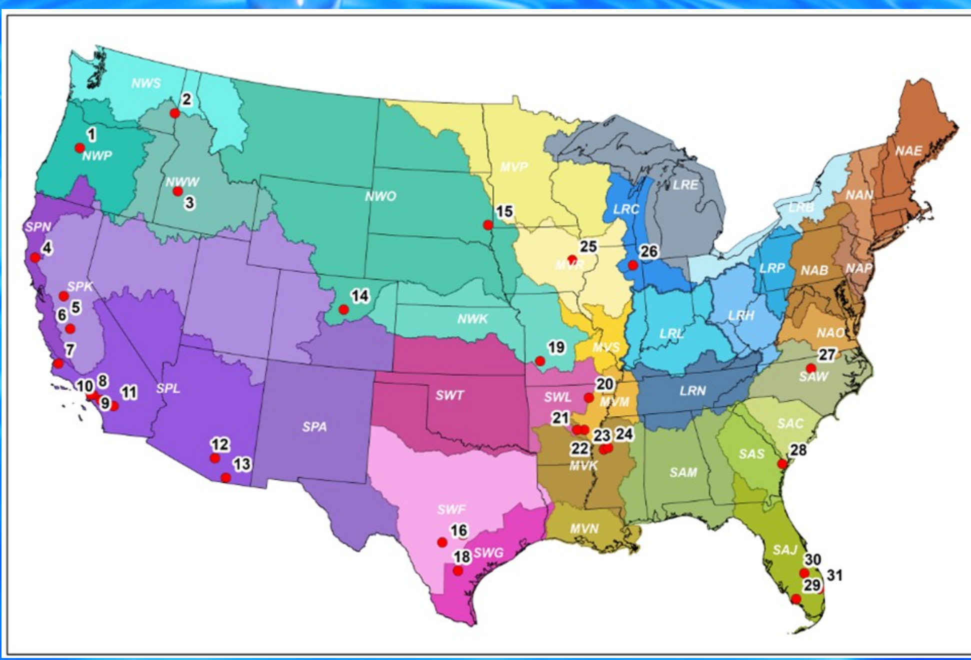
IWR Institute for Water Resources

April 2020

Managed Aquifer Recharge and the U.S. Army Corps of Engineers: Water Security through Resilience

2020-WP-01



US Army Corps of Engineers®

IWR

www.iwr.usace.army.mil

Institute for Water Resources

The Institute for Water Resources (IWR) is a U.S. Army Corps of Engineers (USACE) Field Operating Activity with centers located in Alexandria, VA, Davis, CA; New Orleans, LA; Lakewood, CO; and Pittsburgh, PA. IWR was created in 1969 to analyze and anticipate changing water resources management conditions and develop methods and analytical tools to address economic, social, institutional, and environmental needs in water resources. Since its inception, IWR has been a leader in the development of strategies and tools for planning and executing USACE water resources and water management programs.

IWR strives to improve the performance of the USACE water resources program by examining water resources problems and offering practical solutions through a variety of technology transfer mechanisms. In addition to hosting and leading USACE participation in national forums, these mechanisms include the production of white papers, technical reports, workshops, training courses, guidance and manuals of practice. IWR works to develop new methodologies and tools in planning, socio-economics, and risk-based decision-support, hydraulic and hydrologic engineering methods, and risk based design and assessment of engineered works such as dams and levees. IWR also supports management of national waterborne commerce statistics and other Civil Works data information systems. IWR serves as the USACE expertise center for integrated water resources planning and management, hydraulic and hydrologic engineering, collaborative planning and conflict resolution, and waterborne commerce data and marine transportation systems.

The Institute's Hydrologic Engineering Center (HEC), located in Davis, CA, specializes in the development, documentation, training, and application of hydraulics and hydrologic engineering models. IWR's Navigation and Civil Works Decision Support Center (NDC), located in Alexandria, VA, and Waterborne Commerce Statistical Center (WCSC) in New Orleans, LA, are the USACE data collection organization for waterborne commerce, vessel characteristics, port facilities, dredging information, and information on navigation locks. IWR's Risk Management Center (RMC), located in Lakewood, CO, with a satellite office in Pittsburgh, PA, is a center of expertise whose mission is to manage and assess risks for dams and levee systems across USACE, support dam and levee safety activities, and to develop policies, methods, tools, and systems enhance these activities.

Other enterprise centers at the Institute's National Capital Region (NCR) office include the International Center for Integrated Water Resources Management (ICIWaRM), under the auspices of UNESCO, which is a distributed, intergovernmental center established in partnership with various Universities and non-Government organizations; and the Conflict Resolution and Public Participation Center of Expertise (CPCX), which includes a focus on both the processes associated with conflict resolution and the integration of public participation techniques with decision support and technical modeling. The Institute plays a prominent role within a number of the USACE technical Communities of Practice (CoP), including the Economics CoP. The USACE Chief Economist is resident at the Institute, along with a critical mass of economists, sociologists and geographers specializing in water and natural resources investment decision support analysis and multi-criteria tradeoff techniques.

The Director of IWR is Dr. Joe D. Manous, Sr., P.E., D.WRE. Additional information on IWR can be found at: http://www.iwr.usace.army.mil. IWR's NCR mailing address is:

U.S. Army Corps of Engineers Institute for Water Resources
7701 Telegraph Road, 2nd Floor Casey Building
Alexandria, VA 22315-3868

Managed Aquifer Recharge and the U.S. Army Corps of Engineers: Water Security through Resilience

2020-WP-01

April 2020

Prepared by William S. Logan IV, PhD, USACE Institute for Water Resources

USACE Institute for Water Resources

Institute for Water Resources

Storing water underground (managed aquifer recharge, or MAR) can augment surface storage and increase resilience of USACE projects and improve our nation's water security. USACE and its partners are using, have considered or are considering using MAR, or conjunctive management of ground- and surface water, in at least 17 states in six of the seven USACE divisions in the Continental United States. The authorities for using MAR in USACE projects are modest but increasing.

USACE is using or considering MAR to help fulfill its primary missions of flood risk management and aquatic ecosystem restoration, and for secondary purposes such as drought resilience, water supply, and reducing saltwater intrusion. For secondary mission areas, the agency's role in MAR is typically to support its partners' efforts to meet their water resources needs. MAR can be smoothly integrated into USACE's planning process, including stakeholder engagement, reallocation studies and forecast-informed reservoir operations.

The additional management flexibility provided by MAR may help address allocation conflicts triggered by new water demands or changing conditions; opportunities exist in both eastern (riparian law) and western (prior appropriation law) states. USACE should improve education and training of its staff, and create opportunities for intra- and inter-agency exchanges of knowledge and experience, on uses, roles, and science and engineering behind MAR. This will improve the ability of Corps staff to identify where MAR may be a management measure worthy of consideration.

Preface and Acknowledgements

This project traces its roots to a 2012 event held at the Institute of Water Resources in Alexandria, VA, which was held to brainstorm, draft, and pitch emerging water management concepts and ideas to IWR leadership. IWR staff member Shawn Komlos and the author created a four-page outline, and later, a presentation, titled "Managed Aquifer Recharge and Corps Planning and Management". With support from IWR Directors Robert Pietrowsky (inception-2017) and Joe Manous (2018-present), this concept evolved into a more formal project.

June Mirecki and April Patterson (Jacksonville District) opened up the dual opportunities for the author to serve as Agency Technical Review Team Lead for the Comprehensive Everglades Restoration Plan Aquifer Storage and Recovery Pilot Project (2014), and to coordinate the Independent External Peer Review of the ASR Regional Study Technical Data Report (2015). These activities provided additional impetus to this report.

A 2019 meeting of the Water Supply Working Group, organized by Brad Hudgens (IWR) and the Southwestern Division, was the venue of many helpful discussions. In particular, Katy Breaux (Vicksburg), Cherilyn Plaxco (Southwestern Division), Jeannette Baker (IWR), Elden Gatwood (Wilmington District), Eric Laux (Omaha District), Kathryn Warner (Portland District), Jennifer Henggeler (Kansas City District), Chan Modini (HEC), and David Johnson (Kansas City District) shared plentiful ideas and information.

Several colleagues from IWR provided advice on project scoping and reviewed early versions of this paper. These included Jeannette Baker, Jeff Jacobs, Gene Stakhiv, and Forrest Vanderbilt. In addition, Dan Inkelas and Amber Rudolphi from USACE Headquarters provided a legal review of the Authorities chapter.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures described in IWR's Supplement 1 to IWR Regulation 15-1-1, "Field Operating Activity Boards, Committee, and Partnerships," IWR Editorial Review Board (ERB). The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. We wish to thank the following individuals for their review of this report: Shawn Komlos and Brad Hudgens (IWR); Jon Fenske (Hydrologic Engineering Center, USACE) and Christopher Pitre (Coho Water Resources, Seattle, WA).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse any conclusions and recommendations nor did they see the final draft of the report before its release. The author is grateful to all of those who contributed their ideas, knowledge and critiques to the report.

The review of this report was overseen by Jeff Jacobs, Managing Editor, and Kelly Barnes, Associate Editor for the IWR ERB. Final publication and distribution approval was the responsibility of ERB Publisher, and Director, IWR National Capital Region (NCR), Mike Pfenning.

Table of Contents

Table of Figures

This page is intentionally left blank

1. Executive Summary

As opportunities diminish to build major new surface infrastructure for water storage in the United States, water resources management and planning are more challenging than ever. Much of the existing infrastructure is aging and in need of recapitalization. Funding for infrastructure projects is falling. And the water needs of society are becoming more diverse and often increasing, as evidenced by the large number of reallocation studies among U.S. Army Corps of Engineers (USACE) projects. Water security in all its forms is as important as ever, but seems ever more difficult to achieve.

But in the midst of these challenges lie opportunities as well. Temporarily storing water underground (Managed Aquifer Recharge, or MAR) for a variety of water management purposes has become progressively more important in the US and globally. This storage may be accomplished through recharge wells, spreading basins, dry river courses, and other techniques.

USACE increasingly finds itself engaged in MAR projects. In fact, this report documents that USACE or its state and local partners are considering, evaluating, testing or operating MAR or conjunctive use activities in at least 17 states—from the arid Southwest to the humid Southeast. Some of the General Congressional authorities that govern USACE activities, such as the Flood Control Act of 1944 and the Water Supply Act of 1958, are not necessarily inconsistent with the use of MAR; however, the Water Resources Development Act of 2016, in Sections 1116 and 1118, added new authorities for USACE to engage in MAR. In line with its current strategic documents, USACE and its partners are using, and can make greater use of, MAR to fulfill their water resources missions, including for drought planning and management, flood mitigation, reallocation studies and water supply planning, reservoir management, wetlands and ecosystem restoration, and other purposes.

This report presents conclusions and recommendations regarding the use of MAR to be considered by USACE leadership. They are intended to help USACE increase the resilience of its projects to stressors such as population growth, changing land use, and increasing climate variability. This may help the Nation to prepare, absorb, recover, and adapt to future adverse events or conditions, while extending the functional utility and life of existing water resources management infrastructure. In this sense, MAR may be considered a “least regrets” strategy for improving national water security.

These conclusions and recommendations are as follows:

Conclusion: USACE and its Partners are already involved in MAR, across a broad geographic and thematic landscape, but in an ad hoc manner

> **Recommendation**: USACE should enhance its internal communications relative to MAR and conjunctive use. The creation of a community of practice, working group, and/or center of expertise may help to build such a community.

> **Recommendation**: USACE should upgrade its internal capacity in MAR. It should consider developing one or more training courses on MAR and related topical areas for its planners, managers,

economists and engineers. It should also encourage more informal on-the-job training and mentoring as appropriate, as well as participation in MAR focused conferences and workshops.

Conclusion: The Nation's needs and USACE's strategic directions suggest an important future role for MAR in USACE projects.

Recommendation: USACE leadership, from Headquarters to District offices, should encourage further evaluation of how MAR may help USACE to deliver sustainable and resilient water management solutions.

Conclusion: MAR combines well with USACE's formal planning process and with new initiatives

Recommendation: USACE should consider MAR in conjunction with, not in lieu of, ongoing water resource management initiatives. In doing so, the additional storage created in the service of multiple stakeholders will not be at the expense of lives and property.

Conclusion: USACE has much to learn from other agencies, and the private sector, about MAR.

Recommendation: USACE should use current interagency agreements, subcommittees and other mechanisms to conduct seminars, webinars, meetings and, potentially, cooperative research with other entities to exchange knowledge, experience and lessons-learned in MAR.

2. Introduction and Scope

The U.S. Army Corps of Engineers (USACE) Civil Works programs include a wide range of water resources planning and management activities. Along with its missions in navigation, flood risk management, and aquatic ecosystem restoration, USACE also engages directly or through its partners in recreation, hydropower, and water supply as part of multipurpose projects. Added together, one could restate USACE's mission as promoting national water security, which the United Nations has defined as "The capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability."[1]

As described in the Water Supply Act of 1958, and later in this report, the Federal interest in water supply is generally limited relative to state and local interests.[2] However, with the progressively more complex and multipurpose nature of 21st Century water management, USACE's Civil Works programs increasingly have to factor in water-supply requests (such as for reallocation of stored water) from state and local partners—who find their supplies under pressure from urbanization, drought, environmental requirements, and other stressors.

2.1. New Demands on Finite Supplies

Growing sectorial demands on water supplies place additional constraints on USACE water management practices—and not solely because they may require additional quantities of water for consumptive uses, such as water supply, or non-consumptive uses, such as recreation. They may also require a certain water quality, such as temperature, concentration of dissolved oxygen, chloride, nutrients or heavy metals; timing, such as operations for seasonal fish migration, irrigation for the growing season, hydropower for summer air conditioning, or flood risk management; or distribution, such as floodplain inundation for fish spawning or fry development.

In U.S. states that follow the riparian doctrine of water law, the prior appropriation doctrine of water law, or some combination of the two, additional demands may lead to new conflicts among stakeholders in a basin. These conditions pose challenges to USACE in meeting new needs while staying faithful to existing authorizations. They also place additional management constraints on a finite water supply, which may decrease the overall resilience of a system and make it progressively more vulnerable to extreme events, such as floods and droughts, and human-caused disasters. The National Research Council summarized these challenges from a water storage perspective, as follows:

> "In the future, multiple strategies are likely to be needed to manage water supplies and meet demands for water in the face of scarcity. Various water conservation and management strategies,

[1] UN-Water. 2013. Water Security and the Global Water Agenda. A UN-Water Analytical Brief. Hamilton, Ontario: United Nations University. https://www.unwater.org/app/uploads/2017/05/analytical_brief_oct2013_web.pdf .
[2] Western Governors' Association. 2015. Water Resource Management in the West. WGA Policy Resolution 2015–08. http://westgov.org/images/editor/RESO_Water_Resources_15_08.pdf.

including transfers and water recycling, can be used to stretch available water supplies. However, each of these has its rate of delivery limits. *Water storage facilities will continue to be an essential component of water management, particularly in areas where water availability varies greatly over seasons or years, such as the arid Southwest. Integrated strategies will be needed in which all measures for improving water quality and managing water scarcity are considered and, if appropriate, employed in a balanced, systematic fashion. Seasonal to multi-year storage of water will often be a necessary component of such strategies."* [3]

2.2. The Key Role of Storage for Resilience

Many states have responded to these pressures by creating state water plans and strategies, and regional and local water suppliers have increasingly banded together to create regional partnerships as well. At the Federal level, USACE is aware of the need to preserve or even increase resilience of its water management systems, and in 2015, the Chief of Engineers established USACE's Resilience Initiative. Although USACE has almost always incorporated resilience into its projects at some level, this initiative was designed "to reflect the most current risk-informed decision-making practices for improved project resilience and to provide greater support to community resilience both locally and through national policies."[4]

Using the definition of resilience adopted in the Federal Emergency Management Agency's (FEMA) National Disaster Recovery Framework[5]—"the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions"—multi-year storage clearly has the potential to increase the resilience of water resources infrastructure. This may be especially true for long-term stressors, such as multi-year drought or sustained population growth.

Thus, seasonal to inter-annual storage of water is at the heart of this report. Corps of Engineers-managed reservoirs commonly store water for days to years, depending on their authorized purposes. However, long-term, above-ground water storage faces challenges such as evaporative losses, sediment accumulation, high real-estate or construction costs, environmental and ecosystem needs, and impacts on cultural heritage.[3]

As an alternative to surface- and above-ground storage, water managers in the US and internationally are making increasing use of aquifer storage and recovery wells, artificial recharge from infiltration basins, enhanced recharge through intermittent streambeds, and other techniques—often in conjunction with wastewater reuse and stormwater control. States have been developing laws and regulations defining aquifer recharge for storage as a "beneficial use",[6] allowing formation of groundwater management districts managed locally, subject to a state groundwater commission,[7] and

---

[3] National Research Council. 2008. Prospects for managed underground storage of recoverable water. Washington, DC: The National Academies Press. https://doi.org/10.17226/12057.
[4] http://www.usace.army.mil/Missions/Sustainability/Building-Resilience/.
[5] https://www.fema.gov/media-library/assets/documents/117794.
[6] E.g., Idaho Title 42, Chapter 2, Section 42-234.
[7] E.g., Colorado Code of Regulations 2 C.C.R. 410-1.

creating institutions such as "water banks"[8]—likely accelerating the use of underground storage as a water management strategy. A "portfolio" of water treatment options is now available for reclaimed water to the point that potable reuse is becoming virtually routine;[9] such water is often recharged to groundwater for additional treatment and recovered at a later time. Overall, despite the myriad challenges, The National Research Council concluded that most aquifer recharge, storage and recovery systems "have successfully achieved their stated purposes".[3] It further concluded that given this generally successful track record, and the growing complexity of our water management challenges, such systems "*should be seriously considered as a tool in a water manager's arsenal*".[3]

The improved integration of groundwater into planning and management has been identified as one of the current challenges for "moving water resources planning and management into the twenty-first century".[10] USACE's authorities for engaging directly in groundwater recharge, storage and recovery activities, discussed below, have been modest until recently. However, the Water Resources Development Act (WRDA) of 2016 (P.L. 114-322) provided a renewed impetus with new authorities for such projects in Sections 1116 and 1118, aimed at water supply conservation for drought resilience and water supply availability for water resources development, respectively (see "Authorities" Chapter, below). Underground water storage has the potential to be useful to USACE and its partners in drought planning and management, flood risk management, reallocation studies and water supply planning, reservoir management, wetlands and ecosystem restoration, and other areas.

