studies with column experiments suggest that pre-ozonation of WWTP effluent was better than ozonation after SAT. This is due to ability of ozonation to enhance organic matter’s biodegradability to facilitate greater removal through SAT (Echigo et al., 2015). A soil column study also found that replacing chlorination before recharge with ozonation of tertiary-treated effluent prior to SAT resulted in removals of bulk organic matter, and a wider variety of emerging contaminants and pathogens (Trussell et al., 2015).

In addition to treatment, water quality concerns in recycled water can be addressed through measures such as blending with surface water, as the concentrations of salts, nutrients, and organic compounds are reduced through dilution. This strategy depends on the availability of sufficient volumes of water with an acceptable quality for blending.

7.1.1 Preventing Clogging during Recharge

For systems using infiltration with SAT, the water may need treatment before recharge to reduce suspended solids and thus prevent clogging. This can be accomplished by coagulation, settling ponds, and sand filtration upstream of infiltration basins (Casanova et al., 2016; Hartog and Stuyfzand, 2017).

Also, because microbial growth can cause clogging in the soil, water often needs to be disinfected and potentially chemically treated to reduce organic matter (Hartog and Stuyfzand, 2017). Treatment with sand filtration and UV disinfection prior to recharge has also been successful in reducing clogging and addressing poor infiltration rates. In one study using treated municipal wastewater, adding a filtration step has been found to improve the average infiltration rate in basins by 40 to 100 percent in one project (Barry et al., 2017). As an alternative to treatment, the practice of alternating wetting and drying cycles (e.g., increasing or decreasing the amount of water in a system) in SAT systems can preclude the need for other forms of treatment by reducing clogging at the basin floor.

7.1.2 Considerations of Existing Aquifer Characteristics

Where the release of arsenic and other metals is a concern, it is desirable to match the quality of the recycled water to that of the native groundwater as closely as possible based on available economic and technical capacity. Such adjustments can include dissolved oxygen removal, adjustments to pH and ionic composition, and control of the concentration of residual oxidants from treatment (e.g., hydrogen peroxide, free chlorine, and chloramines). All of these factors affect the overall geochemical environment, and the concentrations of dissolved oxygen and other oxidants affect the oxidation of arsenic-bearing pyrite and release of arsenic, iron, and manganese. The effect of these oxidants on the redox conditions depends on the concentration of organic matter in the sediments, which consumes oxidants (Hokanson et al., 2020). Water quality degradation from the mobilization of arsenic, iron, and manganese may also wane over repeated cycles as the pyrite becomes oxidized and depleted. This concept has been explored experimentally (Antoniou et al., 2014).

If salinity needs to be reduced, wastewater can be treated with reverse osmosis or nanofiltration. Reverse osmosis is highly effective at removing salts and metals, but stabilization with caustic soda or lime is often needed to ensure the water does not corrode the conveyance infrastructure and is compatible with the aquifer (EPA, 2017). Nanofiltration requires less energy than reverse osmosis, and while it will remove less dissolved solids, allowing some monovalent ions such as calcium and potassium to pass through, it will remove larger molecular weight compounds (EPA, 2017).

7.2 Treatment after Recovery

Water recovered from an aquifer may need treatment if its quality has deteriorated in the subsurface or if disinfection byproducts form after extraction and treatment. As well, there may be a need to address the mobilization of iron and manganese, due to the reductive dissolution of iron and manganese (hydr)oxides. The iron and manganese may oxidize in the near-well environment and cause clogging. If arsenic has been mobilized in the aquifer, blending or treatment will also be needed.

8. Methods of Implementation: Opportunities and Constraints

There are different ways to implement EAR and ASR, and the choice of which one to use depends on factors such as local hydrology, hydrogeology, and ambient water quality (Dillon et al., 2019). This section describes two primary methods, infiltration or injection: either may be suitable for recharging aquifers with recycled wastewater, depending on the site-specific conditions.

