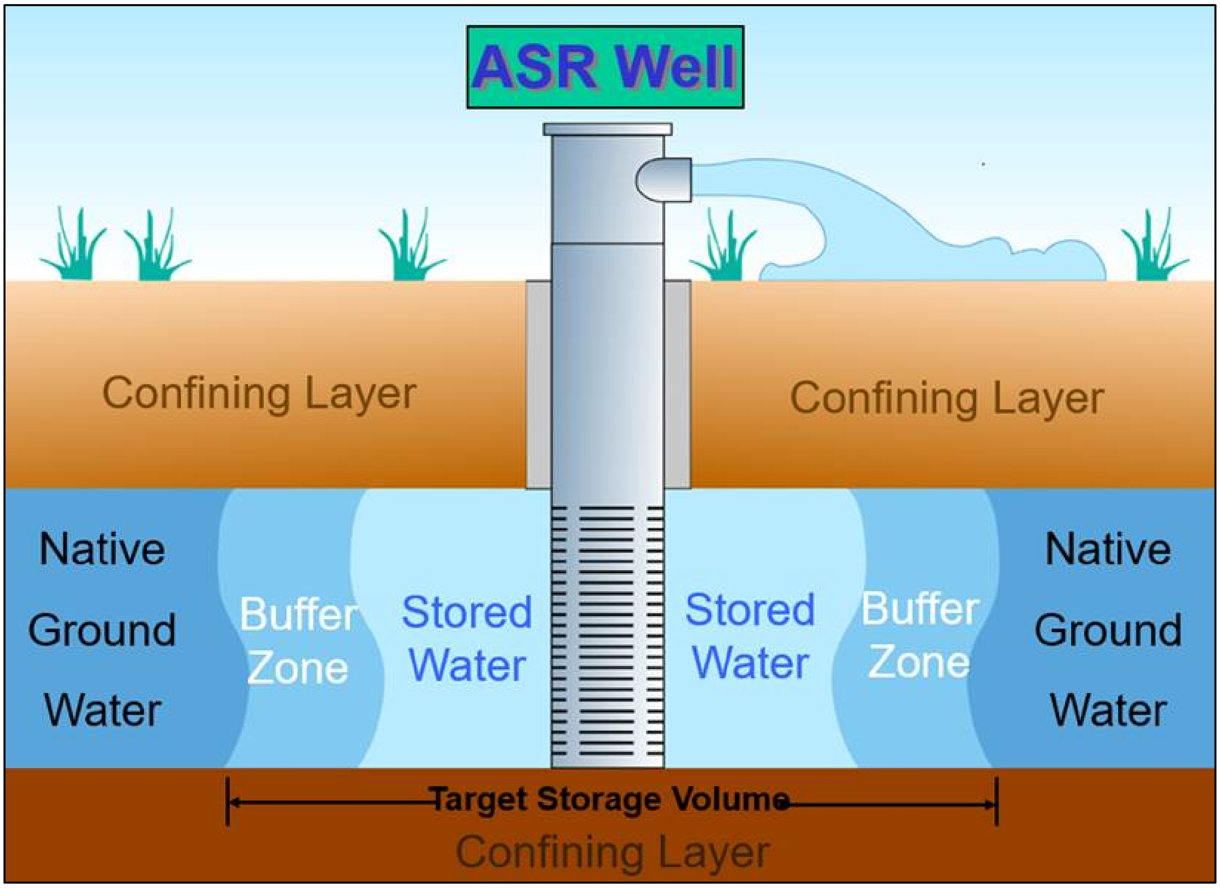
2021 Aquifer Storage and Recovery Science Plan



Final

June 2021

US Army Corps of Engineers®

PREFACE

The South Florida Water Management District (SFWMD) and United States Army Corps of Engineers (USACE) prepared this 2021 Aquifer Storage and Recovery (ASR) Science Plan to address uncertainties identified in the National Research Council's (NRC's) review of the ASR Regional Study Final Technical Data Report. Studies discussed herein will be conducted as ASR wells are constructed in a phased manner. A brief history of the Comprehensive Everglades Restoration Plan (CERP) ASR program is provided here for context.

The 1999 Central and Southern Florida Project Comprehensive Review Study (Restudy) identified the potential use of ASR technology as a means of storing water in aquifers for later use. The Restudy proposed construction of up to 333 ASR wells to recharge, store, and recover water underground to provide water for the Everglades, improve water levels in Lake Okeechobee, prevent damaging releases to the coastal estuaries, and ensure water supply for agricultural and urban development in South Florida. Acknowledging this unprecedented use of ASR technology, the Restudy recommended construction of pilot projects and development of a regional evaluation of the effects of large-scale use of ASR in South Florida. The plans for these projects were developed and reviewed by the NRC during 2001 and 2002.

The results of the construction and testing of the ASR pilot projects along the Hillsboro Canal and C-38 Canal (Kissimmee River) were published in 2013 (CERP ASR Pilot Project Technical Data Report) and 2015 (CERP ASR Regional Study Final Report). Those investigations indicated a reduced number of ASR wells (not 333 as originally proposed) was technically viable without detrimental effects to the aquifer, the environment, and nearby water users. Specifically, the investigations determined that 80 ASR wells could be constructed in the vicinity of Lake Okeechobee. The CERP ASR Regional Study Final Technical Data Report was reviewed by the NRC in 2015. The NRC concurred with the report findings but identified some uncertainties and topics that warranted continued investigation.