2.3. Scope of this Report

As described below (Box 1), the scope of this report is to examine how MAR has been and is being used in conjunction with USACE Civil Works, and consider steps USACE might take to facilitate MAR applications. The report first defines terms related to purposeful groundwater recharge, and reviews some relevant earlier work by USACE on the topic. It then summarizes general and project-specific authorities for USACE to engage in such activities.

---

[8] E.g., Arizona Revised Statutes Title 45. Waters § 45-2473.
[9] National Research Council. 2012. Water Reuse: Potential For Expanding the Nation's Water Supply through Reuse of Municipal Wastewater. Washington, DC: The National Academies Press. https://doi.org/10.17226/13303.
[10] Galloway, G.E. 2009. Making the transition: moving water resources planning and management into the twenty-first century. Pp. 259-284 in Russell, C.S. and Baumann, D.D., eds. The evolution of water resource planning and decision making. Northampton, MA: Edward Elgar Publishing.

The scope of this document is:

a) to examine how managed aquifer recharge (MAR)—whether in lieu of or in combination with surface storage and other resilience efforts—has been, is being, and can be used in conjunction with U.S. Army Corps of Engineers Civil Works water resources projects; and

b) to consider any steps that USACE should take to facilitate the appropriate use of groundwater storage technologies.

Box 1: MAR Report Scope

The core of the report is a chapter describing examples of USACE districts or their partners having considered, proposed, selected, or carried out aquifer recharge (or actively lowered discharge), for a variety of purposes. The parallel expertise of other Federal agencies is then surveyed, followed by a chapter that explores three other USACE water management initiatives to evaluate the degree to which aquifer recharge activities are compatible with them. The main body of the report ends with a discussion of caveats and limitations. Finally, supported by the 31 case studies woven throughout the report, some conclusions are drawn, with corresponding recommendations for USACE water resources planning, management, collaboration, communication, and training.

2.4. Terminology

The primary term used in this paper for such efforts is *managed aquifer recharge,* or *MAR.* Coined by Ian Gale in 2000 as the name of a new commission of the International Association of Hydrogeologists,[11] the term MAR is one of a family of terms concerning water management approaches involving aquifer recharge and/or recovery. For example, the Government of Western Australia, a global leader in research on and applications of MAR, defines it as "the intentional recharge of water to suitable aquifers for subsequent recovery or to achieve environmental benefits".[12] Such recharge is generally done during periods of high supply (i.e., precipitation) or low demand. This report uses MAR and an older term, *artificial recharge* (AR*),* synonymously, although it is argued that the latter is more concerned with water quantity than water quality.[13] However, a plethora of additional, more specific terms exist (Box 2). Typically some of the water is designed to be recovered at a later time, although recharge to create hydrologic barriers to salt-water intrusion is also a common practice. The term *aquifer storage and recovery* (ASR) usually refers specifically to recharging water to aquifers via wells rather than through

[11] https://recharge.iah.org/tribute-ian-gale
[12] http://www.water.wa.gov.au/urban-water/water-recycling-efficiencies/managed-aquifer-recharge.
[13] Dillon, P., Stuyfzand, P., Grischek, T., and 28 others. 2019. Sixty years of global progress in managed aquifer recharge. Hydrogeology Journal 27(1):1-30. https://doi.org/10.1007/s10040-018-1841-z.

- Aquifer storage and recovery (ASR)—injection of water into a well for storage and recovery from the same well.
- Aquifer storage transfer and recovery (ASTR) —injection of water into a well for storage and recovery from a different well, generally to provide additional water treatment.
- Artificial recharge (AR) —intentional banking and treatment of water in aquifers.
- Artificial recharge and recovery (ARR) —recharge to and recovery of water from an aquifer; both artificial recharge of the aquifer and recovery of the water for later use.
- Augmentation pond—water body designed to supply water to river systems at defined rates during particular times.
- Bank filtration—extraction of groundwater from a well or caisson near or under a river or lake to induce infiltration from the surface water body, thereby improving and making more consistent the quality of water recovered.
- Conjunctive use—combining the use of both surface and groundwater to minimize the undesirable physical, environmental, and economic effects of each solution.
- Dry well—synonymous with vadose zone well.
- Infiltration basin—synonymous with recharge basin.
- Managed aquifer recharge (MAR)—intentional banking and treatment of water in aquifers (synonymous with AR).
- Managed Underground Storage of Recoverable Water (MUS)—Purposeful recharge of water into an aquifer system for intended recovery and use as an element of long-term water resource management.
- Recharge basin (or pond)—a surface facility used to increase the infiltration of surface water into groundwater; basins require the physical conditions that enable the vertical percolation of water to an unconfined or perched aquifer system for subsurface storage.
- Recharge well—a well used to directly recharge water to either a confined or an unconfined aquifer.
- Soil aquifer treatment (SAT)—treated sewage effluent is intermittently infiltrated through infiltration ponds to facilitate nutrient and pathogen removal in passage through the unsaturated zone for recovery by wells after residence in the aquifer.
- Surface spreading—recharging water at the surface through recharge basins, ponds, pits, trenches, constructed wetlands, or other systems.
- Spreading basin—synonymous with recharge basin.
- Underground storage and recovery (USR) —any type of project whose purpose is the artificial recharge, underground storage, and recovery of project water.
- Vadose zone well—a well constructed in the interval between the land surface and the top of the static water level and designed to optimize infiltration of water.

Box 2. Terminology for water management approaches involving groundwater recharge.[3]

infiltration ponds, natural stream beds or other methods. *Conjunctive management or use* simply refers to combining the use of both groundwater and surface water in the most favorable way. California Department of Water Resources gives a more precise definition of "the coordinated and planned use and management of both surface water and groundwater resources to maximize the availability and reliability of water supplies in a region to meet various management objectives".[14] If natural recharge rates are high enough, MAR may not be involved. Another comprehensive classification system, with accompanying discussion, has been developed by the International Groundwater Resources Assessment Centre (IGRAC)[15] and can be accessed through the online MAR platform of the Technical University of Dresden (Germany).[16] Methods described there include several not covered in Box 2, such as dune filtration, subsurface dams, and sand dams.

2.5. Components of a MAR System

MAR systems can be viewed as having five major components. These are: (1) the source of water to be stored, (2) the recharge method, (3) the storage method and management approach, (4) the recovery method and, (5) the end use of recovered water.[3] A brief, introductory discussion of these five components follows.

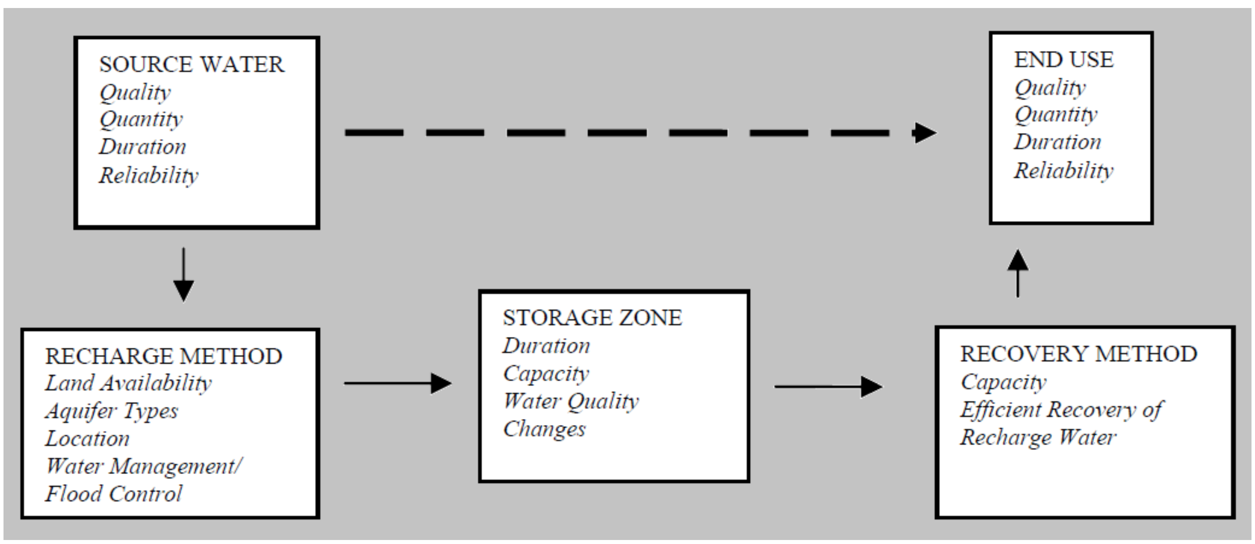


Figure 1. The five major technical components of MAR systems, including some major design criteria.[3]

A variety of *source waters* (1) can be recharged to groundwater, ranging from highly-treated drinking water or wastewater to untreated urban stormwater runoff. The use of poor quality water can cause physical issues such as clogging of wells and basins, as well as regulatory issues with surficial or sole-

[14] California Department of Water Resources. 2016. A Resource Management Strategy of the California Water Plan. Chapter 4: Conjunctive Management and Groundwater Storage. https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/California-Water-Plan/Docs/RMS/2016/08_ConjMgt_GW_Storage_July2016.pdf
[15] Stefan, C. and Ansems, N. 2018. Web-based global inventory of managed aquifer recharge applications. Sustainable Water Resources Management 4(2):153–162. https://doi.org/10.1007/s40899-017-0212-6
[16] https://inowas.com/managed-aquifer-recharge/.

source aquifers. The variable quality and flashiness of floodwaters contrast with the consistent quality and quantity of treated wastewater. Some of this can be mitigated by constructed wetlands or other methods.

The *recharge method* (2) chosen may depend on the value and availability of land at an appropriate location, the depth and degree of confinement of the aquifer, the infiltration capacity of the soils, drilling costs, and other factors. Box 2 contains terminology related to a wide variety of recharge methods. Note that infiltration basins date from the late 19th Century whereas the combination of deep wells, electric power, and electric submersible pumps needed for ASR did not come together until the 1960s. [13]

The characteristics of the *storage zone* (3) matter for reasons of both quality and quantity of stored water. Some of the terms in Box 1 allude to water quality improvements during recharge or storage (e.g., *soil aquifer treatment*). In addition, reactions that improve water quality such as biodegradation of organics, sorption of heavy metals, and inactivation of pathogens are, indeed, common in soils and aquifers. However, increases in salinity, oxidation of sulfides releasing heavy metals and metalloids such as arsenic, and other less desired phenomena are also common. The confined or unconfined nature of a storage zone is also critical, especially in arid regions where the water table may be tens or hundreds of meters deep. Thick, permeable unsaturated zones can accept large quantities of recharge, often with little migration offsite. Recharging confined, incompressible aquifers can lead to offsite migration of stored water and issues with both fractures in confining units and high pumping costs due to elevated injection pressures.

The *recovery method* (4) chosen depends greatly on the natural hydrology of the system as well as the degree of control required for the timing of release. For example, the same wells can be used for recovery as for recharge in the case of ASR for water supply during high-demand periods (e.g., the summer tourist season). The discharge of stored, treated drinking water can be closely controlled as needed. In other cases, water may be stored in floodplain alluvium for gradual seepage into a river for ecological purposes.

Finally, the *end use* (5) typically conditions the water quality requirements of the discharge water. Use for potable water may necessitate expensive treatment of the water prior to use, even if it was already treated during recharge. The same may be true for industrial water use (low total dissolved solids or alkalinity) or environmental use (low nutrient content or temperature).

These five system components lead naturally to questions that may govern, for example, whether a MAR system is even feasible for a given project, at a given site, or for a given purpose. Some of these issues are discussed in the “Caveats” section of this report.

2.6. Early USACE Studies of MAR and Conjunctive Use

In 1983, USACE's Hydrologic Engineering Center (HEC), located in Davis, CA published a study entitled "Survey of Conjunctive Use and Artificial Recharge Activity in the United States".[17] In it, the authors traced the origin of the concept of using groundwater and surface water conjunctively to the 1930 State Water Plan of California, and the concept of storing surplus water underground for later use to the 1949 Central Valley Basin Plan of the Bureau of Reclamation ("Reclamation"). The HEC report's stated purpose was to locate and describe artificial recharge activities in the US. However, one might conclude that the report was also driven by the prescient realization that artificial recharge would soon be playing an increasingly important role in water resources planning, development and management. USACE projects in Gila Bend, Phoenix, and Tucson, AZ, and Sioux Falls, SD, were cited in the study.

Eighteen years later, HEC published the report *Conjunctive Use for Flood Protection*.[18] Prepared at the request of the USACE Sacramento District, this study focused on the Sacramento and San Joaquin River Basins. It investigated the concept that reservoir flood pool storage releases could be transferred to groundwater storage prior to a flood event, thus lowering flood risk while conserving water underground for future beneficial use(s).

Now, the future foreseen by these two HEC studies has arrived. In 1983 and at the time of the first HEC study, the number of artificial recharge systems in the U.S. could be enumerated and mapped relatively easily; this would be a much more challenging task today. In fact, a recent global inventory of MAR sites by the International Groundwater Resources Assessment Center (IGRAC), in association with UNESCO and others, compiled about 1,200 case studies from over 50 countries (Figure 2).

Further, this initiative made no claim as to comprehensiveness. The U.S. Environmental Protection Agency (EPA) estimated that there were between 1,700 and 2,000 aquifer recharge and ASR wells in the United States alone as of 2015.[19] There is now an international symposium series dedicated to the topic of MAR; the 10th International Symposium on Managed Aquifer Recharge ("ISMAR10") was held in 2019

[17] Hydrologic Engineering Center. 1983. Survey of Conjunctive Use and Artificial Recharge Activity in the United States. Research Document 21, 82 p. https://www.hec.usace.army.mil/publications/ResearchDocuments/RD-21.pdf

[18] Hydrologic Engineering Center. 2002. Conjunctive Use for Flood Protection. Unpublished report prepared for the US Army Corps of Engineers Sacramento District.

[19] https://www.epa.gov/sites/production/files/2015-08/documents/fs-aq_rechrg_wells.pdf.

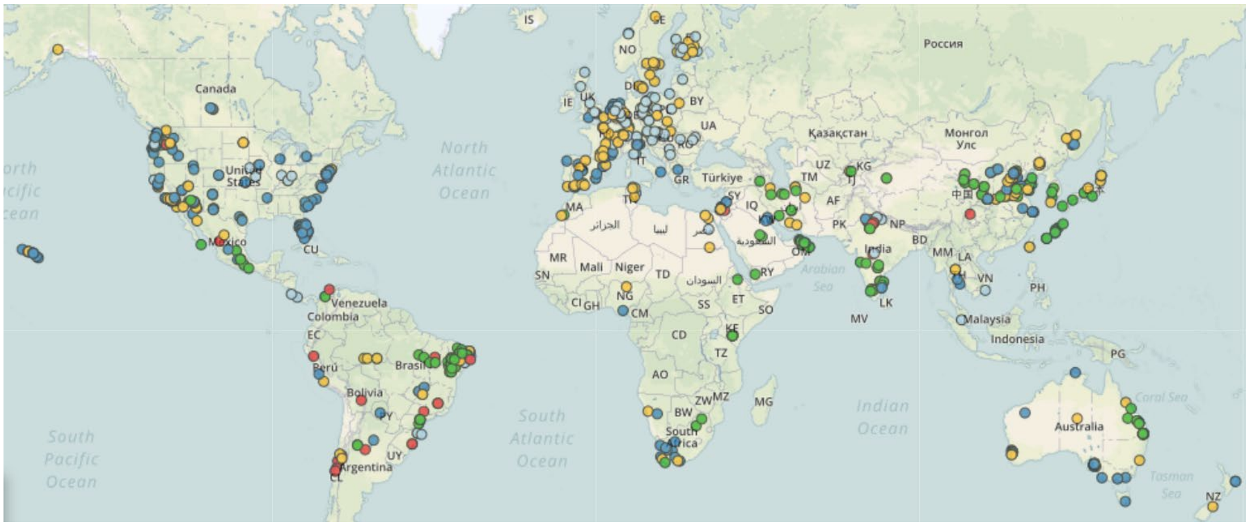


Figure 2. Global MAR Inventory. Source: IGRAC (https://ggis.un-igrac.org/ggis-viewer/viewer/globalmar/public/default; accessed 7 July 2019.