Commonly used methods of infiltration include the following:

- **Infiltration galleries**—diversion of water into buried trenches dug in permeable soils for percolation into an unconfined aquifer. An infiltration gallery can be considered a Class V well under the UIC program if it is deeper than its widest surface dimension, or if it includes an assemblage of perforated pipes, drain tiles, or other similar mechanisms intended to distribute fluids below the ground surface (EPA, 2008).
- **Infiltration ponds and spreading grounds**—diversion of recharge water to off-channel areas not connected to rivers or other waterbodies to allow for infiltration into an unconfined aquifer.

There are several other infiltration methods used for recharge with surface water diversions and other sources of water that this report does not discuss in depth. Such methods are better suited for surface water diversions largely because they are implemented in ephemeral streams or existing surface water bodies where wastewater may not be conveniently available. However, it should be noted that in some regions, such as the southwestern United States, there are streams where the flow consists primarily of treated wastewater through de facto water reuse that could be considered as recharge (Rice et al., 2013). Infiltration methods are suitable for a range of unconfined aquifers, from porous, high-permeability aquifers to fine sands (Goren et al., 2014). These methods are generally inexpensive and fairly simple to construct and maintain (Casanova et al., 2016; Goren et al., 2014), with designs that can be adjusted depending on the project objectives and characteristics of the basin, source water, and aquifer(s). Expected residence times are generally in the range of months to years (Miller, 2006), often depending on aquifer properties and the rate of withdrawal (Goren et al., 2014). All infiltration methods use SAT, which is further discussed in Section 6.2.

Additional infiltration methods include:

- **Percolation tanks, check dams, or recharge weirs**—dams built along ephemeral streams to detain the water and give water more time to infiltrate into the riverbed.
- **Bank filtration**—groundwater extraction from a well near or beneath a lake or river, inducing percolation from surface water. Drawing down the water table by pumping from a nearby well can induce more water to flow through riverbanks and into a pumping well while helping to replenish the aquifer.
- **Recharge releases**—dams on ephemeral streams used to discharge water to the downstream streambed at rates that match the capacity for infiltration into underlying aquifers. This method is typically focused on recharging aquifers when there is available volume.

Injection methods include:

- **Injection well**—a bored, drilled, or driven shaft whose depth is greater than the largest surface dimension, a dug hole whose depth is greater than the largest surface dimension, an improved sinkhole, or a subsurface fluid distribution system (40 CFR 144.3).
- **Dry well**—an injection well, other than an improved sinkhole or subsurface fluid distribution system, completed above the water table so that its bottom and sides are typically dry except when receiving fluids (EPA, 2000).

8.1 Site Selection

The critical site selection factors for an EAR and ASR infiltration project include topographic, geologic/hydrogeologic, environmental, and social considerations (e.g., Ahmadi et al., 2017)[5]. Environmental considerations include soil infiltration capacity, water scarcity, source water availability, and water quality issues. In addition, it is especially important to understand the "complete geologic architecture of the subsurface layer" (e.g., fine vs. coarse soil layers and their extent and connectedness) when siting an EAR or ASR project (Alam et al., 2021).

Examples of topographic and geologic/hydrogeologic factors include:

- **Slope**—for infiltration practices, the slope must be shallow enough to minimize runoff and allow for infiltration.
- **Depth to water table**—if the system involves SAT, the vadose zone should be thick enough to allow for pollutant removal.
- **Soil type**—if the system uses infiltration for SAT, soils should be sandy loam, loamy sand, or fine sand soils that are permeable enough to allow high infiltration rates and also provide removal of trace organics, nutrients, heavy metals, and pathogens.
- **Groundwater quality**—understanding the ambient and recharge water quality can help in ensuring compatibility between the recharge water and the existing groundwater in the aquifer or identifying any anticipated changes in groundwater quality.

Given the various factors involved in site selection, multiple criteria can be taken into consideration to help with project siting. For example, Ahmadi et al. (2017) conducted spatial analysis with each criterion represented by a thematic geographic information system (GIS) layer, which can then be integrated for analysis. The resulting maps were found to be highly valuable for optimizing site selection. As an example of a statewide approach, the Texas Water Development Board has produced an extensive evaluation of site suitability for EAR and ASR in Texas, including a multiparameter scoring methodology (HDR Engineering, 2020).