In 2020, the SFWMD and USACE released the Final Integrated Project Implementation Report and Environmental Impact Statement (PIR/EIS) for the Lake Okeechobee Watershed Restoration Project (LOWRP). The Recommended Plan identified in the LOWRP PIR/EIS included 80 ASR wells, a wetland attenuation feature (shallow impoundment), and two areas of wetland restoration. During public review of the PIR/EIS, stakeholder concerns were raised about the remaining ASR uncertainties highlighted by the NRC review. During the July 2019 Governing Board meeting, the SFWMD committed to developing a plan for scientific research, investigating the uncertainties as ASR wells are constructed in a phased manner. This inaugural ASR Science Plan is the result of that commitment. The ASR Science Plan is intended to be updated annually or as needed as the ASR program is implemented and as data, research, and science become available.

The ASR Science Plan was developed with guidance from an independent ASR peer-review panel of eminent Florida scholars and scientists. The document provides the initial plan of studies and investigations that will take place as the ASR program moves forward. The ASR Science Plan will be reviewed annually by the peer-review panel, to be kept apprised of the investigations' findings and to assist in developing future studies that ensure ASR technology is implemented in a science-led, phased approach. This publication continues the SFWMD and USACE's commitment to communicate with the public as work progresses toward restoration of the South Florida ecosystem.

CONTRIBUTORS

The South Florida Water Management District gratefully acknowledges the many professionals who have contributed to the development of this ASR Science Plan. This document was developed collaboratively by a team of scientists, planners, and engineers with participation and valuable input from the South Florida Water Management District, United States Army Corps of Engineers, United States Geological Survey, and their technical consultants. The professionalism and dedication of the high-caliber experts who prepared this complex and important document are sincerely recognized and appreciated.

For information regarding this document, please contact:

Robert T. Verrastro, P.G.

South Florida Water Management District
3301 Gun Club Road
West Palm Beach, FL 33406
(561) 682-6136
bverras@sfwmd.gov

June Mirecki, Ph.D., P.G.

United States Army Corps of Engineers
701 San Marco Boulevard
Jacksonville, FL 32207
(904) 232-1236
June.E.Mirecki@usace.army.mil

South Florida Water Management District

Matthew Alexander
Elizabeth Caneja
Michelle Ferree
Elizabeth Geddes
Jennifer Gent
Ben Gu
Tom James
Natalie Kraft
Julianne LaRock
Jennifer Leeds
Armando Ramirez
Jennifer Reynolds
Jonathan Shaw
Robert Taylor
Robert Verrastro
Anna Wachnicka
Zach Welch

United States Army Corps of Engineers

Joel Galliard
Timothy Gysan
Jonathan Jenkins
June Mirecki
Gina Ralph

Private Corporations/Consultants

Collier Consulting
Stantec Consulting Services Inc.

United States Geological Survey

John Lisle

Peer-Review Panel

Jonathan Arthur – Florida Geological Survey
Reid Hyle – Florida Fish and Wildlife Conservation Commission
Thomas Missimer – Florida Gulf Coast University
Rene Price – Florida International University
Sam Upchurch – University of South Florida, retired

EXECUTIVE SUMMARY

Aquifer storage and recovery (ASR) is the storage of water in an aquifer by means of a dual-purpose well that is used for both recharge and recovery. ASR technology offers the potential to store and supply vast quantities of water without the need for large tracts of land. As such, it is a vital component of the Comprehensive Everglades Restoration Plan (CERP) implemented by the South Florida Water Management District (SFWMD) and United States Army Corps of Engineers (USACE). CERP is intended to capture, store, and redistribute fresh water and improve the quantity, quality, timing, and distribution of water for the natural system while providing for other water-related needs of the region, including water supply and flood protection. In order to achieve the intent of CERP, there is a critical need for new water storage due to extensive losses of natural storage in the system.

Despite the potential benefits of ASR, there are some technical uncertainties regarding regional effects of large-scale ASR implementation. The technical uncertainties were identified in the National Research Council's (NRC's) 2015 review of the ASR Regional Study Final Technical Data Report. To reduce critical scientific uncertainties, the SFWMD and USACE developed this 2021 ASR Science Plan, describing potential studies to be conducted as ASR wells are implemented in a phased manner. The 2021 ASR Science Plan was developed with review and input from an independent peer-review panel (PRP) of scientists. The panel will meet annually to review the investigations' findings and provide guidance on additional studies. The ASR Science Plan is intended to be a living document, updated annually or as needed based on the best information available at the time of update. The proposed scope, schedule, and budget for ASR Science Plan studies are subject to change as the ASR program progresses and additional information becomes available.

The 2021 ASR Science Plan presents the first version of an overarching program of scientific studies that will support a phased ASR implementation schedule for the Lake Okeechobee Watershed Restoration Project (LOWRP). Although the studies proposed in this 2021 ASR Science Plan are intended to be conducted at ASR locations identified in the LOWRP Integrated Project Implementation Report and Environmental Impact Statement, they have broad application beyond LOWRP's scope. These studies have value anywhere ASR wells are proposed within South Florida and can be used to address ASR uncertainties associated with other CERP and non-CERP projects.

The LOWRP Recommended Plan includes 80 ASR wells, a 46,000-acre-foot wetland attenuation feature (shallow impoundment), and restoration of two wetland areas adjoining the lower reach of the Kissimmee River (C-38 Canal). The implementation schedule for the ASR component of LOWRP is the result of two state legislative appropriations totaling $100 million for the design, engineering, and construction of ASR well clusters.