3. Authorities for USACE to Engage in MAR

As with its other activities, USACE involvement in MAR is circumscribed by its general and specific authorities, given by Congress, and must also be consistent with constitutional constraints and administration policy. Within those boundaries, there are no specific, known restrictions on the nonfederal use for groundwater recharge of water stored or released from USACE reservoirs, as long as that use is consistent with state water-rights and Federal environmental protection laws, and with the operation of USACE projects for their authorized purposes.[20]

USACE is already involved in, or actively planning, many projects that incorporate MAR, often at the request of local partners who wish to improve the robustness and resilience of their water management systems. The 2018 Presidential Memorandum on Promoting the Reliable Supply and Delivery of Water in the West encouraged "innovation, research, and development of technology that improve water management".[21]

3.1. General Congressional Authorities

There are few general Congressional authorities that are directly applicable to MAR projects. This may primarily be due to the fact that MAR was not widespread when many of the fundamental authorities governing USACE activities were created. Although USACE water resource development projects generally may support or contribute to its partners' MAR projects, direct performance of aquifer

[20] U.S. Congressional Research Service. 2018. The Federal Role in Groundwater Supply: Overview and Legislation in the 115th Congress (R45259; July 18, 2018), by Peter Folger, Charles V. Stern, Nicole T. Carter, and Megan Stubbs. https://crsreports.congress.gov/product/pdf/R/R45259.

[21] https://www.whitehouse.gov/presidential-actions/presidential-memorandum-promoting-reliable-supply-delivery-water-west/

recharge by USACE is uncommon. The two long-standing general authorities related to municipal and industrial (M&I) water supply are contained in Section 6 of the Flood Control Act of 1944 (33 U.S.C. 708) and the Water Supply Act of 1958 (43 U.S.C. 390b). More recently, the Water Resources Development Act of 2016 added significant new authorities that include MAR.

Section 6 of the Flood Control Act of 1944 (**33 U.S. Code § 708**)[22] authorizes the Secretary of the Army to make contracts with States, municipalities, private concerns, or individuals, at prices and on terms the Secretary deems reasonable, for domestic and industrial uses for "surplus water" in reservoirs under Army control. Contracts under this authority may not adversely affect existing lawful uses of such water. Since Section 6 only pertains to *surplus* water, this would generally not be an appropriate authority for long-term, sustainable supply from surface storage, since deliveries would likely not be met in drought years. Perhaps due partly to this reason, this authority has only been used sporadically. However, there is no *a priori* reason to assume that such water could not be stored *underground* at the time of such surplus and recovered during a time of deficit.

The Water Supply Act of 1958 (**43 U.S. Code § 390b**)[23] states that developing water supplies for domestic, municipal, and industrial purposes is primarily the responsibility of the states and local interests. It affirms that "the federal government should participate and cooperate with States and local interests in developing such water supplies in connection with the construction, maintenance, and operation of Federal navigation, flood control, irrigation, or multiple purpose projects."

However, USACE's discretion under this authority is somewhat limited. Unlike Section 6 of the Flood Control Act of 1944, which deals with "surplus water," the Water Supply Act refers to storage of water for M&I water supply. This authority could potentially make water supply a new authorized project purpose. The Water Supply Act states that modifications to reservoir projects to include storage that would "seriously affect" the project's authorized purpose(s) or involve major structural or operational changes shall be made only upon the approval of Congress. In addition, state or local interests must agree to pay for all costs of the storage provided, and USACE policy prohibits budgeting for construction of single purpose projects for M&I water supply. In practice, water supply storage requests are often met by reallocating storage at existing USACE projects.

Neither of these two authorities specifically mentions groundwater, aquifers, or subsurface recharge, storage, or recovery of water—the key elements of MAR. However, the 1998 USACE Water Supply Handbook observed that, even where not specifically authorized, "seasonal operation of a project for water supply may be conducted consistent with authorized project purposes and law…This water supply

[22] https://www.govinfo.gov/app/details/USCODE-2011-title33/USCODE-2011-title33-chap15-sec708/summary. The definition of the statutory term "surplus water" is beyond the scope of this report. USACE has published a proposed rule that would, if finalized, set forth a USACE regulatory definition of the term "surplus water" for purposes of Section 6. See 81 Fed. Reg. 91,556 (Dec. 16, 2016).

[23] https://www.govinfo.gov/app/details/USCODE-2010-title43/USCODE-2010-title43-chap12-subchapI-sec390b. Interpretation of this statutory authority is beyond the scope of this report. USACE has published a proposed rule that would, if finalized, set forth USACE regulatory interpretations of the Water Supply Act. See 81 Fed. Reg. 91,556 (Dec. 16, 2016).

could be used to enhance groundwater replenishment, to increase downstream flows, or to otherwise enhance the general usage of the project for M&I purposes…"[24]

As of 1998, the publication date of the Water Supply Handbook, "general Congressional authority to include storage in Corps projects for seasonal use of M&I water supply, either as withdrawals or to improve groundwater supplies" did not exist.[24] However, WRDA 2016 changed the framework for seasonal to inter-annual water storage under some circumstances.

WRDA 2016 ("Water Resources Development Act")[25] added new authority for MAR in two separate sections. Section 1116 emphasizes the role of MAR in conservation and drought, stating that:

> *"In a State in which a drought emergency has been declared or was in effect during the 1-year period ending on the date of enactment of this Act, the Secretary [of the Army] is authorized—*
>
> *" (1) To conduct an evaluation for purposes of approving water supply conservation measures that are consistent with the authorized purposes of water resources development projects…and*
>
> *"(2) To enter into written agreements pursuant to section 221 of the Flood Control Act of 1970 (42 U.S.C. 1962d–5b) with non-Federal interests to carry out the conservation measures approved by such evaluations."*

Eligible MAR-related conservation measures include stormwater capture and releases for groundwater replenishment or ASR. States where drought emergencies were declared or were in effect during the cited timeframe (17 December 2015 – 16 December 2016) include all of Alabama, Arizona, California and Washington as well as parts of Georgia, Idaho, Kansas, Massachusetts, New Hampshire, New York, North Carolina, Oregon, Pennsylvania, and Texas.[26]

Section 1118 emphasized the leveraging of Federal infrastructure for increased water supply and states that:

> *"At the request of a non-Federal interest, the Secretary [of the Army] may review proposals to increase the quantity of available supplies of water at a Federal water resources development project."*

This can be done through modification of the project, including reservoir management or releases. It allows for increasing the storage capacity of the project and diversion of water released or withdrawn from it using MAR-related technologies, to wit:

> *"(A) To recharge groundwater; (B) to aquifer storage and recovery; or (C) to any other storage facility."*

---

[24] USACE Institute for Water Resources, 1998. Water Supply Handbook: A Handbook on Water Supply Planning and Resource Management. Prepared by Theodore M. Hillyer with Germaine A. Hofbauer. IWR Report 96-PS-4, revised December 1998. Online at http://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/96ps4.pdf.
[25] Public Law No: 114-322; https://www.congress.gov/114/plaws/publ322/PLAW-114publ322.pdf.
[26] https://cdm16021.contentdm.oclc.org/utils/getfile/collection/p16021coll5/id/636/rec/3

Such measures and project modifications are not authorized to affect existing contractual rights to water or storage, preempt State water laws or interstate compacts governing water, interfere with or reduce water available for an authorized purpose, or increase costs to other entities. Additionally, with minor exceptions, the non-Federal interest would generally pay all separable costs associated with the evaluation, implementation, operation, and maintenance of an approved project modification or measure.

Section 1118 does not modify any existing authority of the Secretary of the Army. In addition to citing Section 6 of the Flood Control Act of 1944 and the Water Supply Act of 1958 (discussed above), Section 1118 of WRDA 2016 cites **33 U.S.C. 408**[27] as an authority for project modification. Section 408 provides that the Secretary of the Army may, upon the recommendation of the Chief of Engineers, grant permission to other entities for the permanent or temporary alteration or use of any USACE Civil Works project.

Section 1118 of WRDA 2016 also cites the authority of Section 216 of the Flood Control Act of 1970 (**33 U.S.C. 549a**; Review of navigation, flood control, and water supply projects).[28] This authorizes the Secretary of the Army to

> *"…review the operation of projects the construction of which has been completed and which were constructed by the Corps of Engineers in the interest of navigation, flood control, water supply, and related purposes, when found advisable due [to] the significantly changed physical or economic conditions, and to report thereon to Congress with recommendations..."*

Detailed USACE implementation guidance documents have been developed, and are freely available, for both Sections 1116 and 1118 of WRDA 2016.[29]

An additional, statutory authority that may indirectly relate to MAR projects is USACE's authority to regulate wetlands alteration under **Section 404 of the Clean Water Act (CWA)**.[30] Section 404 authorizes the Secretary of the Army, acting through USACE, to issue permits for the discharge of dredged or fill material into waters of the United States, including wetlands. Since many aquifer recharge projects involve activities in wetlands, this can lead to engagement of USACE's Regulatory Program. If, for whatever reason, aquatic ecosystem restoration becomes an element of a project, this can generate a Federal interest that can further engage USACE as a Federal partner.

---

[27] https://www.govinfo.gov/content/pkg/USCODE-2011-title33/pdf/USCODE-2011-title33-chap9-subchapI.pdf

[28] https://www.govinfo.gov/app/details/USCODE-2009-title33/USCODE-2009-title33-chap12-subchapI-sec549a

[29] Guidance on these and other sections of WRDA 2016 are available at https://www.usace.army.mil/Missions/Civil-Works/Project-Planning/Legislative-Links/wrda2016/wrda2016_impguide/

[30] https://www.epa.gov/cwa-404/overview-clean-water-act-section-404

3.2. USACE Project-Specific Authorizations

Specific authorizations for MAR include Section 601 of the Water Resources Development Act (WRDA) of 2000.[31] This act approved the Comprehensive Everglades Restoration Plan (CERP) as a framework "to restore, preserve, and protect the South Florida ecosystem while providing for other water-related needs of the region, including water supply and flood protection." The CERP included USACE's first explicit, large-scale program for MAR as part of a larger Civil Works project (in this case, aquifer ecosystem restoration). As such, it represents a key point on the timeline of both USACE and MAR.

Of the 68 original project components recommended in the CERP, seven involved MAR (in this case, ASR) systems.[32] One such component, Lake Okeechobee Aquifer Storage and Recovery, has a multitude of purposes, including providing regional storage, increasing the lake's capability to meet regional water supply demands, managing regulatory releases to improve Everglades water flow patterns for human and ecological purposes, reducing harmful regulatory discharges to the St. Lucie and Caloosahatchee Estuaries, while maintaining or lowering flood risk. It is important to note that MAR measures were proposed during the investigation phase, without specific authorization, allowing the features to be part of the recommend plan subsequently authorized by WRDA 2000.

In another project-level example, Section 363(a) of WRDA 1996 (Public Law 104-303)[33] authorized a "flood control" project for Grand Prairie Region and Bayou Meto Basin, Arkansas whose scope also included groundwater protection and conservation. Somewhat more broadly geographically, Section 5137 of WRDA 2007 (Public Law 110-114)[34] authorized the Secretary of the Army to "participate with non-Federal and nonprofit entities to address issues concerning managing groundwater as a sustainable resource through [sic] the Upper Mississippi Embayment, Tennessee, Arkansas, and Mississippi, and to coordinate the protection of groundwater supply and groundwater quality of the Embayment with local surface water protection programs."

Other Federal agencies are seeking and, in cases, receiving new authorities for MAR. For example, the ''Water Infrastructure Finance and Innovation Act of 2014'' (WIFIA)[35] in Title V of WRRDA 2014 includes managed aquifer recharge projects as eligible projects for funding by EPA. In 2015, former U.S. Department of the Interior Deputy Secretary Mike Connor testified that:

> "Interior could be funding a wider range of water projects than its historic focus on dams and reservoirs…Typically [the Reclamation] model was, 'Let's plan for a water storage and delivery facility and irrigate X number of acres…' Now we're looking at much more different types of solutions like participating as a cost-share partner in a storage facility that's not a federally owned facility, but that will address federal resources such as…*groundwater recharge facilities* [italics

---

[31] PL 106-541; https://www.govinfo.gov/app/details/PLAW-106publ541
[32] USACE. 2015a. ASR Regional Study Fact Sheet. https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll11/id/3905
[33] PL 104-303; https://www.govinfo.gov/content/pkg/PLAW-104publ303/pdf/PLAW-104publ303.pdf
[34] PL 110-114; https://www.congress.gov/110/plaws/publ114/PLAW-110publ114.pdf
[35] PL 113-121; https://www.congress.gov/113/plaws/publ121/PLAW-113publ121.pdf

ours]…The federal government can participate in different ways based on federal and public interest, and I think there's new authorities that might be appropriate with respect to that…" [36]

In light of these existing and proposed authorities, in conjunction with the advancing science in the field of MAR, it is reasonable to project a trend toward increasing acceptance of by both the Legislative and Executive Branches of the Federal government toward MAR components of USACE projects.

4. USACE Experience with MAR

USACE's most in-depth engagement with MAR has been in the Florida Everglades. Several hundred aquifer storage and recovery (ASR) wells were envisioned in the Comprehensive Everglades Restoration Plan (CERP)[37] to increase inland detention capacity while reducing impacts to interior aquatic ecosystems and minimizing impacts to land uses. Two extensive investigations, a pilot project involving two prospective ASR sites[38] and a regional ASR study,[39] were completed in 2013 and 2015 to evaluate the feasibility of this approach.

However, USACE is engaged in MAR at some level in most of its Divisions and many of its Districts. This chapter summarizes many of these ongoing and planned projects, which illustrate numerous potential applications of MAR. A key message is that USACE is not necessarily directly involved in designing or managing the recharge system, and, in fact, generally is not.

This chapter is organized by purpose, but could just as easily be organized regionally. Naturally, many projects are proposed for multiple purposes, so this organization may be considered illustrative of these purposes. It is not intended to be comprehensive.

There are many ways that MAR and related water management strategies intersect with, and may contribute to improvements in, USACE planning, management and operations. A partial list of ways in which MAR and USACE responsibilities may come together follows here; short summaries of many of the projects referred to are below:

- Drought resilience
- Flood mitigation
- Aquatic ecosystem restoration and constructed wetlands
- Reducing saltwater intrusion
- Multi-use urban environmental restoration projects

---

[36] Environment and Energy Daily, June 4, 2015; http://www.eenews.net/stories/1060019647

[37] USACE and SFWMD. 1999. Central and Southern Florida Project Comprehensive Review Study, Final Integrated Feasibility Report and Programmatic Environmental Impact Statement.

[38] USACE and SFWMD. 2013. Final Technical Data Report, Comprehensive Everglades Restoration Plan Aquifer Storage and Recovery Pilot Project, Kissimmee River ASR System and Hillsboro ASR System.

[39] USACE and SFWMD. 2015. Final Technical Data Report, Comprehensive Everglades Restoration Plan Aquifer Storage and Recovery Regional Study.

MAR also shows promise for complementing USACE integrated water resources management approaches, such as collaborative planning and conflict resolution. MAR may contribute to "win-win" solutions in a basin—for example, by meeting seasonal needs for hydropower while minimizing damage to ecosystems or recreational interests. (See the following chapter on *MAR as Related to other USACE Processes, Tools and Initiatives*).

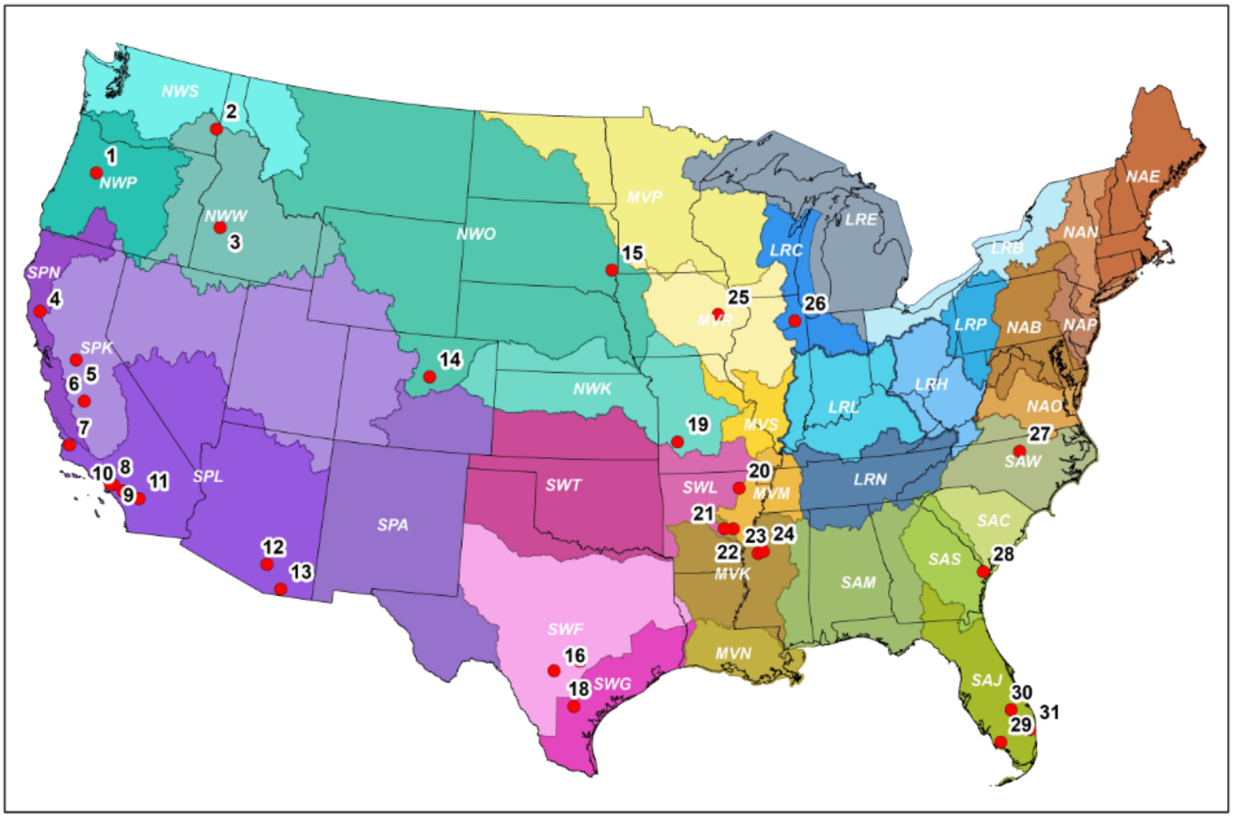
Although this report emphasizes domestic Civil Works applications, international and military opportunities may also present themselves. The Army Water Security Strategy states that there may be "opportunities to have a positive effect on local water sources…through the development of water management systems that help recharge aquifers, such as building reservoirs that capture storm runoff". [40] Rising sea levels and excessive groundwater withdrawals may also lead to salt-water intrusion in and around coastal military bases, leading overseas bases to recharge their treated wastewater and runoff to offset groundwater extraction—consistent with the "Army Net Zero" [41] initiative for more sustainable and efficient energy, water, and solid waste management.