8.2 Clogging

Clogging with fine particulates, mineral precipitates, and/or biofilms is a frequent concern for both injection- and infiltration-based EAR and ASR projects. The resulting reductions in porosity and permeability pose challenges with maintaining injection rates or infiltration rates, especially if the

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[5] The UIC AR/ASR Report (in preparation) contains discussion on siting for aquifer recharge and ASR via injection wells.

recycled water contains a high concentration of suspended solids or is geochemically incompatible with the subsurface solids and groundwater (Barry et al., 2017).

While existing soil characteristics cannot be changed, operational and treatment practices can be optimized to prevent clogging. As discussed in Section 7.1.1, treatment of recycled water prior to recharge can be designed to minimize the potential for clogging—for example, by reducing suspended solids, minimizing the potential for bacterial growth, and adjusting water quality for compatibility with the subsurface geochemical conditions (Casanova et al., 2016). Maintenance measures such as the removal of fine sediments from the bottoms of infiltration basins and control of wet and dry periods are also important to prevent clogging (Barry et al., 2017). More detailed discussions of clogging and other challenges are provided in the Stormwater EAR Report (EPA, 2021) and the UIC AR/ASR Report (in preparation).

Case Study: Montebello Forebay

Since 1962, groundwater replenishment has been conducted at the Montebello Forebay Spreading Grounds in Los Angeles using diverted surface water, tertiary treated municipal wastewater, and stormwater. Considered to be the first such project in the United States (National Research Council, 2008), this project does not require the higher levels of engineered treatment seen in some groundwater injection projects because of the use of SAT and allows multiple sources of water to be integrated into a single project. To investigate the health effects of this project and reuse of treated wastewater for groundwater recharge, a five-year epidemiological study was initiated in 1978. This study concluded that there were no measurable adverse health effects on the surrounding community (National Research Council, 1994). More information on this project is available in the *2012 EPA Water Reuse Guidelines* (EPA, 2012).

9. Regulatory Environment

Groundwater withdrawal in the United States is regulated by the states. As groundwater demand has increased over time, more attention has been given to the potential for certain groundwater basins to be over-pumped, leading to increased pumping costs, the need for deeper wells, land subsidence, and seawater intrusion. In the United States, there are no national regulations specifically for water reuse applications, either potable or non-potable. In lieu of national regulations for water reuse, states have the authority to develop their own, and several have developed regulations for potable and non-potable reuse. A complete compilation of state-level regulations for water reuse has been developed through EPA's REUSExplorer, found at http://www.epa.gov/reusexplorer. Note that for projects using injection wells, EPA or states with primary enforcement authority regulates the construction, operation, permitting, and closure of injection wells through the UIC program.[6]

These regulations vary by state but are generally intended to address different chemical and microbial contaminants through treatment requirements and standards that often go beyond existing regulations under the Clean Water Act and the Safe Drinking Water Act. In all states, finished drinking water from a groundwater source augmented by recycled water must, at a minimum, meet all applicable Safe Drinking Water Act requirements. There are currently no specific state regulations on using industrial wastewater, stormwater, agricultural return flows, and other recycled water sources in EAR or ASR projects, though flows from these sources are often incorporated into wastewater treatment facility influent.

This section summarizes several states' regulations on EAR and ASR using treated municipal wastewater. This is not a comprehensive list: various other states (e.g., Oregon, Oklahoma, New Mexico) can also permit projects on a case-by-case basis with treated municipal wastewater.

Groundwater Management in California

Because the states regulate groundwater management, including extraction and legal rights, it is difficult to generalize in a national context. In California, the Sustainable Groundwater Management Act (SGMA) was passed in 2014. SGMA requires local agencies to develop and implement plans to ensure sustainable groundwater management where there is balance between withdrawal and recharge. This was done to prevent further overdraft in many of the state's groundwater basins to help ensure that groundwater will continue to be available, even in times of drought. These plans must be implemented, with sustainability achieved, by 2042 (CA LAO, 2017). By using recycled water as a source for recharge, some aquifers can be consistently replenished to help ensure that groundwater is managed sustainably.