During development of the ASR Science Plan, the PRP provided guidance and suggestions on how to 1) evaluate stakeholder concerns about ASR implementation at the scale envisioned by LOWRP, and 2) address uncertainties regarding ASR technology as highlighted by the NRC in 2015. In October 2020, the PRP provided a draft report of suggestions to integrate into the initial version of the ASR Science Plan. The studies included in the 2021 ASR Science Plan are organized according to the main topics of the 2015 NRC report.

Project Sequencing, Schedule, Reporting, and Data Management (Chapter 2). The PRP suggested a robust program of scientific data collection, management, and dissemination as the ASR program moves forward.

An annual schedule of formal project reporting and review is included herein, along with a "report card" process of evaluating the progress of the ASR Science Plan towards addressing the NRC uncertainties. A combination of data management tools—primarily Data Access Storage and Retrieval (DASR), Morpho, and Metacat—will preserve all information generated by the ASR program. ASR data will be available to the public within an internet-accessible environment.

Future Construction and Testing (Chapter 3). The NRC recommended that additional local-scale information was needed on the Avon Park permeable zone (APPZ), which is one of LOWRP's target horizons for subsurface water storage. Recommendations included additional study of aquifer heterogeneity, anisotropy, and fracture potential to help determine orientation of ASR and monitoring wells and maximize recovery efficiency. Use of groundwater modeling, geophysical surveys, tracer studies, and injection tests were suggested to augment data from wells.

The initial phase ASR Science Plan includes accumulating data from continuous cores, construction of exploratory well clusters, reactivation and testing of existing ASR systems along the C-38 and L-63N canals, and development of a geophysical program to address these items. Information from the exploratory well clusters will be used to identify the ASR Science Plan needs for subsequent well clusters.

Understanding Phosphorus Reduction Potential (Chapter 4). The NRC and PRP agreed that more research into the potential for ancillary benefits of nutrient reduction via ASR should be pursued.

The SFWMD contracted with the United States Geological Survey (USGS) to perform column studies and flow-through experiments to document the effects of microbiota within the aquifer and their impact on nutrients during storage when placed within deep, anoxic aquifer conditions.

Operations to Maximize Recovery (Chapter 5). There were several recommendations regarding the assessment of methods to increase the quantity and quality of water that is ultimately recovered from ASR systems. Establishment and maintenance of a buffer zone, operational sequencing of multi-well clusters, and location of well systems near surface water bodies were recommended.

The ASR Science Plan includes preparation of well-siting evaluations, design studies, and constructability analyses to locate well clusters near surface water bodies and to optimize recovery efficiency. A cycle testing program is proposed to develop a buffer zone where recovery efficiency is anticipated to be low.

Disinfection/Treatment Technology (Chapter 6). The NRC recommended that design evaluations be conducted to ensure recharge and recovery treatment technologies will be implemented to achieve regulatory compliance and minimize the potential for mobilization of undesirable constituents. Additionally, continuation of subsurface pathogen inactivation studies was recommended.

The ASR Science Plan contains an in-depth evaluation of available technologies for achieving regulatory compliance while minimizing operations and maintenance costs. USGS research on subsurface pathogen inactivation is ongoing and will be coupled with future groundwater and wellfield design modeling.

Ecotoxicology and Ecological Risk Assessment (Chapter 7). There were multiple recommendations for extended duration, larger-volume evaluations of chronic toxicity and bioconcentration on selected species from recovered water. Design studies will be undertaken to minimize effects to fish spawning, entrainment, and thermal effects of recovered water on species of concern. Evaluation of community-level effects was advised, coupled with construction of a more refined, probabilistic, quantitative ecological risk assessment model.

The ASR Science Plan includes proposed ecological studies that will occur during future cycle testing of new multi-well clusters of wells along the C-38 Canal. The plan for an updated ecological risk assessment is included.

Water Quality (Chapter 8). Numerous recommendations were made regarding studies to understand reactions that occur within the storage zones of ASR wells, in terms of mobilization of metals and presence of undesirable constituents in recovered water. The use of the buffer zone concept to prevent degradation of water quality within the aquifer and in recovered water was suggested.

The use of monitoring plans, development of a buffer zone, and geochemical modeling and analysis during well construction and future cycle testing are described in the ASR Science Plan.

Planning-Level Cost Estimate and ASR Well Cost-Benefit Analysis (Chapter 9). Cost estimates were prepared for the research activities described within the ASR Science Plan. The estimates were prepared for planning purposes and are subject to change as the ASR program progresses. The ASR program costs are under development; as the program progresses and treatment technologies are determined, a cost-benefit analysis will be included in future updates to the ASR Science Plan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

ACRONYMS, ABBREVIATIONS, AND UNITS OF MEASURE

2D	two-dimensional
3D	three-dimensional
APPZ	Avon Park permeable zone
ASR	aquifer storage and recovery
CERP	Comprehensive Everglades Restoration Plan
DASR	Data Access Storage and Retrieval
EM	electromagnetic induction
ERT	electrical resistivity tomography
FAS	Floridan aquifer system
FDEP	Florida Department of Environmental Protection
KRASR	Kissimmee River aquifer storage and recovery (site)
LOWRP	Lake Okeechobee Watershed Restoration Project
mg/L	milligrams per liter
NRC	National Research Council
PRP	peer-review panel
QA	quality assurance
QC	quality control
Restudy	Central and Southern Florida Project Comprehensive Review Study
SFWMD	South Florida Water Management District
TDS	total dissolved solids
UFA	Upper Floridan aquifer
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
VSP	vertical seismic profile