Many examples follow to illustrate applications of MAR. Many of these actually use, or propose to use, MAR for multiple purposes. Figure 3 is a location map for examples referred to throughout this report.

4.1. Drought Resilience

Drought is a potent driver of water-supply planning efforts in regions that have not previously engaged in them. USACE is authorized to participate in developing water supplies, assuming that the non-Federal entities that have the primary responsibility for them bear the full financial responsibility. Likewise, USACE can provide water supply storage space (not the water itself) in its multi-purpose reservoirs to non-federal interests, who cover costs associated with that storage. [42] USACE is one of the lead agencies, under the Federal Action Plan of the interagency National Drought Resilience Partnership, [43] for "Increasing Water-Management Flexibility". This instructs USACE and other agencies to "improve drought preparedness by developing and implementing new processes and considerations into reservoir management" and to permit "deviations from an approved USACE Water Control Plan in certain circumstances…to alleviate critical drought impacts". [44] Thus, despite a somewhat constrained role, USACE has ways to support regional drought contingency planning and drought management.

[40] Army Environmental Policy Institute. 2011. Army Water Security Strategy. AEPI Contract Number, W91278-10-D-0041. https://www.sdu.dk/-/media/files/om_sdu/institutter/iti/forskning/nato+arw/literature/armywaterstrategy.pdf
[41] https://www.asaie.army.mil/Public/ES/netzero/
[42] https://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/2016-RES-01.pdf
[43] https://www.drought.gov/drought/resources/national-drought-resilience-partnership
[44] https://www.usda.gov/sites/default/files/documents/ndrp-january-2017-end-of-year-report.pdf



1	Willamette River Basin, OR	17	Blanco River Dam Proposal, TX
2	Palouse Basin Aquifer, WA, ID	18	Nueces River Basin and Tributaries Project, TX
3	Boise River Feasibility Study, ID	19	Stockton Lake Reallocation Study, MO
4	Lake Mendocino and Russian River FIRO, CA	20	Cache River Basin, AR
5	Farmington Groundwater Recharge, CA	21	Bayou Meto Basin Project, AR
6	James Irrigation District, CA	22	Grand Prairie Area Demonstration Project, AR
7	Twitchell Dam, Santa Maria Project, CA	23	Quiver River, Big Sunflower River Basin, MS
8	Los Angeles River Ecosystem Restoration, CA	24	Groundwater Transfer and Injection, MS
9	Whittier Narrows Dam, CA	25	Iowa-Cedar River Multi-Hazard Tournament, IA
10	Prado Dam, CA	26	Lockport Prairie Ecosystem Restoration, IL
11	Bautista Creek Recharge, CA	27	Falls Lake Multi-Purpose Project, NC
12	Tres Rios del Norte, AZ	28	Savannah Harbor Expansion Project, GA
13	Fort Huachuca Treated Effluent Recharge, AZ	29	Picayune Strand Restoration Project, FL
14	Chatfield Reservoir Storage Reallocation, CO	30	Lake Okeechobee ASR Pilot Project, FL
15	Big Sioux River Diversion Channel, SD	31	Western Hillsboro ASR Pilot Project, FL
16	Medina Reservoir, San Antonia area, TX		

Figure 3. Location Map for projects referred to in this report. The word "projects" is used here generically to refer to any activity of USACE (District, Division, ERDC, HQ or IWR) or one of its collaborators or partners where MAR was or is being considered. Map design by Ben Silvernail (IWR).

For example, the Central Texas drought of the 1950s led the Texas Legislature to create the Edwards [Aquifer] Underground Water District—the precursor to the current Edwards Aquifer Authority (EAA)[45]—in 1959. By early 1961, "an agreement was made with the U.S. Army Corps of Engineers to make a study in cooperation with the District to see exactly what could be done to make more water available for use from the reservoir".[46] This included the first study of the recharge potential of the Edwards Aquifer, and led to consideration of a dam on the Blanco River "operated to release water at the maximum recharge rate of the downstream channel".[47] USACE work related to the Edwards Aquifer is discussed in several other sections of this report.

Prado and Whittier Narrows Dams, Southern California

In the 2011-2017 drought in California, USACE used temporary exceptions to dam safety policy to support MAR-based drought management in several sites in Orange and Los Angeles Counties, southern California. Whittier Narrows Dam, on the San Gabriel River in Montebello, California, and Prado Dam on the Santa Ana River in Riverside County, are both authorized for flood control and, in the latter case, also for water conservation. Based on this and risk assessment studies, both are subject to policies that govern their water conservation storage.

Both dams are located upstream of groundwater spreading grounds, operated by Los Angeles County Flood Control District and Orange County Water District, respectively. These MAR facilities have finite maximum recharge rates, and under current policy it is possible that water would have to be released from one or both of the reservoirs at rates that exceed these facilities' recharge capacities. With the additional stresses placed on the regional water-supply system by drought conditions in much of the 2010's, it did not seem prudent to allow for water to be allowed to flow to the ocean unless absolutely necessary. This is especially true given that in the case of the Prado system, excess water would flow to the ocean down a concrete channel (there is no significant ecosystem in the channel).

Therefore, temporary exceptions to dam safety policy prohibiting reallocation of water conservation storage at the dams were requested of, and granted by, USACE beginning in 2014, and water from local storms that would otherwise have flowed unutilized to the ocean could be stored for future potable use by the county water suppliers.[48]

In 2019, USACE and the Orange County Water District completed a Prado Basin Ecosystem Restoration and Water Conservation Study Draft Integrated Feasibility Report. This describes a plan to restore ecosystems in Prado Basin that would also permanently increase the amount of water that can be stored behind Prado Dam during flood season from October to February. The report states that advances in the accuracy and reliability of weather forecasting allow for a higher water surface elevation

---

[45] Edwards Aquifer Authority home page. See: https://www.edwardsaquifer.org/

[46] Edwards Underground Water District. 1961. Untitled summary report of district activities. Available at http://www.edwardsaquifer.org/

[47] HDR Engineering, Inc. and Espey, Huston & Associates, Inc. 1993. Guadalupe-San Antonio River Basin Recharge Enhancement Study: Volume I—Executive Summary. Prepared for Edwards Underground Water District. https://www.edwardsaquifer.org/documents/1993_HDR_RechargeEnhancementGuadalupeSA-Report.pdf.

[48] Unpublished letters, both dated February 18, 2014, from James C. Dalton, then-Corps Dam Safety Officer, to the Commander, USACE South Pacific Division.

even during the flood season, while ensuring acceptable flood risks for downstream areas protected by the dam.[49]

Western Hillsboro Aquifer Storage and Recovery (ASR) Pilot Project, South Florida

The Western Hillsboro ASR project, located southeast of Lake Okeechobee and southwest of West Palm Beach, is one of the original elements of the Comprehensive Everglades Restoration Plan, or CERP. The ASR wells would be located in close proximity to the canal, which is used for drainage in wet periods and for water supply in dry periods. The proposed ASR recharge and discharge rates would have little impact on flow rates in the canal, and thus the drought management function of the groundwater storage is probably the primary one. ASR in this area has been proposed due to reduced costs compared with surface storage facilities, lower losses due to evapotranspiration, lower land acquisition costs and especially the ability to recover large volumes of water during severe droughts, when reservoir levels would be very low.[37] The site was one of two that were described in the USACE-SFWMD Everglades ASR pilot project Final Technical Data Report.[38]

Big Sioux River Diversion Channel, South Dakota

The Big Sioux River Diversion Channel was built by USACE in the 1960s to protect the city of Sioux Falls, South Dakota from floods. However, it quickly became apparent that it could also be used to recharge the glacial outwash aquifer that underlies the river's floodplain. This aquifer provides most of the water pumped by the city. With periodic dredging of the channel to remove fine-grained sediment, this additional infiltration has helped Sioux Falls to continue supplying water to its residents even during droughts.[17]

Raleigh, North Carolina Water Supply

Finally, ASR was also briefly considered as one of the "potential measures and preliminary alternatives" to address the water supply challenges facing the City of Raleigh, North Carolina, and environs. This evaluation was conducted as part of the Draft Integrated Water Supply Reallocation Feasibility Study and Draft Environmental Assessment (March 2017) for Falls Lake, a Corps of Engineers multi-purpose project. However, the fractured nature and low storage capability of the potential storage unit suggested that this alternative was not feasible, and it was not carried forward for further analysis.[50]

4.2. Flood mitigation

The concept of combining flood risk reduction with recharge enhancement is quite ancient. So-called "recharge dams" have been used for millennia in Middle Eastern wadis to capture floodwaters of infrequent but high discharge events while protecting settlements downstream.[51] Closer to home, HEC's

[49] Prado Basin Ecosystem Restoration and Water Conservation Study: Draft Integrated Feasibility Report. 2019. USACE Los Angeles District and Orange County Water District.
https://usace.contentdm.oclc.org/digital/collection/p16021coll7/id/3015
[50] https://www.saw.usace.army.mil/Portals/59/docs/recreation/fallslake/Falls%20Lake%20Draft%20Report%20Combined%20with%20Appendicies%20and%20Attachments%20for%20Corps%20Web%20Page%2016Mar2017.pdf
[51] Netherlands National Committee and International Association of Hydrogeologists. 2002. Management of Aquifer Recharge and Subsurface Storage: Making Better Use of Our Largest Reservoir. Albert Tuinhof and Jan Piet

publication on Conjunctive Use for Flood Protection[18] (summarized earlier) examined the potential for stored water in USACE reservoirs to be selectively released for recharge to groundwater to further lower flood risk, while conserving the water underground for other permissible uses. Recharging stormwater upstream of, or co-located with, surface structures can also assist water managers by moderately dampening flood peaks, accelerating recovery of floodwater detention capacity while reducing risk of later water deficits, and simultaneously assisting with recovery of flood storage, while recharging overexploited aquifers.

Edwards Aquifer Recharge Projects, Central Texas

The Edwards Aquifer provides most of the water supply for the city of San Antonio, Texas and surrounding area. As far back as the mid-1960s, USACE and the Edwards Underground Water District[52] identified potential projects located near the Edwards Aquifer recharge zone (areas to the west and north of San Antonio) to capture and recharge additional flood flows which would not have naturally recharged the aquifer. This dual purpose was apparently discovered by accident in the case of Medina Reservoir (Bexar, Medina, and Atascosa counties) which while "constructed [in 1913] and operated for irrigation purposes, became virtually ineffective during periods of moderate to severe drought because of leakage." Over the two decades following that discovery, USACE and other cooperators constructed a series of dams on the nearby Seco, Parkers, Verde, and San Geronimo Creeks with a primary purpose of flood control but a secondary goal of recharge enhancement.[46, 53] At least one such structure's benefit-cost ratio included an estimated value of the groundwater recharge.[54]

Currently, staff of the Edwards Aquifer Authority support maintaining existing recharge structures but not construction of new ones, holding that other supply- and demand-side strategies will make greater contributions to "firm yield" of the aquifer.[55]

Bautista Creek Recharge Basin Expansion Project, Southern California

The Riverside County [California] Flood Control and Water Conservation District is one county-level organization that has taken this dual purpose of MAR to heart. The mission of this institution is both "to protect people, property and watersheds from damage or destruction from flood and storm waters" as well as "to conserve, reclaim and save such waters for beneficial use."[56]

To help fulfill these missions, the district and the Lake Hemet Municipal Water District (LHMWD), are proposing to design, construct, operate and maintain the "Bautista Recharge Basin Expansion Project" to

---

Heederik, eds. NNC-IAH Publication no. 4. http://siteresources.worldbank.org/INTWRD/Resources/GWMATE_Final_booklet.pdf.

[52] USACE and Edwards Underground Water District. 1965. Survey Report on the Edwards Underground Reservoir Guadalupe, San Antonio, and Nueces River and Tributaries, Texas. https://www.edwardsaquifer.org/wp-content/uploads/2019/05/1965_USACOEEUWD_GuadalupeSanAntonioNuecesSurvey-Vol1.pdf

[53] http://www.edwardsaquifer.net/recharge.html#recharge_article

[54] Jarrett, F. and Voigt, E.E. 1973. And So We Did: The Story of a Bexar County Rancher as told by Erwin E. Voigt to Frank Jarrett. Self-published. Cited at http://www.edwardsaquifer.net/salado.html

[55] https://www.edwardsaquifer.org/science_docs/re-conceptualizing-the-edwards-aquifer-authority-recharge-program-staff-recommendations-to-optimize-and-protect-the-edwards-aquifer/

[56] http://www.rcflood.org/

promote infiltration and increase recharge in groundwater basin areas. Six new infiltration basins would be built as a continuation of existing USACE recharge basins; these would be hydraulically connected to the proposed basins. The goal of the nearby Green Acres Dam is "to expand groundwater recharge within the area" but project documents also state that "the project will reduce flooding over areas located south of its location" and "following the project, a FEMA mapped floodplain should be able to be reduced or eliminated, saving residents money on flood insurance.[57] The project would also provide water quality treatment as a secondary feature.

USACE would be involved in CWA Section 404 permitting (for Stormwater Management Facilities), and 33 U.S.C. Section 408 permitting for modifications of existing USACE Projects. USACE also has extensive infrastructure along Bautista Creek and downstream of it.[58]

Boise River Feasibility Study, Idaho

USACE and the Idaho Water Resource Board (IWRB) have been partnering on a feasibility study on the Boise River to evaluate alternatives to reduce flood risk, and meet current and future water supply needs in the lower watershed. The study also seeks to provide ancillary ecosystem-restoration benefits, while minimizing socioeconomic effects and impacts to sensitive species.

MAR has been one of the measures considered in various alternatives, which also included raising the height of an existing dam, upgrading irrigation headgates and bridges, flooding mining pits, enhanced water conservation and non-structural measures. MAR was examined for potential aquifer recharge while also providing flood-risk management benefits. It was primarily viewed as an alternative to raising Arrowrock Dam, when combined with conservation, and non-structural, and additional measures.

The option of raising the height of Arrowrock Dam showed the most promise in preliminary modeling and economic investigations. However, the results of more detailed analyses indicated that this alternative would not generate enough economic benefits to exceed project costs over a 50-year period of analysis. As formulated, the ~0.7 benefit-to-cost ratio did not allow the project to be recommended for implementation, and as of May 2016, the IWRB was considering whether to reformulate or terminate the study.[59]

4.3. Aquatic Ecosystem Restoration and Constructed Wetlands

Given the status of aquatic ecosystem restoration as a "primary mission" of USACE, aquatic ecosystem restoration often can be a principal driver of USACE engagement in MAR projects. Wetlands are often used as a component of treatment of wastewater for reuse, and existing or created wetlands may also be used as percolation ponds for MAR. Further, modifying wetlands for the purpose of creating groundwater recharge basins generally involves the Regulatory program of USACE through Section 404

---

[57] http://www.floodcontrol.co.riverside.ca.us/CapitalImprovementProjects.aspx; July 2, 2018 version.
[58] http://rcflood.org/Documents/CEQA/IS_MNDBautista_clean.pdf
[59] http://www.nww.usace.army.mil/Missions/Projects/Lower-Boise-River-Feasibility-Study/ and http://www.nww.usace.army.mil/Portals/28/docs/programsandprojects/lbrfs/FS_BoiseFeasibilityStudyUpdateMay2016.pdf.

of the Clean Water Act, even if the work is performed by local or state entities. Several examples of such projects follow.

Lake Okeechobee, South Florida

Lake Okeechobee is one of the primary surface water storage features of the Everglades system and is important for recreational boating and fishing. At the same time, it has an important littoral ecosystem, and supplies water to the downstream Everglades ecosystem. Increasing water demands on the system will require additional storage to provide flexibility for water distribution during wet and dry seasons.