9.1 California

For groundwater recharge with recycled water, California regulations include specific treatment requirements for pathogens and chemicals, and projects must be reviewed and permitted on a site-specific basis by the Regional Water Board (SWRCB, 2018). For pathogens, there are requirements of a total of 12 $\log_{10}$ enteric virus reduction, 10 $\log_{10}$ *Giardia lamblia* cyst reduction, and 10 $\log_{10}$

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[6] More information on the regulation of injection wells can be found on EPA's Underground Injection Control program website.

Cryptosporidium oocyst reduction, where each log corresponds to removal or inactivation of 90 percent of initial concentrations. These requirements apply to both groundwater recharge through surface spreading as well as injection (California Code of Regulations, Title 22, §60320.108).

For the control of chemicals in injection projects, treatment must include reverse osmosis as well as advanced oxidation to provide a minimum of 0.5 log reduction of 1,4-dioxane (California Code of Regulations, Title 22, §60320.201). Finished water must meet a limit of 0.5 mg/L for TOC (California Code of Regulations, Title 22, §60320.218) and is subject to monitoring requirements for various compounds of emerging concern. However, for projects using surface spreading, only tertiary treatment and disinfection is typically required, with SAT providing the additional necessary treatment for both chemicals and pathogens. There is also a minimum retention time of two months in the aquifer.

9.2 Massachusetts

Massachusetts can permit the use of recycled water for aquifer recharge in a Zone II ("That area of an aquifer which contributes water to a well under the most severe pumping and recharge conditions that can be realistically anticipated [180 days of pumping at safe yield, with no recharge from precipitation]") or an Interim Wellhead Protection Area ("a half mile radius from the well or well field for sources whose approved pumping rate is 100,000 gallons per day or greater"). Zone I is an area closer to a public water supply well and may not be replenished with recycled water. There are no treatment specifications, but special conditions are included in permits on a case-by-case basis (Code of Massachusetts Regulations, Title 314, §5.00 and §20.00).

9.3 Nevada

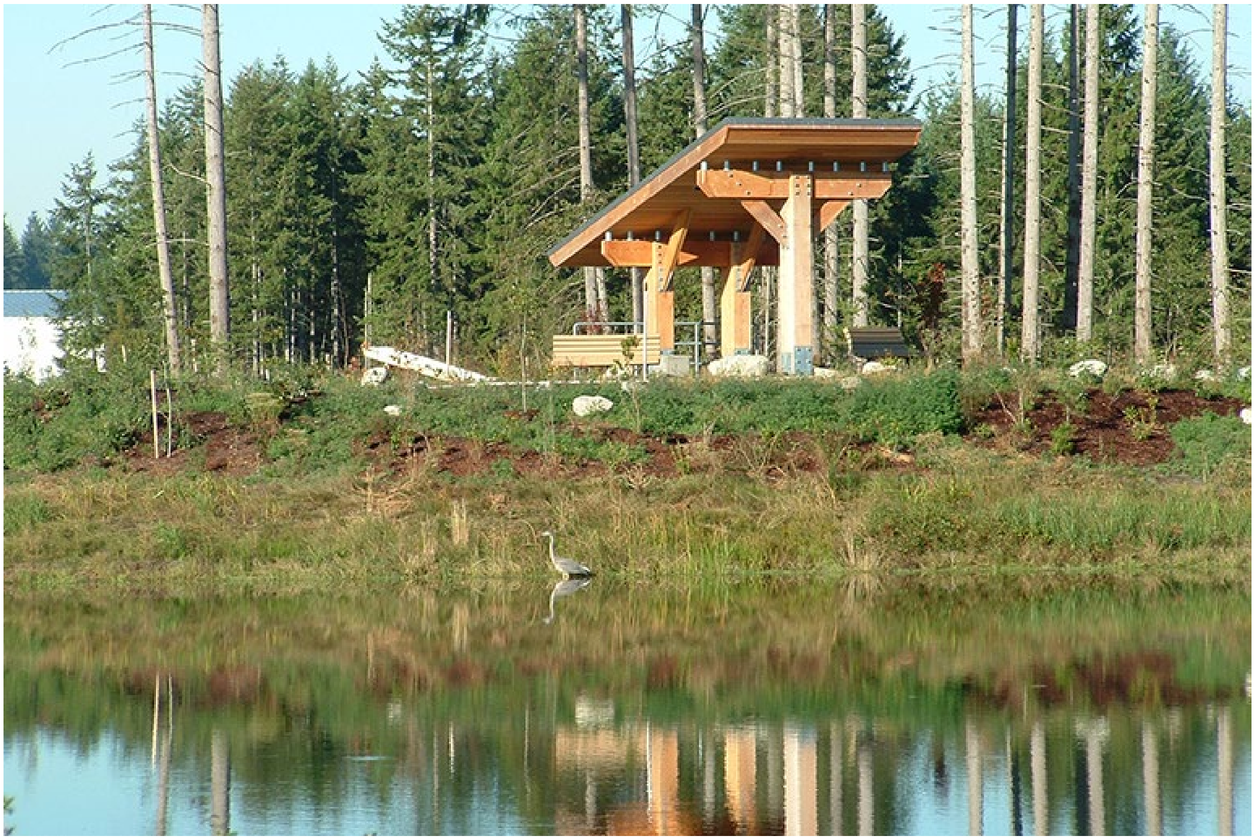
Nevada has regulations for groundwater recharge with recycled water that are similar to California's. While Nevada has the same pathogen removal requirements as California, it does not have the same treatment requirements for chemicals and TOC. The primary difference is that Nevada does not require the use of reverse osmosis for injection projects (Nevada Administrative Code, §445A.276), largely because there is no ability to use an ocean outfall to discharge brine concentrate into. Not requiring the use of reverse osmosis allows alternative treatment options that may better fit the needs of inland communities.