1 INTRODUCTION

1.1 ASR REGIONAL STUDY BACKGROUND

Aquifer storage and recovery (ASR) is the storage of water in an aquifer by means of a dual-purpose well that is used for both recharge and recovery. ASR technology has been employed successfully in Florida since 1983 (Pyne 2005). This technology offers the potential to store and supply vast quantities of water without the need for large tracts of land. As such, ASR is a vital component of the Comprehensive Everglades Restoration Plan (CERP), implemented by the South Florida Water Management District (SFWMD) and United States Army Corps of Engineers (USACE). CERP is intended to capture, store, and redistribute fresh water and improve the quantity, quality, timing, and distribution of water for the natural system while providing for other water-related needs of the region, including water supply and flood protection. In order to achieve the intent of CERP, there is a critical need for new water storage due to extensive losses of natural storage in the system. Of the many project components in CERP, seven include ASR wells. These components include as many as 333 ASR wells, with a total pumping capacity of 1.7 billion gallons of water per day. Of the original 333 ASR wells, as many as 200 wells were conceptualized to be integrated with Lake Okeechobee.

ASR wells should not be confused with deep injection wells, which are commonly used for disposal of wastewater into deep portions of the Floridan aquifer system (FAS). Deep injection wells have been used successfully for many decades; however, they do not provide the water supply benefits of eventual water recovery like ASR wells. Additionally, because ASR wells typically are completed within potential drinking water aquifers, the water recharged into ASR wells is treated to meet federal drinking water compliance standards.

Despite the potential benefits of ASR, there are some technical uncertainties regarding regional effects of large-scale ASR implementation as envisioned in CERP. To address these uncertainties, the SFWMD and USACE conducted the 11-year ASR Regional Study, focusing on the hydrogeology of the FAS, possible ecological risks posed by recovered water, and the regional capacity for ASR implementation. In 2015, the SFWMD and USACE published the ASR Regional Study Final Technical Data Report (SFWMD and USACE 2015). The report included findings from numerous scientific investigations and pilot projects that were constructed to address ASR uncertainties. The ASR Regional Study was the result of a multi-agency project delivery team composed of planners, engineers, and scientists who formulated a series of evaluations to determine if up to 333 ASR wells could be constructed and operated as envisioned in CERP. The evaluations were developed to address questions originally posed by the 1999 ASR Issue Team formed by the South Florida Ecosystem Restoration Working Group. The project delivery team formulated plans to construct ASR pilot projects, then expanded the analyses to a more regional scope to address critical reviews of the project plans by the National Research Council (NRC) in 2001 and 2002. A full list of the scientific milestones, reports, and technical publications generated from SFWMD and USACE ASR projects is included in **Appendix A**.

Key findings from the 2015 ASR Regional Study Final Technical Data Report (SFWMD and USACE 2015) included the following:

- Large-capacity ASR systems can be built and operated in South Florida. To date, no “fatal flaws” have been uncovered that might hinder the implementation of CERP ASR.
- Variability in aquifer characteristics will result in varying well performances, making it prudent to conduct an exploratory program before constructing surface facilities.
- Groundwater modeling indicated the overall number of wells should be reduced from 333 wells. The model indicated approximately 130 wells in the upper and middle portions of the FAS would meet the performance criteria. Of those, 80 ASR could be constructed around Lake Okeechobee.
- Water recovered from the ASR pilot projects did not have any persistent acute or chronic toxicologic effects on test species. However, there were a few instances where reproduction was inhibited, warranting further investigation.
- Arsenic mobilization occurred during early cycle testing but attenuated over time as the storage zone was conditioned.
- Reduction in phosphorus concentrations was observed during ASR storage. This process was postulated to result from microbial uptake, adsorption, dilution, or mineral precipitation.
- Further implementation of CERP ASR should proceed as a phased approach, including expansion and continued construction and testing of pilot facilities.

1.2 SUMMARY CONCLUSIONS OF THE 2015 NRC REVIEW

Upon completion of the ASR Regional Study Final Technical Data Report (SFWMD and USACE 2015), the USACE requested the NRC’s Water Science and Technology Board convene a committee of experts to review the report and assess progress regarding uncertainties related to full-scale CERP ASR implementation. The NRC provided a critical review of the methodology, findings, and report conclusions (NRC 2015). The NRC agreed with the essential finding that no “fatal flaws” associated with ASR had been discovered but some remaining uncertainties warranted additional study. Highest-priority recommendations to address uncertainties included the following:

- Develop operations to maximize recovery and reduce water quality impacts
- Conduct longer ecotoxicological studies and develop a quantitative ecological risk assessment
- Understand the mechanisms of phosphorus reduction
- Evaluate treatment technologies for optimal water quality during recharge, storage, and recovery
- Compare ASR costs and benefits with other water storage alternatives

The report concluded that phased implementation of ASR construction and testing would provide opportunities to address remaining uncertainties while also providing some early restoration benefits. The intent of the ASR Science Plan is to identify potential plans of study to address the remaining uncertainties from the NRC (2015) review as ASR wells are constructed in a phased approach.