ASR in the Lake Okeechobee area was envisaged in the original 1999 Comprehensive Everglades Restoration Plan[37] to have multiple purposes including:

- Helping restore the ecological health of the Lake through appropriate lake levels;
- Increasing the Lake's capability to meet water demands for agriculture, urban areas, and the Everglades ecosystem;
- Reducing damage to the St. Lucie and Caloosahatchee Estuaries, on the East and West coast, respectively, due to harmful, high-volume regulatory discharges; and
- Maintaining or lowering the existing flood risk while limiting evaporation losses and land consumption relative to building additional above-ground storage.

The current Lake Okeechobee Watershed Restoration Project (LOWRP) is similar, with goals to improve water levels in the lake; improve water supply for existing legal users; improve the quantity and timing of discharges to the estuaries; and restore degraded habitat for fish and wildlife while increasing the spatial extent and functionality of wetlands.[60, 61]

The project concept is to store partially or fully treated surface water, when it is available, underground through ASR wells completed within the underlying Floridan Aquifer System (FAS) for subsequent recovery during dry periods. There are remaining technical challenges to using ASR at this site—for example, appropriate water treatment prior to recharge and attaining the desired quality of the water discharged to the lake—but overall ASR at this site at a reduced scale relative to the CERP seems likely to be feasible. A 2015 National Research Council study of regional scale ASR in the region noted that no "fatal flaws" have been discovered, although "many uncertainties remain that merit additional study before large-scale ASR should be implemented".[62]

An unusual feature of this site is that the MAR would be adjacent to the surface storage components (i.e., Lake Okeechobee and a planned "wetland attenuation feature", or WAF), as opposed to downstream of them. This would allow water managers to discharge groundwater into the lake at the optimal time and in the appropriate quantity. In many other case studies within this report, recharge would occur *downstream* of the reservoir; recovered water would be available for water supply or other downstream uses, but not for ecological or recreational uses within the reservoir itself. Since the Lake

[60] https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll11/id/3833
[61] https://www.saj.usace.army.mil/LOWRP/
[62] National Research Council. 2015. Review of the Everglades Aquifer Storage and Recovery Regional Study. Washington, DC: The National Academies Press. https://doi.org/10.17226/21724

Okeechobee case proposes well injection into confined aquifers, where there is no concern that recharged water will re-enter the lake through hydraulically connected sediments.

In addition to co-location of ASR with Lake Okeechobee, co-location with surface storage in the WAF would help provide relief to the lake and minimize estuary releases by recharging water as the WAF is filling, increasing the WAF's effective storage capacity and improving overall performance.

Not all water systems are as complex as the Everglades, and ASR is not without its own challenges there; but this example illustrates the possibilities for maintaining environmental flows and levels while enhancing the robustness of existing infrastructure to a range of climatic conditions. An extensive investigation of the potential use of ASR for management of Lake Okeechobee and the downstream portions of the South Florida Ecosystem may be found in the ASR pilot project and regional study reports.[38, 39]

Nueces River Basin and Tributaries Project, Texas

The Nueces River basin in South Texas flows southeast into Nueces Bay near Corpus Christi. Land use practices, droughts, and conflicting water management objectives have led to significant environmental degradation. This degradation includes a) hyper-saline conditions in the estuary from construction and operation of two upstream reservoirs, and b) degradation of rare and unique habitats from the lowering of water levels in the Edwards Aquifer and concomitant reduction in spring flows from the San Marcos and Comal Springs[63]. In addition to modification of systems operations of Choke Canyon Reservoir and Lake Corpus Christi, USACE and its partners are examining the potential for recharging the Edwards Aquifer in key locations to increase spring-flow to habitats that support endemic threatened and endangered species. Thus, ecosystem restoration would be occurring both at the upstream end of the basin, in the spring habitats, as well as at the downstream end of the basin, in the estuaries by the Gulf of Mexico.[64]

Lockport Prairie Ecosystem Restoration, Northeastern Illinois

Located on the lower Des Plaines River active floodplain in Illinois, the Lockport Prairie Nature Preserve contains a wet prairie landscape and a globally rare type of plant community. The site has two federally listed plant species (Lakeside Daisy and Leafy Prairie Clover), and critical habitat for the federally listed Hine's Emerald Dragonfly. However, ecosystem degradation has caused the decline in Hine's Emerald Dragonfly habitat and in floristic quality. One major driver of this degradation has been a decrease in groundwater discharge into the Preserve. This, in turn, is believed to be partly due to an area of the local recharge zone having been impacted by an extensive system of drain tiles, which conveys precipitation and soil water into surface channels and impedes infiltration.[65]

---

[63] These are the two primary springs in the Edwards Aquifer segment near San Antonio.
[64] http://www.swd.usace.army.mil/Portals/42/docs/civilworks/Fact Sheets/Fort Worth/FY13 Nueces River and Tribs, TX.pdf
[65] USACE. 2015. Lockport Prairie Ecosystem Restoration: Feasibility Study and Integrated Environmental Assessment. Chicago District.
https://www.lrc.usace.army.mil/Portals/36/docs/projects/lockportprairie/01%20Lockport%20Prairie_FS_Public_04AUG2015.pdf

To help reestablish the higher, historic recharge volumes to drive more groundwater toward the Preserve, and thereby increase discharge rates in the degraded part of the system, several measures were considered. Infiltration trenches using runoff from a highway west of the Preserve were considered but eventually eliminated from further plan formulation because of the large amount of road salt dissolved in surface runoff.[66] An alternative strategy to restore the natural hydrology at the Preserve —disablement of a drainage tile system in the up-gradient Prairie Bluff Preserve—was recommended instead, in conjunction with other measures.[65] This plan would install water control valves at certain intervals to back up water in appropriate locations, making it available for recharge. Whether restoring a more natural recharge rate using engineered methods should be considered as MAR or not is undetermined.

Fort Huachuca, Arizona

Fort Huachuca (Arizona) is in the transboundary San Pedro River Basin—a water-stressed region with numerous federally threatened and endangered species. To help counteract decreases in groundwater base flow to the river, the Fort introduced a water conservation program that has been highly effective in decreasing water use. However, base flow is still not recovering in many areas in and around the fort. In response, Fort Huachuca has begun recharging treated effluent in detention ponds near its wastewater reclamation facilities to the local aquifer, thereby decreasing Fort Huachuca's net impact on the water budget of the basin, and especially on the groundwater that feeds the San Pedro River.[67]

James Irrigation District Water Augmentation Project, Central California

The Sacramento District of USACE evaluated a permit application by the James Irrigation District, in western Fresno County, CA to construct a Water Augmentation Project. The irrigation district wished to decrease their "reliance on Central Valley project water from the San Joaquin-Sacramento Delta, to provide capacity for peak irrigation demands, to provide for efficient re-regulation of flows and to allow for groundwater recharge/banking in a critically overdrafted groundwater basin…"[68]

To do this, the James Irrigation District proposed to construct a phased water banking expansion project involving the creation of some 155 acres of above-ground recharge cells within Fresno Slough Bypass. Between the additional recharge cells and the drilling of additional wells, the project would provide for regulation, recharge, banking, storage and recovery of water for irrigation. The U.S. Bureau of Reclamation was designated the lead Federal agency; the USACE 404 program was involved because the irrigation district proposed to excavate earth from existing recharge basins, and use the excavated soil to construct basin and channel improvements and recharge cell berms.

---

[66] Ibid. Appendix A - Hydrology and Hydraulic Analysis. https://www.lrc.usace.army.mil/Portals/36/docs/projects/lockportprairie/AppendixABackup_Lockport_HH.pdf

[67] U.S. Geological Survey. 2016. Hydrological Conditions and Evaluation of Sustainable Groundwater Use in the Sierra Vista Subwatershed, Upper San Pedro Basin, Southeastern Arizona. Scientific Investigations Report 2016–5114, Version 1.1. https://pubs.er.usgs.gov/publication/sir20165114

[68] http://www.spk.usace.army.mil/Media/Regulatory-Public-Notices/Article/479560/spk-2009-01080-fresno-county-ca/

Due primarily to regulatory and financial uncertainties, the irrigation district decided not to move forward with the project in 2016.[69]

Other examples of MAR projects involving the USACE Regulatory Program include the San Antonio Creek Spreading Grounds Rehabilitation Project, Ventura County, CA and the New River Agua Fria River Underground Storage Project (NAUSP) of Phoenix, AZ.

4.4. Reducing Saltwater Intrusion

The prevention or reduction of saltwater intrusion (SWI), as with other goals for MAR, can be accomplished by using either recharge wells or surface water recharge basins.

Picayune Strand Restoration Project, Collier County, Southwestern Florida

The Picayune Strand Restoration Project, in the southwestern corner of Florida, was the first project of the Comprehensive Everglades Restoration Plan (CERP) to begin construction. Authorized in 2007 to restore an unsuccessful real estate development to a more natural state, the project has multiple purposes, including habitat enhancement for the Florida Panther and other species, improved water quality, flood risk management, recreation, and control of exotic species. However, its first listed purpose is to "improve aquifer recharge to protect water supply and prevent saltwater intrusion".[70] This is to be accomplished by plugging canals and removing roads that were constructed for the non-existent development, thus allowing for fresh water to help restore drained wetlands, restore historic sheet flow, and bring back the native ecosystem. By replenishing groundwater, this process helps move the freshwater-saltwater interface further seaward.

Farmington Groundwater Recharge Program, Northern California

The Farmington Groundwater Recharge Program (FGRP; originally the "Farmington Groundwater Recharge and Seasonal Habitat Study") in the San Joaquin Valley, California may also be viewed partly as a salt-water intrusion (SWI)-control MAR project. Decades of high-volume groundwater pumping for agricultural and urban water demands has lowered groundwater levels throughout the San Joaquin Valley. Part of the threat to water supply to the region is due simply to the cost of pumping from these deeper water levels, but concomitant salt-water intrusion from below the Sacramento-San Joaquin River Delta has made the groundwater unsuitable for domestic use in some areas from a water-quality perspective as well.

MAR using flood-season and excess irrigation water supplies is being considered in this context. Initial site screening and percolation tests are being done to minimize environmental impact and maximize groundwater recharge potential. USACE and the Stockton East Water District are conducting a feasibility study using four sites for pilot-scale recharge testing over the next several years, to determine their

[69] Steven Stadler, General Manager, James Irrigation District, oral communication, 20 February 2020.
[70] https://www.saj.usace.army.mil/Portals/44/docs/Environmental/Picayune%20Strand/PSRP%20PumpEcosystem24x36.pdf

suitability for this purpose. The temporary ponding would also provide seasonal habitat for migratory birds along the Pacific Flyway and for other animals.[71]

Los Angeles County Seawater Barriers, Southern California

Los Angeles County operates and maintains three longstanding hydraulic barriers to salt-water intrusion to protect its heavily exploited groundwater basins. Fresh water is recharged in three locations near the coast to raise the groundwater levels or potentials enough to prevent salt water from migrating from the southwest into the basin.[72] Some of the injected water has historically come from USACE-managed reservoirs, such as Whittier Narrows (see Drought Resilience section, above), and as the county moves towards independence from water outside of the basin for groundwater recharge, they cite additional management changes in the Whittier Narrows Conservation Pool as a means to capture more storm water for this purpose.[73]

Several other USACE activities could have been included in this section. First, a successful result from USACE's Forecast-Informed Reservoir Operations (FIRO) pilot project in the Russian River basin, California (discussed below) will likely enable the downstream utility, Sonoma Water, to help combat salt-water intrusion as part of a sustainable water-supply strategy. Second, a USACE investigation of the potential for SWI in the Upper Floridan Aquifer from the Savannah Harbor (Georgia) Expansion Project concluded that the amount of SWI would not be significantly affected by the project,[74] but monitoring in the aquifer and overlying confining unit will continue.[75] In theory, recharge wells could be used to limit the extent of such intrusion.

4.5. Multi-use urban environmental restoration projects

MAR projects are often most desired in urban areas in the arid west, since rapidly-growing western US cities often have the greatest demands for additional water supplies. Highly-altered river channels across the western U.S., including some in urban areas, provide natural opportunities to combine environmental restoration with groundwater recharge. The complication is often the quality of recharge water. Highly-treated wastewater that has passed through wetlands may be desirable for recharging aquifers, but often the available water is from runoff events whose water may contain high levels of heavy metals, fertilizers and pesticides, and components of gasoline and diesel fuel. Still, many such projects are under consideration, and among their environmental benefits may be the dampening of such peak flow which may otherwise lead to erosion and flooding. Examples follow:

---

[71] Sources: http://www.farmingtonprogram.org/ and http://www.spk.usace.army.mil/Missions/CivilWorks/Farmington.aspx
[72] https://dpw.lacounty.gov/wrd/barriers/index.cfm
[73] https://www.wrd.org/content/other-projects-and-programs
[74] USACE. 2007. Supplemental Studies to Determine Potential Ground-Water Impacts to the Upper Floridan Aquifer: Savannah Harbor Expansion Project. Final report. Prepared by USACE Savannah District. http://www.sas.usace.army.mil/Portals/61/docs/SHEP/Reports/GRR/36 Potential Ground-Water Impacts to the Upper Floridan Aquifer June 2007_PART_A.pdf.
[75] USACE. 2015. Groundwater Monitoring Report: Savannah Harbor Expansion Project. Prepared by USACE Savannah District. http://www.shep.uga.edu/docs/reports/2015-04 Groundwater Monitoring 2nd Quarter Report.pdf.

Los Angeles River Ecosystem Restoration

Overseen by the USACE Los Angeles District office, the purpose of the Los Angeles River Ecosystem Restoration Feasibility Study is to define environmental degradation and related problems, and to investigate the feasibility of implementing alternative solutions to address the loss of riparian habitat, water quality, water conservation, lack of recreation, and open space along a 32-mile corridor within the City of Los Angeles. Past flood control projects in the region and channelization of the river itself have substantially altered the nature of the channel and its hydrological regime. Combined with the intensive urbanization of the watershed, these changes have resulted in a concrete-lined river channel virtually devoid of native vegetation, and subject to high-velocity flood flows that inhibit reestablishment of a more natural stream channel. This multipurpose study will consider water supply and groundwater recharge opportunities, recreation and open space alternatives, and incidental flood risk management in addition to restoring degraded urban habitat and improving ecological conditions of the Los Angeles Basin.[76]

Tres Rios Ecosystem Restoration and Flood Control Project, Phoenix, Arizona

The Tres Rios Ecosystem Restoration and Flood Control Project was approved by Congress in 2000. USACE and the City of Phoenix were the primary partners. The project, which was constructed from 2007-2012, improved and enhanced about 1500 acres along a seven-mile stretch of the Salt and Gila Rivers in southwestern Phoenix. In addition to flood risk management, and re-establishment of native riparian vegetation and habitat for several threatened and endangered bird species, the site was also designed for recreation and environmental education. It also improves quality of the source water, which is highly treated wastewater effluent from the City of Phoenix.[77]

In addition to these many benefits, the project supplies groundwater recharge into the alluvial aquifer below the facility and in the receiving Gila River. It likewise maintains high groundwater elevations which support riparian habitat in both areas.[78]

Tres Rios del Norte, Pima County (Tucson area), Arizona

The purpose of the Tres Rios del Norte Environmental Restoration Feasibility Study was to determine the feasibility of providing riparian habitat restoration along 18 miles of the Santa Cruz River near Tucson, Arizona. It was a cooperative effort between USACE's Los Angeles District Office, the Pima County Regional Flood Control District, the City of Tucson, and the Town of Marana.

This study began a process of analyzing the potential to restore and enhance native vegetation and riparian habitat within the Santa Cruz River's channel, its overbank areas, and on some of the major tributaries. Groundwater replenishment was considered as an additional element of the study, as were recreational improvements, cultural resource preservation, and flood damage reduction. In late 2015, however, the Town of Marana withdrew as a local sponsor of the feasibility study—the City of Tucson had previously withdrawn in 2009—citing the rising cost and scarcity of water, and the unlikelihood of

---

[76] http://www.lariver.org/
[77] https://www.phoenix.gov/waterservices/tresrios/wetlandsinfo
[78] https://bsmar.site/field-trip

securing federal funding to help implement the study's recommendations.[79] As of February 2020, USACE was planning to close out the project.[80]

4.6. Conjunctive Use

The primary focus of this report has been on projects where managed aquifer recharge is a component of the activities. Conjunctive use of groundwater and surface water (Box 2) is a broader term encompassing projects where there may or may not be direct, or "artificial", recharge through wells, basins or dry rivers. Rather, the use of the resource is coordinated in such a way as to permit aquifers to naturally recharge themselves. Such projects are fairly common and at a detailed level are beyond the scope of this report. However, several USACE-related examples are given here to provide context and to contrast with explicit MAR projects.