9.4 Pennsylvania

Pennsylvania has different requirements for groundwater recharge for both surface spreading and direct injection (Pennsylvania DEP, 2012). In contrast to some other states that use numerical targets for pathogen and chemical control, Pennsylvania has prescriptive treatment requirements with additional treatment required for injection compared to surface spreading. More specifically, much as in California, reverse osmosis is required for direct injection, but not for surface spreading. In addition, direct injection requires a residence time in the aquifer of 12 months compared to 9 months for surface spreading.

Water Rights

A common legal consideration for EAR and ASR projects using recycled water is water rights. Each state has its own system for determining who has the legal right to surface water and how much they have the right to use. In general, states in the East (e.g., east of the 100th meridian) apply the riparian doctrine, which generally means that water belongs to the person whose land borders a body of water; this person may make reasonable use of that water as long as it does not unreasonably interfere with reasonable use by others with rights to use of this water (National Agricultural Law Center, 2022). In the West (e.g., west of the 100th meridian), the prior appropriation doctrine is generally used. This doctrine can be summarized by the phrase "first in time, first in right," meaning that the first person to use or divert water for beneficial use can obtain rights to that water (National Agricultural Law Center, 2022). Some states, such as California and Oklahoma, have adopted a hybrid of the riparian and prior appropriation doctrines (National Agricultural Law Center, 2022). While this simplistically defines the issue, the nuances could affect a community's ability to use recycled water for EAR or ASR and may require consultation with water law experts in each state.



At the Hawks Prairie Ponds in Lacey, Washington, reclaimed water flows through several wetland ponds before entering groundwater recharge basins.

10. Costs and Benefits

As has been described, EAR and ASR practices vary widely on source of water, end-use, and the site-specific conditions and geology of an aquifer. Even so, there are some general themes regarding costs and benefits for different practices. For example, recharge of unconfined aquifers using infiltration basins and minimally treated water (e.g., relying only on SAT for additional treatment) will cost less than recharge through injection using water that requires higher levels of engineered treatment (Ross and Hasnain, 2018). The details of these costs are driven by different factors including the cost of different unit treatment processes before recharge and the cost of conveyance (including injection). The benefits largely correspond the drivers mentioned above (see Section 3) and can be evaluated and quantified using a triple-bottom-line (TBL) framework or similar approach. There are also additional cost considerations from land acquisition for infrastructure, including the need for land to be used for infiltration basins.