1.3 LAKE OKEECHOBEE WATERSHED RESTORATION PROJECT

As part of CERP, the USACE and SFWMD initiated the Lake Okeechobee Watershed Restoration Project (LOWRP) planning effort in July 2016. LOWRP is intended to address water resource issues identified in the 1999 Central and Southern Florida Project Comprehensive Review Study (Restudy; USACE and SFWMD 1999) for the northern portion of the Lake Okeechobee watershed, Lake Okeechobee, and the Caloosahatchee and St. Lucie estuaries (northern estuaries). The project area covers a portion of the Lake Okeechobee watershed and includes four major drainage basins: Fisheating Creek, Indian Prairie, Taylor Creek/Nubbin Slough, and portions of the Lower Kissimmee (S-65D and S-65E), totaling approximately 920,000 acres. The LOWRP objectives are to 1) improve the quantity, timing, and distribution of flows into Lake Okeechobee; 2) improve the timing and volume of freshwater flows from Lake Okeechobee to the northern estuaries; 3) increase the spatial extent and functionality of aquatic and wildlife habitat within Lake Okeechobee and the surrounding watershed; and 4) increase availability of water supply to existing legal water users of Lake Okeechobee.

The LOWRP planning effort evaluated combinations of aboveground water storage features, ASR wells, and wetland restoration sites to meet project objectives. The LOWRP Recommended Plan (Alternative 1BWR) includes a 46,000-acre-foot wetland attenuation feature, 80 ASR wells, and approximately 4,800 acres of wetland restoration in the Paradise Run and Kissimmee River Center areas (**Figure 1-1**). By increasing water storage capacity within the watershed, the LOWRP Recommended Plan will improve the amount of time Lake Okeechobee is within the ecologically preferred stage envelope, benefitting native vegetation and wildlife. The LOWRP Recommended Plan will reduce the return frequency, volume, and duration of freshwater flows from Lake Okeechobee to the northern estuaries, thus reducing turbidity, sedimentation, and unnatural changes in salinity that are detrimental to estuarine communities. The wetland restoration components of the LOWRP Recommended Plan will increase the spatial extent and functionality of aquatic and wildlife habitat within the Lake Okeechobee watershed. Additionally, the LOWRP Recommended Plan will reduce water supply cutback volumes and frequencies to existing legal water users of Lake Okeechobee by keeping the lake within the ecologically preferred stage envelope, which is above water supply cutback trigger levels.

1.4 SPECIFIC APPROPRIATION 1642A

In Fiscal Year 2019-2020, the Florida State Legislature appropriated \$50 million to the SFWMD for LOWRP. An additional \$50 million was appropriated in Fiscal Year 2020-2021. Upon consideration, the SFWMD and USACE determined that the ASR component of LOWRP was most feasible for early implementation because systems could be constructed within existing SFWMD- and USACE-owned lands and canal rights-of-way, without the need for lengthy real estate acquisition. The current ASR program areas of focus are potential well cluster locations along the northern perimeter of Lake Okeechobee (**Figure 1-2**).