Grand Prairie Region and Bayou Meto Basin, Eastern Arkansas

The Grand Prairie Region and Bayou Meto Basin projects, located in eastern Arkansas in the Memphis District of USACE, are not strictly speaking MAR projects. They were originally authorized for flood control in Section 204 of the Flood Control Act of 1950, and re-authorized together in Section 363 of WRDA 1996 (PL 104-303) with the project scope to include "ground water protection and conservation, agricultural water supply, and waterfowl management".[81]

The Grand Prairie Area Demonstration Project (GPADP) is a comprehensive water management plan designed to protect and preserve both the Mississippi River Valley Alluvial Aquifer and the Sparta Aquifer. The Alluvial Aquifer is currently overpumped at rates higher than natural recharge, leading to severe drawdown in the region of the project. The project utilizes excess surface water, and water from the White River, to fill on-farm reservoirs that store the water, to partially replace groundwater usage and thereby reduce further depletion of groundwater aquifers. The project also provides benefits for large numbers of waterfowl that annually migrate through the region.[82]

The Bayou Meto Basin project is also designed to protect and conserve the groundwater resources of the region—especially the Alluvial Aquifer which was nearing complete depletion at the time the project was initiated. In addition to its flood control and environmental components—the area is renowned for waterfowl hunting and is an important wintering habitat for mallards—the project will bring extra surface water supply to the basin through diversion of excess water from the Arkansas River via a system of pump stations, new canals, existing streams, and pipelines. Like the Grand Prairie project, the

---

[79] https://www.tucsonlocalmedia.com/marana/article_a69e8fb6-a8f8-11e5-a77b-3f3b2ee1e6c5.html

[80] https://www.spl.usace.army.mil/Portals/17/docs/congressional/Fact_Sheets/PPMD/PimaCountyTresRiosDelNorteFactSheet.pdf?ver=2020-02-20-124705-483

[81] https://www.govinfo.gov/app/details/PLAW-104publ303/summary

[82] http://www.mvm.usace.army.mil/Missions/Projects/GrandPrairieAreaDemonstrationProject.aspx

availability of surface water will take stress off of the groundwater system and allow the Alluvial Aquifer to recover through natural recharge.[83]

Thus, while in both projects only limited recharge will be *directly* added the groundwater system, they will likely lead to a decrease in pumpage and thereby allow the system to recover over time.

In the neighboring Cache River Basin, a USACE Water Management Plan noted declining groundwater levels and identified groundwater conservation as a potential opportunity. It also stated that "using excess springtime in-stream flow to recharge the Alluvial Aquifer in an enhanced manner would be an approach worth considering". [84] The US Department of Agriculture (USDA) Agricultural Research Service (ARS) conducted a MAR experiment in the basin using an infiltration basin, with encouraging results.[85]

Willamette River Basin, Western Oregon

The Willamette River Basin Review Feasibility Study[86] is being conducted to determine if and how space in the reservoirs can be reallocated to provide stored water for water supply, irrigation, and ecological uses. It is an example of a study in which USACE would not be directly involved in MAR, but which assumes the possibility of MAR by its partners. Within the basin, the cities of Salem and Beaverton have existing ASR systems. Salem stores treated drinking water sourced from the North Santiam River during high river flows in the winter and recovers it to meet peak demand in the summer.[87]

USACE's November 2017 Draft Integrated Feasibility Report and Environmental Assessment for the basin found that ASR "is able to meet a significant portion of the unmet future M&I peak season demand throughout the basin, and meets the criteria of completeness, effectiveness, efficiency, and acceptability."[88] The Tentatively Selected Plan would instead reallocate Willamette Valley Project (WVP) conservation storage as the least-cost alternative in terms of both initial capital costs, and annual costs.[89] However, the legal situation regarding water storage rights is complex; Reclamation's water rights allowing the federal government to store water in WVP reservoirs are designated exclusively for irrigation. Since timely, consensus-based disentanglement of these legal issues is far from certain, it is quite possible that additional ASR systems may end up playing an important role in meeting future peak season demand in the basin. And indeed, both Salem and Beaverton are working to expand their current systems.

---

[83] http://www.mvm.usace.army.mil/Missions/Projects/BayouMetoBasinProject.aspx
[84] https://www.mvm.usace.army.mil/Portals/51/docs/PPPMD/FINAL Cache River WMP 2017-1-24.pdf
[85] Reba, M.L., J.H. Massey, M.A. Adviento-Borbe, D. Leslie, M.A. Yaeger, M. Anders and J. Farris. 2017. Aquifer Depletion in the Lower Mississippi River Basin: Challenges and Solutions. Journal of Contemporary Water Research & Education 162: 128-139.
[86] https://www.nwp.usace.army.mil/willamette/basin-review/
[87] https://www.cityofsalem.net/drinking-water
[88] https://usace.contentdm.oclc.org/digital/collection/p16021coll7/id/8219
[89] https://usace.contentdm.oclc.org/digital/collection/p16021coll6/id/2084

Chatfield Reservoir Storage Reallocation & Related Non-Federal Projects, Denver area

Chatfield Reservoir is located about 15 miles south-southwest of Denver, CO, on the main stem of the South Platte River. The Chatfield Reservoir Storage Reallocation Final Integrated Feasibility Report and Environmental Impact Statement (July 2013) examined whether a portion of the flood control storage space in the Chatfield Lake project could be reassigned to "joint flood control-conservation purposes", including municipal and industrial water supply.[90]

The report concluded that 20,600 acre feet of water storage could be reallocated without compromising its flood control function. MAR using the bedrock and/or alluvial aquifers was evaluated as part of the study, but was eliminated from further consideration as unnecessary since the existing, on-channel reservoir could be used with modest additional cost. However, the report notes that conjunctive use of groundwater, including MAR, will likely be pursued by the non-Federal partners as a complementary measure to assure reliable supply during droughts. In particular, the South Metro Water Supply Authority (SMWSA) is leading a coordinated regional effort to evaluate the feasibility, economic constraints, and benefits of a regional ASR program.[91] In fact, reallocated Chatfield Reservoir water could be used downstream to recharge Denver Basin groundwater, which is currently being pumped at an unsustainable rate. This, along with water reuse, agricultural transfers, demand management and other measures, will likely help provide reliable M&I water supply well into the future.

Quiver River, Big Sunflower River Basin, Northwestern Mississippi

In northwestern Mississippi, the Quiver River lies in the Big Sunflower River Basin, which is a sub-basin of the Yazoo River Basin. Like other streams in the Big Sunflower River Basin, agriculture, irrigation, and flood risk management projects have has substantial impacts on aquatic habitat. In particular, channelization and reduced instream flows in the river have lowered dissolved oxygen levels and raised water temperatures. Limited riparian vegetation, high nutrient concentrations, limited in-stream cover, high turbidity, reduced habitat complexity, and low aquatic species richness and diversity are all issues.

At the regional level, many areas of the Mississippi Delta area have experienced severe groundwater depletion over recent decades, with water use from the Mississippi River Valley Alluvial Aquifer exceeding natural recharge by about 500,000 acre feet per year during the last decade. This unsustainable use is leading to deeper wells, and higher drilling and maintenance costs. As a result, the 2015 Mississippi Ground Water Quality Assessment prioritized "developing and implementing conjunctive water management strategies" in the Mississippi Delta area.[92]

In response to these needs, a USACE study was initiated to investigate potential aquatic habitat restoration of the Quiver River—a Federal interest—and to consider compatible opportunities to provide agricultural water supply—a non-Federal partner interest. The resulting Tentatively Selected Plan would address increased sedimentation, reduced stream flow and resultant poor water quality, and

---

[90] Chatfield Reservoir Storage Reallocation Final Integrated Feasibility Report and Environmental Impact Statement. https://usace.contentdm.oclc.org/digital/collection/p16021coll7/id/10/.
[91] SMWSA 2016 Regional Master Plan Update. https://southmetrowater.org/application/files/9615/7867/2371/MP-Publication-Final.pdf
[92] https://www.mdeq.ms.gov/wp-content/uploads/2017/06/305b_2015-Final.pdf

loss of a forested riparian corridor by establishing a forest buffer along several miles of the river. It would also transfer water from the Tallahatchie River to provide a minimum Quiver River flow of 100 cubic feet per second (cfs). This latter effort will ensure a more natural stream flow and will improve water quality during late summer and autumn. It would also supply an additional 300 cfs to irrigate tens of thousands of acres of rice, soybeans, and corn. All of these acres are currently irrigated with groundwater, so use of available surface water would lessen overextraction of groundwater from the Alluvial Aquifer.[93]

Nearby in Leflore County, a pilot project for the direct transfer of surface water via bank filtration from the Tallahatchie River to the Alluvial Aquifer was planned for late 2019 or 2020. The water would be pumped overland for 2 miles, and injected via two ASR wells at a depth of about 130 feet. Authorization and funding is through the USDA Agricultural Research Service, but they contracted with the USACE Vicksburg District for support on project design, plans, specifications, permitting, contract administration, and construction oversight.[94] A successful project may potentially lead to operational ASR wells in the region.

Stockton Lake Reallocation Study, Southwestern Missouri

A similar situation exists with the ongoing USACE Stockton Lake reallocation study in Southwest Missouri, where the regional Tri-State Water Resource Coalition is interested in using lake water to supplement existing groundwater supplies. Reallocation for drinking water would be from reservoir space currently reserved for either flood control or hydropower. The Ozark Aquifer is the main source of water for all but a few communities in Southwest Missouri, but a U.S. Geological Survey (USGS) modeling study forecasted serious water-level declines in the aquifer from 2016-2060 with just modest increases in pumping due to population growth.[95] Reallocation of surface water from Stockton (and potentially Table Rock) Lake could contribute to extending the life of the major aquifer in the region.[96]

5. Other US Government Involvement in MAR

Although USACE's direct involvement in MAR activities has been modest, other federal agencies have been quite engaged. These notably include the U.S. Bureau of Reclamation, but the U.S. Environmental Protection Agency and U.S. Geological Survey are also involved in regulatory and scientific activities, respectively. In addition, the Natural Resources Conservation Service (NRCS) has begun engaging in on-farm flood capture and recharge projects that would flood agricultural lands to mitigate large-scale flood risks and offset groundwater overexploitation.

---

[93] Big Sunflower River Watershed (Quiver River), Mississippi: Draft Feasibility Report with Integrated Environmental Assessment. https://www.mvk.usace.army.mil/Portals/58/docs/PP/Peer Review Plans/Quiver River Draft Report.pdf

[94] Draft Environmental Assessment: Groundwater Transfer and Injection Pilot Project, Leflore County, Mississippi. September 25, 2019 version.

[95] Clark, B.R., L.L. Duncan, and K.J. Knierim. 2019. Groundwater availability in the Ozark Plateaus aquifer system: U.S. Geological Survey Professional Paper 1854, 82 p., https://doi.org/10.3133/pp1854

[96] Southwest Missouri Water Resource Study – Phase I: Forecast of Regional Water Demands (2010-2060). https://www.swl.usace.army.mil/Portals/50/docs/planningandenvironmental/Phase I - Southwest Missouri Water Study Final Report.pdf

5.1. Bureau of Reclamation

Reclamation's authorities have allowed it to show considerable leadership on Federal engagement in MAR, and in fact Reclamation has no federal restrictions on its authority to deliver project or excess water for groundwater recharge. Likewise, the parties recharging, storing and recovering the water "are not required to seek any special approvals beyond what is normally required by Reclamation."[20]

Reclamation also has several authorities specific to groundwater storage. The Reclamation States Emergency Drought Relief Act of 1991 (P.L. 102-250), for example, states that "In order to respond to a drought, the Secretary is authorized to participate in water banks established by a State."[97] Some major water banks, such as Arizona Water Banking Authority, store the banked water underground, including on behalf of the Southern Nevada Water Authority.[98] Section 4011 of WRDA 2016 created a "Water Storage Enhancement Program" and authorized Reclamation to participate in non-Federal storage projects, which Reclamation defines to include groundwater storage facilities.[20]

Historically, the High Plains States Groundwater Demonstration Program Act of 1983 gave Reclamation authority to design, construct and operate groundwater recharge systems in a variety of geologic and hydrologic environments.[99] Through this program, from 1984 to 2000, Reclamation eventually funded 14 "artificial recharge" demonstration projects in the Western States, developing much information on the costs and benefits of artificial recharge for the different regions.

To follow up on this program, in 2009, Congress passed the SECURE Water Act (Title IX, Subtitle F, P.L. 111-11), which directed the Department of the Interior to develop a sustainable water management policy. As a next step, in 2010, Interior established WaterSMART (Sustain and Manage America's Resources for Tomorrow).[100] Among WaterSMART's activities is the Drought Response Program, and five of the program's 18 grants in 2019 are for groundwater recharge projects. A separate WaterSMART program (Title XVI of P.L. 102-575) targets recycling and reuse of water, which is often used in conjunction with MAR (for example, in Orange County, California). Like the Drought Response Program, the cost is shared with state or local government entities, thus leveraging the Federal dollars.

An example of Reclamation work involving MAR is the Yakima River Basin Integrated Water Resource Management Plan.[101] The plan's March 2012 Final Programmatic Environmental Impact Statement,[102] jointly prepared by Washington State Department of Ecology, included pilot projects for two

---

[97] https://www.govinfo.gov/content/pkg/USCODE-2010-title43/html/USCODE-2010-title43-chap40-subchapI-sec2211.htm

[98] https://waterbank.az.gov/sites/default/files/ThirdAmendedandRestatedInterstateBankingAgreement-Exec.5-20-13.pdf

[99] https://www.govinfo.gov/content/pkg/USCODE-2008-title43/html/USCODE-2008-title43-chap12-subchapI-sec390g.htm

[100] https://www.usbr.gov/watersmart/

[101] Bureau of Reclamation and Washington State Department of Ecology. 2012. Final Programmatic Environmental Impact Statement. Department of Ecology publication number 12-12-002. http://www.usbr.gov/pn/programs/yrbwep/reports/FPEIS/fpeis.pdf.

[102] https://fortress.wa.gov/ecy/publications/documents/1212002.pdf

groundwater storage actions—shallow aquifer recharge via infiltration basins, and ASR.[103] Permanent facilities would allow for water withdrawals for various uses, while allowing continuation of natural high-flow events that provide biologic and channel configuration benefits. Infiltration basins would likely be placed near the Yakima River, thus providing a source of cool discharge water, preferred by several native and listed species, to the lower river in summer months. As of 2019, the City of Yakima ASR Project was fully permitted.[104]

Additional legislation has been proposed, e.g., the "S. 1932: Drought Resiliency and Water Supply Infrastructure Act".[105] This proposed legislation, targeted at Reclamation, would give priority to water recycling and reuse projects that "…provide multiple benefits, including water supply reliability, ecosystem benefits, groundwater management and enhancements…"

5.2. Joint Reclamation-USACE

A joint Reclamation-USACE effort, the Twitchell Dam and Santa Maria Project (San Luis Obispo County, California) authorized by Public Law 83-774,[106] is managed for both flood risk management (USACE) and MAR for agricultural and minor urban water supply (Reclamation). The USACE component was solely "for levees and channel improvements", but the project was driven from the beginning by overexploitation of the downstream aquifer system, which was being pumped faster than it was being naturally replenished, threatening salt-water intrusion.

Thus, "[t]he objectives of the Santa Maria Project were to recharge the critically-depleted groundwater reservoir underlying the basin and to eliminate the future flood threat to valley lands [and] what water was captured would typically be immediately released to replenish underground supplies…Operation of the conservation side of the project would be such that dam operators would attempt to most closely replicate the stream channel's percolation rate, releasing flood water stored in the conservation space of the reservoir at a rate that was determined to be approximately 300 cfs. Anything less would be absorbed by the river channel and fail to make it to deposits tapped downstream; too large a flow would waste to the sea".[107]

The maintenance and operations of Twitchell Dam are now overseen by the Santa Maria Valley Water Conservation District.

---

[103] Pitre, C. 2014. Programmatic Framework for Aquifer Storage and Recovery in the Ahtanum Valley. U.S. Bureau of Reclamation. Contract # R08PC10677 ID/IQ. https://www.usbr.gov/pn/programs/yrbwep/reports/index.html.
[104] https://www.yakimaherald.com/news/local/city-effort-to-bank-naches-river-water-in-aquifer-moves/article_b6cfdf20-4c60-11e9-852f-5708381b6126.html
[105] https://www.govtrack.us/congress/bills/116/s1932/text, introduced June 20, 2019.
[106] http://resreg.spl.usace.army.mil/pages/twcl.php
[107] Latousek, Thomas A. 1996. The Santa Maria Project. Series on Research on Historic Reclamation projects. Denver, Colorado: Bureau of Reclamation. https://www.usbr.gov/projects/pdf.php?id=189

5.3. Environmental Protection Agency

The Environmental Protection Agency has an important role to play in MAR, primarily driven by its regulation of aquifer recharge and ASR wells (but not infiltration basins) through its Underground Injection Control program, promulgated under the Safe Drinking Water Act.[108] ASR wells are included among "Class V Wells for Injection of Non-Hazardous Fluids into or Above Underground Sources of Drinking Water."[109]

Given these responsibilities, the EPA's Office of Research and Development, National Risk Management Research Laboratory, has conducted and summarized research in several key areas. One of these is arsenic mobilization driven by the introduction of oxygenated ASR water into a more reduced environment with iron sulfides in the rock matrix.[110] This is ubiquitous in ASR wells in South Florida, for example, with important implications for Everglades restoration.[111] Another area of concern to the EPA is the formation of disinfection byproducts. Typically, direct injection MAR requires disinfection such as chlorination prior to recharge to control biofouling of the wells. If there is significant soluble organic carbon in the injectate, chlorinated disinfectants may react with it to form byproducts such as trihalomethanes, whose levels can approach regulatory limits in the aquifer. As a third example, EPA's STAR program has funded external grants on related topics such as Assessment of Stormwater Harvesting via [MAR] to Develop New Water Supplies in the Arid West.[112]

More broadly, EPA has produced an extensive decision support system for aquifer recharge and ASR planning, design and evaluation.[113] The system covers ASR regulations and permitting needs, water demand projections, climate change and water availability, sites and technical information, planning and assessment, and design and evaluation. It includes analytical and numerical models aimed at examining water availability, hydraulic control and rate of recovery, contaminant fate and transport, and geochemical changes such as arsenic mobilization.