10.1 Cost of Treatment

The cost of treatment in an EAR or ASR system using recycled water will depend on many factors including the source of water, its quality, and the treatment standards and requirements based on the applicable regulations. For example, an EAR or ASR system using captured stormwater as a source will likely have very different treatment requirements than a system using treated municipal wastewater. These additional treatment requirements for municipal wastewater are likely to result in greater costs compared to systems using other sources of water.

For the cost of treatment for municipal wastewater used for EAR and ASR to supplement drinking water supplies via indirect potable reuse, site-specific information may be available that can be used to identify some key factors. For example, in 2014 treatment for the Orange County Water District's (OCWD's) Groundwater Replenishment System (GWRS) was estimated to cost about $700 per acre-foot (Raucher and Tchobanoglous, 2014). Estimates were based on the actual operating expenses of the GWRS treatment train, which includes reverse osmosis—an energy-intensive process. This treatment approach is required in California for projects with municipal wastewater as the source for groundwater injection.

With projects using different treatment approaches than reverse osmosis, the cost of treatment can be substantially different, in large part due to differences in energy demand. Evaluations of the costs of different treatment options for potable reuse have shown that treatment trains using ozonation and biofiltration are less costly than reverse osmosis-based treatment (Plumlee et al., 2014; Funk et al., 2019). This is in large part due to the high energy demand of reverse osmosis. The cost may be even lower for facilities using spreading grounds that take advantage of SAT, but the cost of operating and maintaining spreading grounds would need to be taken into account.

10.2 Cost of Conveyance

Once recharge water is treated to a suitable quality, it must be conveyed to the point of recharge. The cost of this conveyance is site-specific and depends on the distance and elevation between the point of treatment and recharge (Raucher and Tchobanoglous, 2014). Ideally, the two sites would be co-located, which is feasible for some sources of water that do not require much engineered treatment. For municipal wastewater, though, the treatment facility may be several miles from the point of recharge. For example, OCWD's GWRS is about 13 miles from groundwater infiltration basins, resulting in conveyance costs of $120 per acre-foot as of 2014 (Raucher and Tchobanoglous, 2014).

Case Study: Hampton Roads Sanitation District

As part of its Sustainable Water Initiative for Tomorrow (SWIFT), the Hampton Roads Sanitation District (HRSD) plans to inject treated effluent from seven of its wastewater treatment plants into the Potomac Aquifer, which is the primary source of groundwater in eastern Virginia (Lang and Kane, 2017). Unlike in other communities, the main drivers for this project are improving surface water quality, saltwater intrusion, and the need to address groundwater overdrafts in Virginia's Coastal Plain (Green Nylen, 2021). As a discharger to the Chesapeake Bay, HRSD must meet strict nutrient limits for its effluent. While HRSD was able to meet those effluent discharge limits, there were concerns that regulators might impose more stringent ones in the future.

Once SWIFT is fully implemented, HRSD is expected to recharge a total of 100 MGD from five wastewater treatment plants (Green Nylen, 2021). HRSD currently has a research facility operating at its Nansemond Wastewater Treatment plant, which treats and injects 1 MGD. The projected cost of the full-scale SWIFT implementation is $1.1 billion in capital costs, with annual operating costs estimated at between $21 million and $43 million per year (Green Nylen, 2021). HRSD expects that full implementation will bring a 90 percent reduction in nutrient load from each of the SWIFT-equipped treatment plants, generating enough nutrient credits to enable 11 of the municipalities within the HRSD service area to avoid spending $2 billion on otherwise-necessary improvements. The primary beneficiaries of these credits are HRSD ratepayers that are funding the SWIFT project. Thus, no charge is to be assessed to them. In addition, HRSD plans to explore opportunities to sell credits at market price to other interested parties, thereby obtaining another source of revenue to offset costs (Green Nylen, 2021). This approach is expected to generate millions of pounds of nutrient pollution credits annually through the Chesapeake Bay Watershed Nutrient Credit Exchange Program, while also replenishing scarce groundwater resources, staving off saltwater intrusion, and counteracting land subsidence (Green Nylen, 2021).