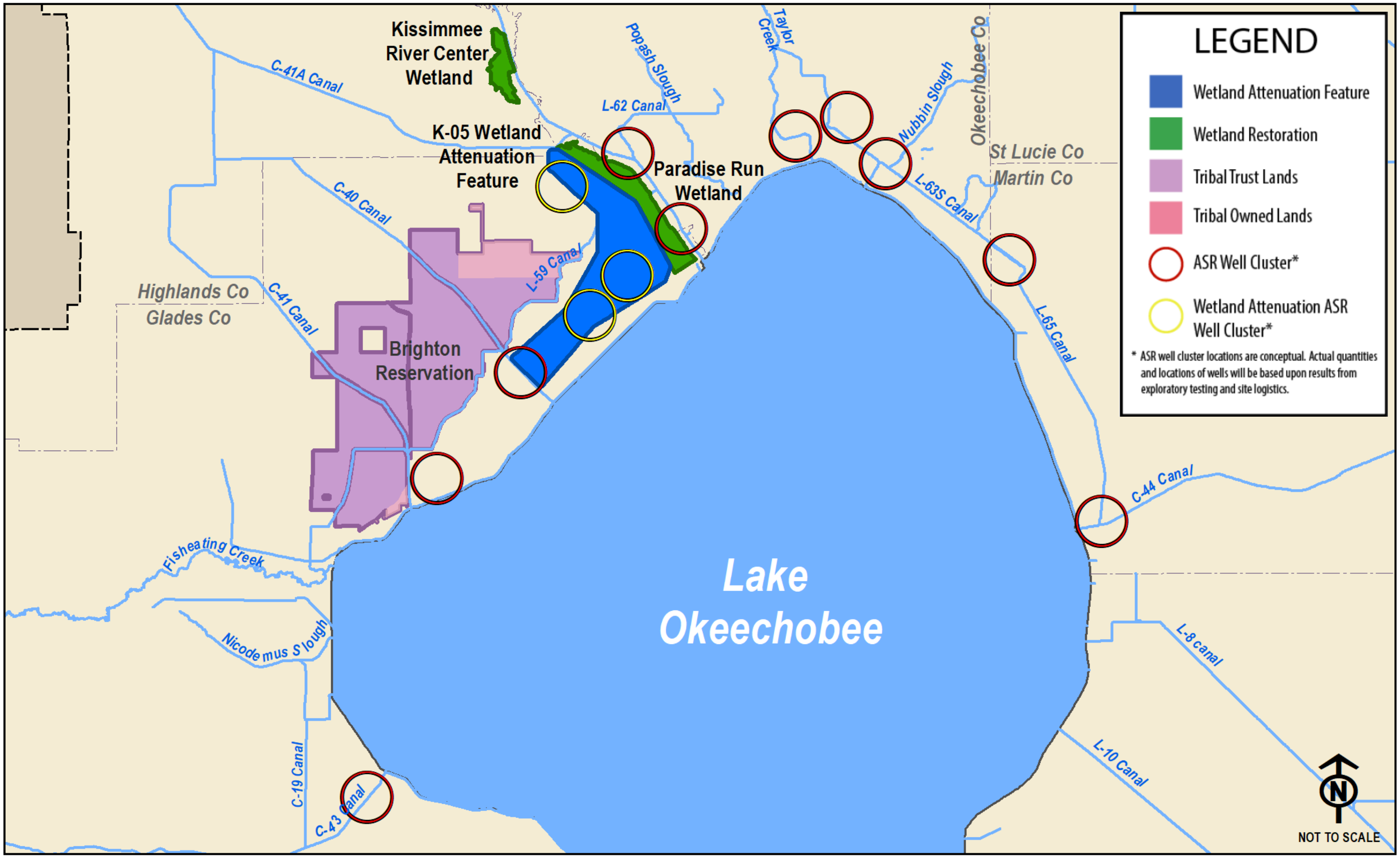


Figure 1-1. Lake Okeechobee Watershed Restoration Project Recommended Plan features.

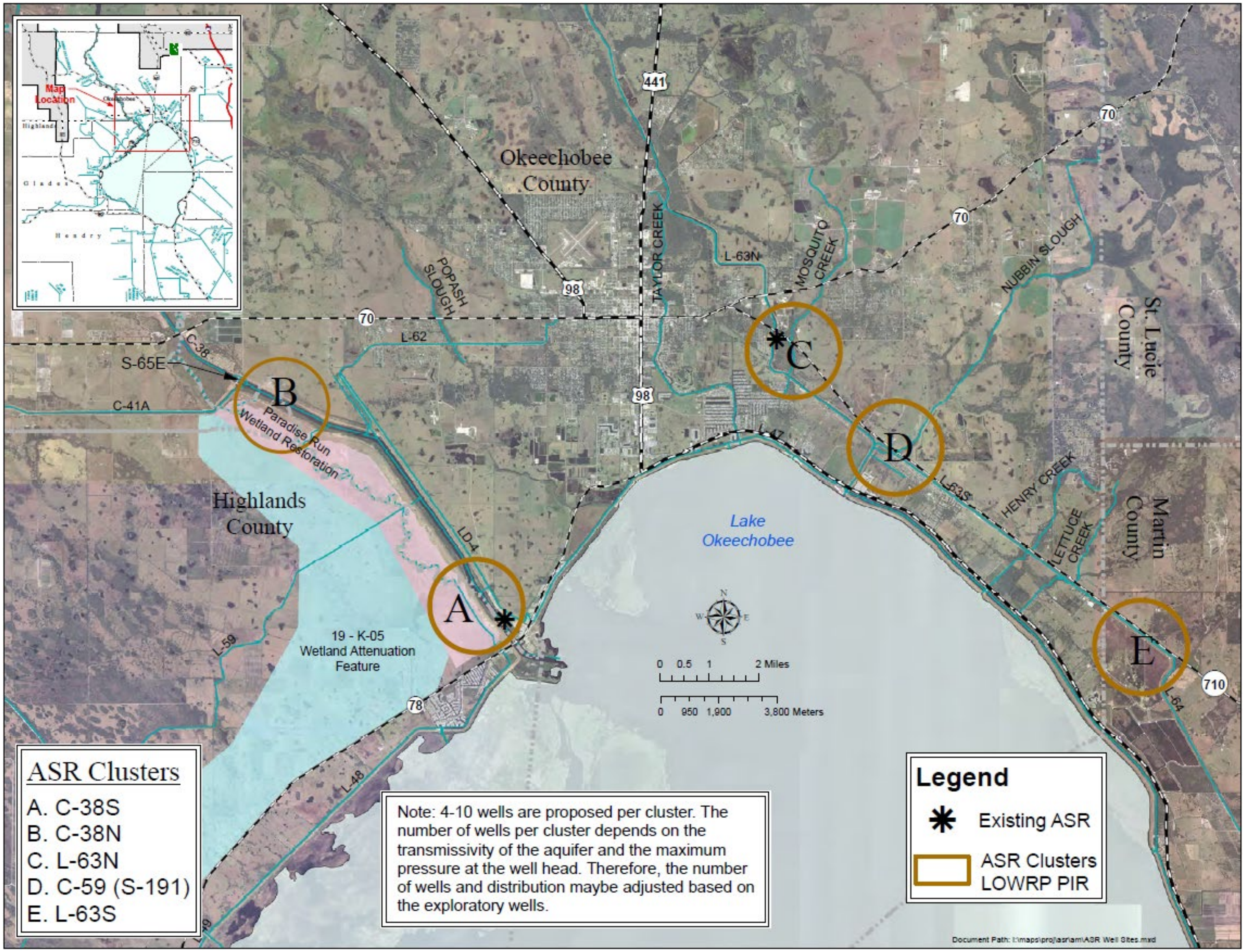


Figure 1-2. Initial ASR locations of focus along the northern perimeter of Lake Okeechobee.