The EPA also monitors water quality issues related to groundwater that is recovered and discharged to surface water bodies. In addition, EPA has organized workshops on ASR issues, especially with respect to water quality.

Finally, the draft National Water Reuse Action Plan,[114] coordinated by EPA, refers extensively to MAR. Proposed Action 2.7.4 is "Coordinate Research and Compile Best Practices for Enhanced Aquifer

---

[108] https://www.epa.gov/uic/aquifer-recharge-and-aquifer-storage-and-recovery
[109] https://www.epa.gov/uic/class-v-wells-injection-non-hazardous-fluids-or-above-underground-sources-drinking-water
[110] For example, Neil, C., Y. J. Yang and Y. Jun. 2012. Arsenic mobilization and attenuation by mineral–water interactions: implications for managed aquifer recharge. J. Environ. Monitor. 14(7):1772-1788.
[111] Mirecki, J., M. Bennett and M. López-Baláez. 2012. Arsenic Control during Aquifer Storage Recovery Cycle Tests in the Floridan Aquifer. Ground Water 51.10.1111/j.1745-6584.2012.01001.x.
[112] https://www.epa.gov/sites/production/files/2016-11/documents/3-ryan_dupont.pdf
[113] USEPA. 2016. Decision Support System for Aquifer Recharge (AR) and Aquifer Storage and Recovery (ASR) Planning, Design, and Evaluation – Principles and Technical Basis. Report No. 600-R-16-222.
[114] https://www.epa.gov/sites/production/files/2019-09/documents/water-reuse-action-plan-draft-2019.pdf

Recharge…among federal agencies, institutes, foundations, and universities that could leverage scientific expertise…" Thus, EPA considers MAR a technology that will be increasingly used in the future.

5.4. U.S. Geological Survey

The US Geological Survey (USGS) has a long history of basic and applied groundwater research. As groundwater use increased throughout the 20th century, this has gradually led from studies of regional aquifer frameworks to a greater focus on highly managed or overexploited systems. By the mid-1900s, the USGS had conducted major studies of artificial recharge in Long Island, NY[115] and in the states of Oregon and Washington.[116] In recent decades, the USGS has conducted an increasing number of scientific studies involving MAR in the US, especially in areas such as regional impacts[117] and recharge rate potential.[118] Their applied, cooperative projects with local states in their field offices (e.g., the Equus Beds ASR Project with the City of Wichita, Kansas,[119] Sand Hollow Reservoir in Washington County, Utah,[120] arroyos in the Rio Grande Valley of northern New Mexico,[121] and throughout California[122]) include assessments of aquifer over-abstraction, subsidence, and potential uses of MAR to slow or reverse these trends.

An extensive collaboration on MAR between USACE and the USGS took place as part of the CERP ASR Regional Study[32, 39] for the Everglades restoration effort. Hydrogeologic evaluations were conducted with the USGS and the Florida Geological Survey to improve our knowledge of the hydrostratigraphy and structure of the Floridan Aquifer System. New wells, aquifer tests, water levels and quality, rock cores, geotechnical analyses, seismic surveys, and other geophysical measurements were combined with groundwater modeling to help establish the number, location and safe pumping rates for ASR wells that could be used for the many purposes envisioned in the restoration plan. The USGS played an especially

---

115 Brashears, M.L.1946. Artificial recharge of ground water on Long Island, New York. Econ. Geology 41:503-516.
116 Price, D., D.H. Hart and B.L. Foxworthy. 1965. Artificial Recharge in Oregon and Washington 1962. USGS Water Supply Paper 1594-C. https://doi.org/10.3133/wsp1594C .
117 Scanlon, B. R., R. C. Reedy, C. C. Faunt, D. Pool and K. Uhlman. 2016. Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona. Environ. Res. Lett. 11 035013. https://doi.org/10.1088/1748-9326/11/3/035013
118 E.g., Niswonger, R. G., E. D. Morway, E. Triana and J. L. Huntington. 2017. Managed aquifer recharge through off-season irrigation in agricultural regions. Water Resources Research 53(8): 6970-6992. https://doi.org/10.1002/2017WR020458
119 https://pubs.usgs.gov/gip/0174/gip174.pdf
120 Marston, T.M. and V.M. Heilweil. 2016. Assessment of managed aquifer recharge at Sand Hollow Reservoir, Washington County, Utah, updated to conditions through 2014. U.S. Geological Survey Open-File Report 2016–1078, 35 p. http://dx.doi.org/10.3133/ofr20161078
121 https://www.usgs.gov/news/understanding-managed-aquifer-recharge-a-water-storage-option-pojoaque-river-basin
122 https://www.usgs.gov/centers/ca-water/science/aquifer-storage-and-recovery?qt-science_center_objects=2#qt-science_center_objects

important role in establishing the hydrogeologic framework and geologic structure of the aquifer system.[123]

It should also be noted that not all expertise in MAR lies within Federal, state, or local governments. In particular, progress on recharge basin technology, including such critical areas as clogging, well placement and recharge optimization, has been led by potable water suppliers and their consultants.

6. MAR as Related to other USACE Processes, Tools and Initiatives

The previous chapter has shown an increasing awareness throughout USACE of potential uses of underground storage. Overall, however, the potential future utility of MAR for water resources planning and management activities at USACE is best evaluated in the context of the formal planning process, existing tools and approaches in the planner's "toolbox", and initiatives currently under investigation for future USACE activities.

6.1. MAR as Part of the Planning Process

Most critically, a review of the examples described above, and their references, establishes that proposed or planned MAR activities are discussed in *standard USACE technical and planning documents*. These include one or more of the following: Final Technical Data Reports, Feasibility Studies, Environmental Assessments, Project Implementation Reports, Watershed Management Plans as part of Basin Comprehensive Studies, Draft and Final Integrated Feasibility Reports, Programmatic Environmental Impact Statements, and Draft Programmatic Agreements with other parties. MAR does not require new kinds of technical reports or planning documents.

This smooth integration may be facilitated by the fact that, in most of the examples, MAR is not viewed as *replacing* surface infrastructure. Rather, it is generally viewed as *augmenting or complementing it*. This may be partially due to the history of USACE Civil Works, which is replete with dam and reservoir construction. These facts-on-the-ground may condition the kinds of projects that state and local partners request USACE to investigate and potentially engage in.

More fundamentally, however, the respective strengths and weaknesses of surface and underground storage can complement each other. Reservoirs may be able to sequester large volumes of water in a short period of time; recharge basins or wells can augment that storage, but may require weeks or longer to fully recharge the desired amount of water. MAR may be especially preferred for multi-year storage in regions such as the southwestern U.S. where reservoirs may lose up to two meters of depth

[123] Reese, R.S., 2014. Hydrogeologic framework and geologic structure of the Floridan Aquifer System and Intermediate Confining Unit in the Lake Okeechobee area, Florida. US Geological Survey Scientific Investigations Map 3288. http://pubs.usgs.gov/sim/3288/

per year from evaporation,[124] in regions where migratory species such as salmon are important, or where real estate costs are prohibitively high. However, surface storage may be more energy efficient.

MAR can in places serve as a risk management measure for times when USACE might need to release water from reservoirs that might be missed later if precipitation and surface water inflows prove to be less than anticipated. This complementary function was discussed briefly in the Drought Resilience section above, but has broader application. For example, Section 601 (Everglades restoration) of WRDA 2000 (Public Law 106-541)[31] contains a "Savings Clause" stating that "Until a new source of water supply of comparable quantity and quality as that available on the date of enactment of this Act is available to replace the water to be lost as a result of implementation of the Plan, the Secretary and the non-Federal sponsor shall not eliminate or transfer existing legal sources of water…". The inclusion of MAR in the CERP decreased downside risks of forecast and risk-informed operational decisions that existed, or were being proposed, at that time and needed to be considered during formulation of the plan.

Thus, while MAR is not appropriate for all projects—depending on engineering, physical, biological, economic, social, political and institutional conditions in the basin—where it does make sense as a component of storage, it may be viewed as a "least regrets" strategy that can enhance the amount of storage available in a region while providing additional benefits for people or ecosystems.[125]

6.2. Consistency of MAR with Other USACE Initiatives

If MAR is to play an important role in future USACE activities, it must not only be consistent with the current planning process, but also blend well with other initiatives that are being undertaken to potentially improve that process. Three quite different initiatives are discussed here, to illustrate how MAR can complement them. These are: the National Portfolio Assessment, forecast-informed reservoir operations, and techniques being applied for conflict resolution and stakeholder engagement in water resources planning.

National Portfolio Assessment

The National Portfolio Assessment effort began in the 2000s with the goal of reviewing how the Corps' portfolio of 356 reservoir projects could best continue to "support and enhance contemporary economic and ecosystem values, identify changes in operational policies requiring more in-depth studies, and support state and local planning efforts, such as state water plans".[126] It currently focuses on five topics, including a) reallocations of project storage to serve increasing water supply needs, b) water management data and trends, c) project changes to sustain and enhance environmental conditions for

[124] Hanson, R.L. 1991. Evapotranspiration and Droughts. In Paulson, R.W., Chase, E.B., Roberts, R.S., and Moody, D.W., Compilers, National Water Summary 1988-89–Hydrologic Events and Floods and Drought. U.S. Geological Survey Water-Supply Paper 2375:99-104. https://geochange.er.usgs.gov/sw/changes/natural/et/.
[125] Travers, C., Vogel. J., Raucher, R. and Jones, R. 2012. Groundwater Sustainability Under Climate Change: A Literature And Research Review. Prepared by Stratus Consulting Inc. for Water Research Foundation, Denver, CO.
[126] USACE Institute for Water Resources. 2016. Status and Challenges for USACE Reservoirs. A product of the National Portfolio Assessment for Water Supply Reallocations. Report 2016-RES-01. 232 pp. https://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/2016-RES-01.pdf

water quality and aquatic ecosystems, d) reservoir sedimentation, and e) uncertainty in future conditions.

Groundwater has been engaged with only peripherally in the assessment and its reports. MAR and conjunctive use of groundwater and surface water often come up as potential project elements in reallocation discussions, given their common use for municipal and industrial water supply. In fact, MAR has the potential to contribute to at least three of the five lines of effort in the Assessment. MAR can be part of a reallocation plan to store and release water at appropriate times for increasing water-supply needs. It can support management approaches that are more robust to unknown future conditions with respect to precipitation and temperature, land use, and population growth. And it can play a role in operational and structural changes to protect the environment and enhance ecosystem conditions.

With respect to the latter, MAR can also potentially contribute to the joint USACE-Nature Conservancy Sustainable Rivers Program (SRP), with which the National Portfolio Assessment has also engaged. The SRP aims to identify ways to operate Corps dams to "achieve more ecologically sustainable flows, while maintaining or enhancing project benefits".[127] Some of the SRP project sites are located in river basins discussed elsewhere in this report. However, SRP projects have also been carried out in the Green (KY), Bill Williams (AZ), Connecticut (CT, MA, NH, VT) and Roanoke (NC, VA) River basins and Big Cypress Bayou (TX, LA).

Forecast-Informed Reservoir Operations (FIRO) and Forecast-Based Operations (F-BO)

Each USACE reservoir has a water control plan, which provides instructions for operating the reservoir—for example, how and when water should be stored and released during different seasons or hydrologic conditions. However, demographic, land-use and climatic conditions, and the legal and policy framework, can change. Weather and climate forecasting also improve with time due to better data and advances in science. There are, therefore, procedures for updating water control manuals and plans.

In this context, Forecast-Informed Reservoir Operations, or FIRO, was developed as a Federal-State-Local government and university initiative. The goal of FIRO is to develop a "management strategy that uses data from watershed monitoring and modern weather and water forecasting to help water managers selectively retain or release water from reservoirs in a manner that reflects current and forecasted conditions".[128] Lake Mendocino, in the Russian River basin, northern California, was chosen as the location of a pilot study, which is examining the use of such data (in particular, on "atmospheric rivers"[129]) to inform water management decisions. Several USACE Districts and ERDC currently participate in this study. In January 2019, USACE's South Pacific Division approved a major deviation that allows for FIRO-developed tools and concepts to be tested at Lake Mendocino.[130] This would allow

[127] https://www.iwr.usace.army.mil/Missions/Environment/Sustainable-Rivers-Project/

[128] https://cw3e.ucsd.edu/firo/

[129] "A long, narrow, and transient corridor of strong horizontal water vapor transport..." See full definition at http://glossary.ametsoc.org/wiki/Atmospheric_river.

[130] https://www.spd.usace.army.mil/Media/News-Stories/Article/1747991/the-corps-approves-major-deviation-for-forecast-informed-reservoir-operations-e/

enough water to supply almost 100,000 people to be stored in the lake during the winter rainy season while ensuring appropriate flood risk management.

Such a water management strategy could be very helpful to downstream users, because in the lower basin Sonoma Water has been testing an ASR and groundwater banking system that would divert Russian River water through the utility's riverbank filtration/treatment system during the wet season (winter) and recover and convey it to depleted aquifers in neighboring groundwater basins for storage and use in the dry season (summer). Groundwater levels in Sonoma Valley have dropped as much as 30 feet in the past 15 years—in cases to below sea level—and salt water intrusion from San Pablo Bay has impacted water quality. FIRO could provide enough water at an appropriate time to replenish the aquifers to provide sustainable water supply while staving off this saline intrusion.[131]

The use of FIRO is also being investigated for the Prado Dam in the Santa Ana River Basin, discussed earlier in this report, to allow additional reservoir storage even during flood season if hydro-meteorological forecasts are favorable. Likewise the current Lake Okeechobee regulation schedule allows for "additional operational flexibility" to consider seasonal forecasting (e.g., El Niño-based);[132] this information could be used to help plan storage in the lake, aquifer and adjacent wetland attenuation feature.

At a broader scale, the California Dept. of Water Resources' multi-phase "System Reoperation Study" of its statewide water,[133] conducted in tandem with USACE's Central Valley Integrated Flood Management Study, California, Draft Watershed Plan,[134] recommended consideration of Forecast-Based Operations (F-BO; similar to FIRO) along with conjunctive use of groundwater and surface water (including direct recharge) in reoperation strategies. F-BO's flexible definition of use of the flood control pool is one method to provide extra water-supply storage in the system—at least for the short run. MAR also has the potential for multi-year storage.

Collaborative Planning, Multi-Hazard Tournaments and Public Participation

Reallocation studies and water control manual updates are activities that can lead to conflict among stakeholders—including those who benefitted from the original allocation, those who might benefit from the reallocation, and other interest groups. USACE's collaborative planning (or "Shared Vision Planning"; SVP) approach can be very helpful in such environments.[135] SVP can assist in the development and comparison of new water management solutions by integrating structured public

---

131 https://www.sonomawater.org/groundwater-banking

132 USACE. 2018. Memorandum for the Record (MFR): Lake Okeechobee Regulation Schedule Operational Flexibility Justification and National Environmental Policy Act Coverage Determination. Jacksonville District. https://usace.contentdm.oclc.org/digital/api/collection/p16021coll7/id/8424/download

133 https://water.ca.gov/Programs/All-Programs/System-Reoperation-Program

134 USACE. 2015. Central Valley Integrated Flood Management Study, California: Draft Watershed Plan. Prepared by US Army Corps of Engineers Sacramento District. http://www.spk.usace.army.mil/Portals/12/documents/civil_works/CVIFMS/CVIFMS_Draft_Watershed_Plan_Public_Release_DEC2015.pdf

135 https://www.iwr.usace.army.mil/Missions/Collaboration-and-Conflict-Resolution/Shared-Vision-Planning/

participation and collaborative computer modeling with USACE's traditional water resources planning methods. As such, SVP can be easily integrated into USACE's planning process as well.

An example of the use of SVP, termed Participatory Modeling in this case, was by the Palouse Basin Aquifer Committee (PBAC) to explore alternatives to provide a long-term, high-quality water supply for the region. The original Palouse Basin Participatory Model[136] "helped promote a shared vision of the problem and potential solutions through discussion and model development." In 2017, the PBAC produced a report "to evaluate previously studied water supply projects to determine the most promising supply projects for meeting existing and future supply needs in the Palouse groundwater basin." [137] The study compared four alternatives, the first of which was a modified version of the 1989 Reconnaissance Report, Palouse River Basin, Idaho and Washington, published by USACE.[138] All four are designed to operate conjunctively to prevent further drawdown of the aquifer using combinations of interbasin transfers, aquifer recharge and wastewater reuse.

A related tool USACE and others have begun to use is the Multi-Hazard Tournament (MHT). An MHT is an exercise that invites participants to collaborate in teams of 5-6 players, in friendly competition with other teams, to find the best ways to reduce the effects of drought, flooding, and/or water quality hazards in the basin. MHTs are useful for improving communication among stakeholders, creating new collaborations to address common problems, and identifying strengths, weaknesses, costs and trade-offs among various strategies for solving these problems.[139] MHTs have now been run in various basins where USACE has equities, including in both temperate (Iowa-Cedar River) and semi-arid (San Antonio River) regions.