10.3 Quantifying Benefits

While the direct costs of EAR and ASR can largely be quantified through economic and financial analyses, estimating the complete suite of benefits is more difficult. Such benefits are diverse. They include providing additional water supply and water security for communities, industries, and agriculture; providing a reserve water supply for emergency use; and improving groundwater quality (Zheng et al., 2021). For a scenario in which the main benefit is additional water supply, the benefit can be estimated by looking at the volume of water recovered or supplied and multiplying it by the cost of the supply, or by comparing it to the alternative cost of production (Zheng et al., 2021).

Costs and benefits are often evaluated in tandem on a life-cycle basis using a variety of economic, environmental, and social factors through a TBL framework. This type of evaluation is often complex and includes a variety of potential costs and benefits to consider (see Table 1). The precise metrics used to evaluate projects vary based on the details of the project, as well as the desired outcome for the community. How a community views the TBL factors for a proposed project will depend on site-specific factors including the project goals. Several tools have been created for the evaluation of alternate water reuse and water supply projects that use various approaches, scoring criteria, and frameworks such as multi-criteria decision analysis (Hadjikakou et al., 2019; Piper, 2014). This topic is being explored further in WRAP Action 7.7, Life Cycle Analysis to Support Cost-Effective Enhanced Aquifer Recharge.

Table 1. Examples of Triple-Bottom-Line Costs and Benefits for a Water Supply Project

Economic	Environmental	Social
Lifecycle cost	Carbon footprint	Impact on public health
Local and regional job creation	Impact on nutrient discharges	Public acceptance
Amount of water produced	Impact on other pollutant discharges	Implementation risk
Avoided costs due to inaction	Residuals production and disposal	Impacts on recreation
	Drought and climate resilience	

An important concept to consider when evaluating the climate resilience benefits of EAR and ASR projects is the benefits of action, compared to the costs of inaction. While there are upfront costs associated with any drought mitigation project, including EAR or ASR with recycled water, the costs are often smaller than costs associated with the impacts of drought. For example, the 2011 drought in Texas resulted in an estimated $7.6 billion in agricultural losses throughout the state, including livestock and crop production losses (Texas Comptroller of Public Accounts, 2014). Meanwhile, the Millennium Drought in Australia that officially ended in 2012 resulted in $AUD 4.5 billion in government emergency assistance expenditures from 2001 to 2008 (Productivity Commission, 2009). This figure just includes the amount in emergency aid that the Australian government provided and is not a true reflection of the broader economic impact that occurred as a result of the drought. While investments in water reuse through EAR and ASR will not eliminate the economic impact of drought, such projects can be helpful to mitigate the impacts. It is important that water managers consider not just the direct costs and benefits of a water supply project, but the avoided costs of climate-change-induced drought.

The Hampton Roads Sanitation District's Sustainable Water Initiative for Tomorrow will replenish the Potomac Aquifer to improve water quality in the Chesapeake Bay and mitigate land subsidence.

11. Summary and Conclusions

As the impacts of climate change continue to drive drought, it is more critical than ever for communities to look toward alternative sources of water. Overreliance on unsustainable groundwater extraction is only a temporary solution to drought, and recharge with recycled water in appropriate locations can help restore and protect local groundwater supplies.

Implementing an EAR or ASR project with recycled water can seem daunting with all the different factors that must be taken into consideration, as each aquifer and potential project location is unique in its native water quality, geochemical characteristics, and other conditions. Site-specific conditions have a direct influence on project siting, design, and operations that need to be developed to ensure public health protection and compliance with applicable state and federal regulations. Regulations vary from state to state, but water quality goals can be met with a combination of engineered treatment and natural processes such as SAT. Once site-specific issues and treatment requirements are understood, many communities can design and implement EAR and ASR projects with recycled water to meet growing demands for water while also protecting vital groundwater supplies.

There have been successful projects in the United States implementing EAR or ASR with recycled water to enhance local water supplies and become more resilient to climate change impacts. This report serves as an introductory guide to lead toward increased understanding of using recycled water for EAR and ASR, where appropriate, as part of a more resilient and integrated water resource management strategy. Communities can build off the successes of existing projects and use the information and resources identified in this report to help make these projects a reality while protecting public health and the environment.

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