1.5 INDEPENDENT PEER-REVIEW SCIENCE PANEL

An independent panel of scientists was assembled to review the phased approach of ASR construction and help develop a science-based approach to address the technical uncertainties identified in the NRC (2015) review. The independent ASR peer-review panel (PRP) includes the following members:

- Jonathan Arthur, Ph.D., P.G., Director and State Geologist, Florida Geological Survey
- Thomas Missimer, Ph.D., P.G., Professor and Director of the Emergent Technologies Institute, Florida Gulf Coast University
- Reid Hyle, Fish and Wildlife Research Institute, Florida Fish and Wildlife Conservation Commission
- Rene Price, Ph.D., P.G., Professor and Chair, Department of Earth and Environment, Florida International University
- Sam Upchurch, Ph.D., P.G., Senior Fellow of the Geological Society of America, former Geology Department Chairman, University of South Florida

A 2-day PRP technical workshop was conducted in July 2020 to review ASR studies conducted over the past 20 years, present the proposed ASR implementation schedule, and discuss the NRC recommendations for addressing remaining uncertainties. The PRP subsequently published a final report of suggested scientific evaluations and technical studies to address regional ASR implementation uncertainties (Arthur et al. 2020; **Appendix B**).

The PRP will convene annually throughout implementation of the ASR program to review the progress of the scientific investigations contained in the most recent ASR Science Plan. During the annual review meetings, the PRP likely will make suggestions or recommendations for future tasks, based on the previous year's findings.

1.6 ASR SCIENCE PLAN TO ADDRESS REMAINING UNCERTAINTIES

Although ASR technology has been used successfully in Florida since 1983 (Pyne 2005), concerns have been raised about large-scale application of ASR as envisioned in CERP. The NRC's (2015) review of the ASR Regional Study Final Technical Data Report (SFWMD and USACE 2015) identified uncertainties that merit additional study before large-scale ASR should be implemented. To reduce critical scientific uncertainties, the SFWMD and USACE developed this 2021 ASR Science Plan, which outlines potential studies to be conducted as ASR wells are implemented in a phased manner. The 2021 ASR Science Plan was developed with review and input from the PRP as well as subsequent reviews and comments from the public, interested stakeholders, and subject matter experts from the USACE and the Florida Department of Environmental Protection (FDEP). The ASR Science Plan is intended to be a living document, updated annually or as needed based on the best information available at the time of update. The proposed scope, schedule, and budget for ASR Science Plan studies are subject to change as the ASR program progresses and additional information becomes available.

The 2021 ASR Science Plan presents the first version of an overarching program of scientific studies to support a phased ASR implementation schedule for LOWRP. Although the studies proposed in the 2021 ASR Science Plan are meant to be conducted at ASR locations identified in the LOWRP Final Integrated Project Implementation Report and Environmental Impact Statement (USACE and SFWMD 2020), they have broad application beyond the scope of LOWRP. These studies have value anywhere ASR wells are proposed within South Florida and can be used to address ASR uncertainties associated with other CERP and non-CERP projects.

The ASR Science Plan can be implemented across a broad front of sequential, overlapping studies and evaluations in a tiered approach over the next several years. Some microbiological and geophysical studies have been ongoing since completion of the CERP ASR Regional Study in 2015. Design studies regarding well siting and sequencing, water treatment technology, and mechanical evaluations were initiated in early 2020. Several of those projects and reports are noted in subsequent sections and presented as appendices.

During 2021, a series of continuous cores are anticipated to be collected at locations of interest to the ASR program. The cores will provide important lithologic and groundwater quality data from the FAS, where ASR wells have been proposed to be completed. Portions of the cores will be examined for geotechnical properties and mineralogic components and subjected to tests for microbial activity and nutrient reduction. Water quality data collected while drilling the cores can be used to ascertain the proclivity for arsenic mobilization from the storage intervals through geochemical modeling. However, while the cores provide critical, early, site-specific hydrogeologic data, they provide limited information to design an actual ASR well system.

To evaluate actual well capacities, aquifer parameters, wellfield orientation and size, and water treatment and pumping systems, an exploratory well program is needed for each ASR cluster. The exploratory well program involves installing large-diameter, paired test wells and surrounding monitoring wells. By pumping the test wells individually and together, the local hydraulic aspects of the aquifer will be ascertained (e.g., anisotropy, heterogeneity, drawdown interference, injection/fracture pressures). Geophysical surveys such as seismic tomography and tracer tests can be performed by observing responses in the monitoring wells. The data can be integrated into models to simulate groundwater responses over a larger area. Groundwater models will be used to finalize the design of multi-well clusters, including well spacing, pump sizes, and treatment capacities. Additionally, the design evaluations will address concerns regarding protection of wildlife, including fish entrainment and thermal impacts to manatees.

While continuous cores are collected and exploratory wells are constructed, there is benefit from reactivating the existing ASR systems along the Kissimmee River (KRASR) and L-63N Canal. Both systems provided information about ASR performance in the Upper Floridan aquifer (UFA) and the Avon Park permeable zone (APPZ). When reactivated, the KRASR can be used to continue bioconcentration, ecological, and nutrient reduction studies on recovered water. The L-63N ASR well is completed in the APPZ and permitted with an aquifer exemption; this allows for evaluation of ASR without a disinfection treatment process, which can provide assessment of microbial inactivation during storage.

When the design studies are complete, permits will be applied for and obtained to construct new multi-well clusters. Upon completion of construction, the new ASR systems will begin operation with a series of cycle tests. During the first few years, an intensive water quality monitoring program will be implemented to assess the operational efficiency of the system and ensure regulatory compliance. Cycle testing typically is sequenced for progressively larger durations of recharge, storage, and recovery. The water recovered from the ASR systems will provide valuable information on the potential impacts to biota within the Lake Okeechobee ecosystem and in downstream Everglades communities. Ultimately, as longer-term data are obtained from the operational clusters, a comprehensive quantitative ecological risk assessment can be conducted.