MAR or conjunctive use of groundwater figured in both cases. Multiple "teams" in the 2016 Iowa-Cedar MHT recommended off-channel aquifer recharge using approaches such as infiltration banks, strategic creation of wetlands, dams or barrages, and deep well injection for drought management and/or adaptation to changing conditions.[140] Additional wells were also an "adaptation option" considered at the 2015 San Antonio River MHT for making local investment decisions.

A final example of the role of MAR in resolving conflict and achieving consensus-based solutions is provided not by USACE but by the Governor's Commission for a Sustainable South Florida. In a step towards creation of the CERP, the commission included ASR as one of 13 thematic concepts in their 1996 "Conceptual Plan for the Central and South Florida Project Restudy."[141] Subject to pilot testing,

---

[136] Allyson Beall, Fritz Fiedler, Jan Boll and Barbara Cosens.2011. Sustainable Water Resource Management and Participatory System Dynamics. Case Study: Developing the Palouse Basin Participatory Model. Sustainability 3:720-742; doi:10.3390/su3050720.

[137] Palouse Basin Aquifer Committee. 2017. Palouse Groundwater Basin Water Supply Alternatives Analysis Report. 166 p. http://palousebasin.org/wp-content/uploads/2018/07/PBAC_Water_Supply_Report-final.pdf

[138] USACE. 1989. Reconnaissance Report, Palouse River Basin, Idaho and Washington. Walla Walla District.

[139] National Drought Mitigation Center. 2016. DroughtScape. Fall 2016 edition, pp. 14-16. https://drought.unl.edu/archive/Documents/NDMC/DroughtScape/DS2016fall.pdf

[140] Unpublished summary of the Cedar Rapids and Surrounding Area Multi-Hazard Tournament, 1 Sep 2016. Available from the Institute for Water Resources, Alexandria, VA.

[141] https://evergladesrestoration.gov/content/documents/archives/Gov's_Commission_Conceptual_Plan_082896.pdf

ASR was cited as a potential "alternative water storage method" to fulfill as many restoration goals as possible without significantly compromising existing water uses. Inclusion of ASR was a key to the adoption of this plan by unanimous vote of the 47-member commission representing federal, tribal, state, regional and local governments, and business, agricultural, public and environmental interests.

At their core, SVP, MHTs and related approaches seek to contribute to water management solutions for a basin that are acceptable to a broad array of stakeholders. MAR can contribute to developing and implementing such solutions, by allowing for more flexible, multi-purpose reservoir management, by meeting needs of local and regional water management agencies, and by increasing USACE's ability to provide water for environmental purposes. The net effect would ideally serve to ameliorate conflict and increase mutual trust and communication among stakeholders in a watershed or basin.

6.3. Caveats and Challenges

MAR systems, like surface storage systems, may face technical challenges. These include clogging of wells, interactions with aquifer materials that release heavy metals or metalloids, aquifer inhomogeneity and anisotropy, and other uncertainties—leading to high maintenance and energy costs. These challenges are covered extensively in National Research Council reports[3, 9] and elsewhere. Feasibility considerations were broadly summarized by the California Dept. of Water Resources as:

• Hydrogeologic feasibility (e.g., a permeable aquifer or soils);
• Available groundwater storage capacity;
• An appropriate water source (e.g., imported water, local runoff, or treated wastewater);
• Costs to convey the water from its source to the recharge location, and from the discharge facility to the point of demand; and
• Availability of real estate for recharge, extraction and pre- and/or post-treatment facilities.[142]

The term "appropriate water source", in reality, obscures a host of water-quality challenges that are the subject of extensive research. These issues correlate to some extent with the source of the recharge water. Treated wastewater requires particular attention to pathogens, nutrients (particularly nitrogen species) and "emerging contaminants" (e.g., pharmaceuticals, endocrine-disrupting compounds and personal care products). Urban runoff, especially the initial pulse of runoff in heavy storms, may contain high levels of heavy metals (e.g., cadmium, chromium, lead, copper and zinc) from industry, vehicles and their emissions, hydrocarbons including known carcinogens (e.g., benzene) derived from fuels, and chlorinated solvents widely used in industry and elsewhere for degreasing. Agricultural runoff may contain high concentrations of pesticides and fertilizers. Required treatment of source-water contaminants can add greatly to the cost of MAR.

---

[142] Conjunctive Management and Groundwater Storage: A Resource Management Strategy of the California Water Plan. 2016. California Department of Water Resources. https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/California-Water-Plan/Docs/RMS/2016/08_ConjMgt_GW_Storage_July2016.pdf

Due in large part to the broad range of considerations listed above, the economics of MAR compared to those of above-ground storage are complex and beyond the scope of this paper. Myriad factors, such as land acquisition costs, distance from end use, water treatment costs (prior to injection and subsequent to withdrawal), and recovery efficiency are involved. Systems analysis and optimization modeling clearly have roles to play,[143] and state-level suitability indices have been performed, for example, for the state of Washington.[144]

Using highly simplified assumptions, MAR has in places been shown to compare quite favorably. For example, surface and groundwater storage have been compared quantitatively in California in the context of the Water Quality, Supply, and Infrastructure Improvement Act of 2014 (Proposition 1). The act earmarked $2.7 billion for water storage projects to improve the state water system and provide public benefits cost-effectively. It has been estimated that while $2.7 billion spent on surface water storage would fund about 1.4 million acre-feet of new capacity, the same amount spent on groundwater storage would yield about 8.4 million acre-feet of new capacity—about six times as much.[145] More extensive discussions on the comparative economics of MAR may be found in other sources.[146]

As with water resources planning and management in general, many of the challenges to implementing a MAR project are not technical or scientific, but rather, legal, regulatory and institutional. These include:[3, 147, 148]

- Overall regulatory complexity, with a multiplicity of state laws and regulations governing groundwater recharge, storage and discharge;
- The inclusion of aquifer storage and recovery wells within the same EPA Underground Injection Control classification (V) as lightly treated waste injection wells;
- Questions of ownership of the recharged water, especially if it migrates off of the utility's property and/or is connected to streams, lakes or wetlands;
- Water rights, transfer and banking laws for groundwater, which vary widely. Most critically, is MAR defined explicitly or by implication as a "beneficial use" in "prior appropriation" states, and can that water be banked, traded and sold?
- Public resistance to consumption of even highly treated wastewater (i.e., "toilet to tap"). This resistance is mitigated with increasing time and distance between recharge and recovery of the

---

143 Zhang, X. 2015. Conjunctive surface water and groundwater management under climate change. Front. Environ. Sci. 3:59. doi: 10.3389/fenvs.2015.00059
144 Gibson, M.T., M.E. Campana, and D. Nazy. 2018. Estimating Aquifer Storage and Recovery (ASR) Regional and Local Suitability: A Case Study in Washington State, USA. Hydrology 5:7.
145 Perrone, D. and Rohde, M. 2014. Storing Water in California: What Can $2.7 Billion Buy Us? Research Brief, Water in the West. http://waterinthewest.stanford.edu/sites/default/files/Storing_Water_in_CA_0.pdf.
146 Megdal, S., and Dillon, P. 2014. Policy and Economics of Managed Aquifer Recharge and Water Banking. Special issue of MDPI open access journal "Water". http://www.mdpi.com/journal/water/special_issues/MAR.
147 Mortimer, E. and D. Tuthill. 2014. Managed Aquifer Recharge: Legal Issues in the Western United States. The Water Report, 129:13-22.
148 National Ground Water Association. 2014. Managed Aquifer Recharge: A Water Supply Management Tool. Information Brief. https://www.ngwa.org/docs/default-source/default-document-library/publications/information-briefs/managed-aquifer-recharge.pdf?sfvrsn=255f4c65_2

water, regardless of its flow path. WateReuse Foundation has an extensive discussion of "best practices" for developing indirect potable reuse projects.[149]

Finally, in a combination of scientific and regulatory considerations, the creation of recharge structures can result in environmental impacts—both by eliminating habitat through construction or permanent inundation as well as by altering the downstream hydrograph. This may be mitigated in other instances by the creation of wetland habitat, as described in several previous sections. Experimental decision-support systems have been created to help with ASR feasibility analysis, planning and assessment, and engineering design and evaluation.[150]

7. Conclusions and Recommendations

The discussion thus far leads to four broad conclusions.

- First, USACE and its partners are already engaged in MAR across a broad landscape—both geographically and thematically.
- Second, the Nation's current needs and USACE's strategic documents both point toward an important future role for MAR in USACE projects.
- Third, USACE is fortunate in that an increased use of MAR would require little or no change in its formal planning process, and generally would integrate well with new initiatives.
- Finally, USACE has much to learn from other agencies, and the private sector, about MAR.

These four themes will be further expanded upon below, and lead to five actionable recommendations.

7.1. USACE and its Partners are Already Involved in MAR, Across a Broad Geographic and Thematic Landscape, but in an Ad Hoc Manner

In addition to arid-to-temperate California and humid subtropical to tropical Florida, where USACE is most visibly engaged in MAR, USACE Districts or their partners are considering, evaluating, testing or operating MAR or conjunctive use projects in Arizona, Arkansas, Colorado, Georgia, Idaho, Illinois, Iowa, Mississippi, Missouri, North Carolina, Oregon, South Dakota, Tennessee, Texas and Washington—17 states in all. These 31 projects are located in Northwestern, South Pacific, Southwestern, Mississippi Valley, South Atlantic and Great Lakes & Ohio River Divisions—six of the seven USACE divisions in the continental United States (Figure 3). The Regional Center of Expertise for Groundwater Modeling of the seventh—the North Atlantic Division—has conducted much of the Everglades ASR modeling, so all have engaged in MAR at some level. Their purposes include drought planning and management, flood risk

[149] WateReuse Foundation. 2004. Best Practices for Developing Indirect Potable Reuse Projects: Phase 1 Report. Report of Project WRF-01-004. Alexandria, VA: WateReuse Foundation.
[150] Yang, J., C. Neil, J. Neal, J. Goodrich, M. Simon, D. Burnell, R. Cohen, D. Schupp, R. Krishnan, and Y. Jun. 2017. Decision Support System for Aquifer Recharge (AR) and Aquifer Storage and Recovery (ASR) Planning, Design, and Evaluation - Principles and Technical Basis. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/222.

management, reallocation studies and water supply planning, reservoir management, and ecosystem restoration.

At the USACE district level, MAR's visibility varies considerably. In the South Pacific Division's Los Angeles District, MAR has a fairly high profile due to its prevalence in semi-arid southern California and Arizona. But this is not common. For example, while six of the case studies in this report are in the Northwestern Division, they are in four districts covering six states stretching from Washington to Missouri. Fewer than 10 of the 45 USACE districts have more than one current project involving MAR; about two-thirds have none.

This suggests a need for an organized mechanism for USACE-wide communication of successes and failures; questions, answers and surprises; and conclusions and recommendations with respect to MAR projects. There are loci of MAR and conjunctive management expertise in the district level in states such as California and Florida, in groundwater modeling groups in the Philadelphia and Jacksonville districts, and at ERDC and HEC. However, there is no USACE-wide groundwater community of practice, working group, or national center of expertise.

Recommendation: USACE should enhance its internal communications relative to MAR and conjunctive use. The creation of a community of practice, working group, and/or center of expertise may help to build such a community.

Although most MAR projects may be led by state and local partners, USACE will need to have the capacity for independent analysis of these projects at the district level to make sure federally stored water is well managed and federal funds are being spent wisely. Is there sufficient in-house expertise in groundwater hydrology, law and policy, modeling and broader systems analysis, and related areas such as urban and environmental water supply, or are there areas where USACE may need to "build its bench"?

Recommendation: USACE should upgrade its internal capacity in MAR. It should consider developing one or more training courses on MAR and related topical areas for its planners, managers, economists and engineers. It should also encourage more informal on-the-job training and mentoring as appropriate, as well as participation in MAR focused conferences and workshops.

7.2. The Nation's Needs and USACE's Strategic Directions Suggest an Important Future Role for MAR in USACE Projects

In the US and elsewhere, populations are growing and civil society is increasingly aware of local and regional water issues. Demands on USACE-stored water are increasing in their complexity with respect to quantity, quality, timing and distribution. Complex and increasing demands for multiple uses of water require advances in the science and applications of sustainable, resilient water management. MAR has evolved from an experimental technology several decades ago to one that has been applied in 1,200 case studies around the world. In tandem with MAR's increasing prevalence, new authorities such as Sections 1116 and 1118 of WRDA 2016 allow and seemingly encourage USACE and its partners to consider MAR both as a "conservation measure" for droughts and to "increase the quantity of available supplies of water".

Internally, MAR is also consistent with the strategic direction of USACE. Currently, the most important strategic change document for USACE is its "FY18-22 USACE Campaign Plan". It is designed to provide a common vision, purpose, and direction for USACE with four goals: "Support National Security", "Deliver Integrated Water Resource Solutions", "Reduce Disaster Risks", and "Prepare for Tomorrow". [151]

Wise use of MAR opportunities potentially contributes to all four of these goals. By buttressing the Nation's water, energy and environmental security, USACE can support our national security. By adding groundwater storage to its water management tools, it can deliver more integrated and balanced water resource solutions. By providing additional options for dampening flood peaks, it can reduce disaster risks and thereby save lives and reduce property damage. And by providing additional training and collaboration opportunities for its engineers, managers and planners, USACE is preparing its people for tomorrow's challenges.

Recommendation: USACE leadership, from Headquarters to District offices, should encourage further evaluation of how MAR may help USACE to deliver sustainable and resilient water management solutions.

7.3. MAR Combines Well with USACE's Formal Planning Process and with New Initiatives

The many proposed or planned MAR activities discussed in this report are considered in standard USACE technical and planning documents. These include Technical Data Reports, Environmental Assessments and Impact Statements, Project Implementation Reports, Integrated Feasibility Reports, and partnership agreements. The consideration or use of MAR seems not to require new kinds of technical reports or formal planning documents.

Underpinning these formal documents, USACE is increasingly engaged with multiple state and local government sponsors, and a complex community including interest groups and civil society. MAR can help USACE planners to consider a systems approach, public involvement, collaboration and coordination, and leveraging of resources as part of integrated water resources management. Collaborative planning techniques, including multi-hazard tournaments, can identify settings in which MAR can be combined with ecosystem restoration and improved flood-risk management. Forecast-informed reservoir operations can help optimize releases such that MAR is carried out when conditions allow, while not compromising the safety of those downstream. And new climate preparedness and decision-analysis tools can help USACE to visualize the long-term sustainability of a water management plan incorporating MAR, and evaluate whether it is likely to be economically justified.

Outside of USACE, a host of other techniques and approaches for water management are being developed as well. These include water reuse and desalination to increase supply, high-tech sensors in

[151] https://www.usace.army.mil/About/Campaign-Plan/.

municipal and agricultural settings to decrease demand, and water banking and water markets to improve market efficiency. Most of these are in the domain of the non-Federal interests. Yet USACE will be encouraged to engage with these technologies in an IWRM framework—regardless of whether it is directly involved in their construction or implementation.

Recommendation: USACE should consider MAR in conjunction with, not in lieu of, ongoing water resource management initiatives. In doing so, the additional storage created in the service of multiple stakeholders will not be at the expense of lives and property.

7.4. USACE has much to Learn from other Agencies, and the Private Sector, about MAR

Despite the additional authorities provided by WRDA 2016, USACE's authorities related to MAR are relatively modest. In contrast, the U.S. Bureau of Reclamation's broader authorities allow for delivering project or excess water for groundwater recharge, and participating in water banks and non-Federal groundwater storage projects. This has allowed Reclamation to show considerable leadership on Federal engagement in MAR. It has designed, constructed and operated groundwater recharge systems in a variety of geologic and hydrologic environments, developing knowledge on the costs and benefits of MAR along the way. Its WaterSMART program is currently funding groundwater recharge projects. Other agencies have experience as well. The U.S. Geological Survey has been studying artificial recharge on Long Island (NY) since the 1960s. The U.S. Environmental Protection Agency has had regulatory authority over injection wells since the early 1970s, and has a well-developed ASR regulatory program. Even the USDA's Agricultural Research Service is developing some experience in MAR.

Recommendation: USACE should use current interagency agreements, subcommittees and other mechanisms to conduct seminars, webinars, meetings and, potentially, cooperative research with other entities to exchange knowledge, experience and lessons-learned in MAR.

There have been considerable advances in hydrology and the related sciences in recent decades. Nonetheless, great uncertainties surround the projections of future hydro-climate conditions surrounding any given USACE project. Stressors of uncertain impact may include population growth, changing land use, increasing temperatures or climate variability, and changes in timing, phase (rain vs. snow), and quantity of precipitation. By improving the resilience of water resources systems and, in cases, extending the functional utility and life of existing infrastructure, MAR has the potential to help USACE and its partners to prepare for, absorb, recover from, and adapt to, many kinds of future adverse events or conditions. With the caveat that rates of groundwater recharge, use and discharge may also be impacted by these same unknowns, MAR may also be considered a "least regrets" strategy for adaptation to changing conditions to help ensure the Nation's water security for years to come.

US Army Corps of Engineers®

IWR

www.iwr.usace.army.mil

2020-WP-01