While evaluations are ongoing, an annual ASR Science Plan update will be prepared, summarizing the results of the previous year’s studies. The report will be presented during an annual review meeting with the PRP (**Section 1.5**), which will be available for public viewing. The PRP will prepare an annual summary evaluation report of the program’s progress, including recommendations for upcoming work tasks and future studies.

The subsequent chapters of the ASR Science Plan provide specific near- and longer-term tasks to address each of the recommendations and remaining uncertainties elucidated in the NRC (2015) review as well as an anticipated schedule of future construction activities. The schedule will be updated annually and included in the ASR Science Plan updates.

1.7 PRE-PLAN ACTIVITIES

Prior to and during preparation of the 2021 ASR Science Plan, several ongoing evaluations and processes already were under way. For instance, the SFWMD, with assistance from Stantec Consulting Services Inc., has been repairing and maintaining the inactive KRASR system to reactivate the facility and continue cycle testing. The SFWMD performed a mechanical integrity test on the L-63N (Taylor Creek) ASR facility, completed in the APPZ. Stantec Consulting Services Inc. was contracted to evaluate the options of recharge and recovery water treatment technologies to meet regulatory compliance. Permit applications were filed with the FDEP to construct exploratory ASR wells at the C-38S and C-38N locations. The United States Geological Survey (USGS) was contracted by the SFWMD to perform continuing studies on microbial inactivation, nutrient reduction within the subsurface, geophysical characteristics, and detailed core analysis. Many of these activities will provide scientific data to support the ASR Science Plan updates. Several reports have been completed for these activities and are described in subsequent chapters and included as appendices.

1.8 REPORT ORGANIZATION

The following chapters are organized into broad topics that were addressed in the NRC (2015) report. The anticipated project sequencing, schedule, reporting, and data management are presented in **Chapter 2**. Within each subsequent chapter are specific areas of remaining uncertainty identified by the NRC. For each NRC comment, there is a brief summary of previously completed work related to the topic and a summary of guidance from the PRP (Arthur et al. 2020; **Appendix B**) or NRC review panel (NRC 2015) that could be applied to resolve the topic. A plan of action is then presented, describing the investigations and studies that can address the uncertainties.

2 PROJECT SEQUENCING, SCHEDULE, REPORTING, AND DATA MANAGEMENT

This chapter presents a summary of activities to support the advancement of the ASR Science Plan, including a discussion of project sequencing, a schedule of near-term activities, project reporting, and the data management plan.

2.1 PROJECT SEQUENCING

As recommended by the NRC, implementation of LOWRP ASR wells will proceed in a phased approach and will include continued monitoring and research activities as construction proceeds. **Figure 2-1** and **Figure 2-2** show phases of project progression for a specific cluster of ASR wells and highlight studies that will occur during the various phases, as currently planned. The dates indicate time frames associated with building out the first ASR well cluster. Subsequent clusters will have different time frames but will follow the same pattern. The studies correspond to the NRC comments presented throughout subsequent chapters of the ASR Science Plan. Numerous studies are anticipated to occur during each project phase, and multiple project phases will occur concurrently. The studies and phases are subject to change as the ASR program is implemented and more data are available.

2.2 PROJECT SCHEDULE

Near-term project activities for the first ASR well clusters and an estimated schedule for their initiation are presented below. Factors that could influence the project sequencing and schedule include funding availability, regulatory requirements and approvals, annual PRP reviews and input, and integration of projects constructed by other agencies or entities. Many of the near-term activities can be described with some certainty, while activities in more distant years are less clearly defined and will be formulated based on the findings of earlier studies through adaptive management. Details of future studies beyond 2026 or related to subsequent ASR clusters will be provided in subsequent updates of the ASR Science Plan as the ASR program progresses and additional information becomes available.

2021

- Collect continuous cores at two locations
- Analyze cores for mineralogic and geotechnical properties
- Continue water treatment technology evaluations
- Develop a project quality assurance/quality control (QA/QC) plan
- Initiate USGS column studies of nutrient reduction/plugging potential
- Permit/procure exploratory well construction at C-38S and C-38N
- Repair/refurbish the KRASR facility
- Design evaluations for reactivation of the L-63N ASR system
- Develop a plan for the probabilistic, quantitative environmental risk assessment

2022-2023

- Initiate cycle testing at the KRASR system
- Collect continuous cores at two new locations
- Construct exploratory wells at C-38S and C-38N
- Perform geochemical benchtop modeling
- Finalize water treatment design studies

- Conduct geophysical assessments at exploratory wells
- Perform local (wellfield) groundwater modeling
- Initiate preliminary studies in support of the environmental risk assessment

2023-2024

- Finalize the design of surface facilities/treatment systems at cluster locations
- Initiate construction of two new multi-well clusters at C-38S and C-38N
- Perform subregional groundwater modeling of new cluster sites
- Initiate construction at the L-63N ASR system
- Evaluate buffer zone concept at the KRASR system
- Utilize the Lake Okeechobee Environment Model to initiate risk assessment
- Complete USGS study of pathogen inactivation and nutrient reduction/well clogging

2024-2026

- Initiate cycle testing of multi-well clusters at C-38S and C-38N
- Conduct recovered water mesocosm tests at C-38S and C-38N cluster locations
- Perform a regional groundwater model evaluation
- Finalize quantitative environmental risk assessment

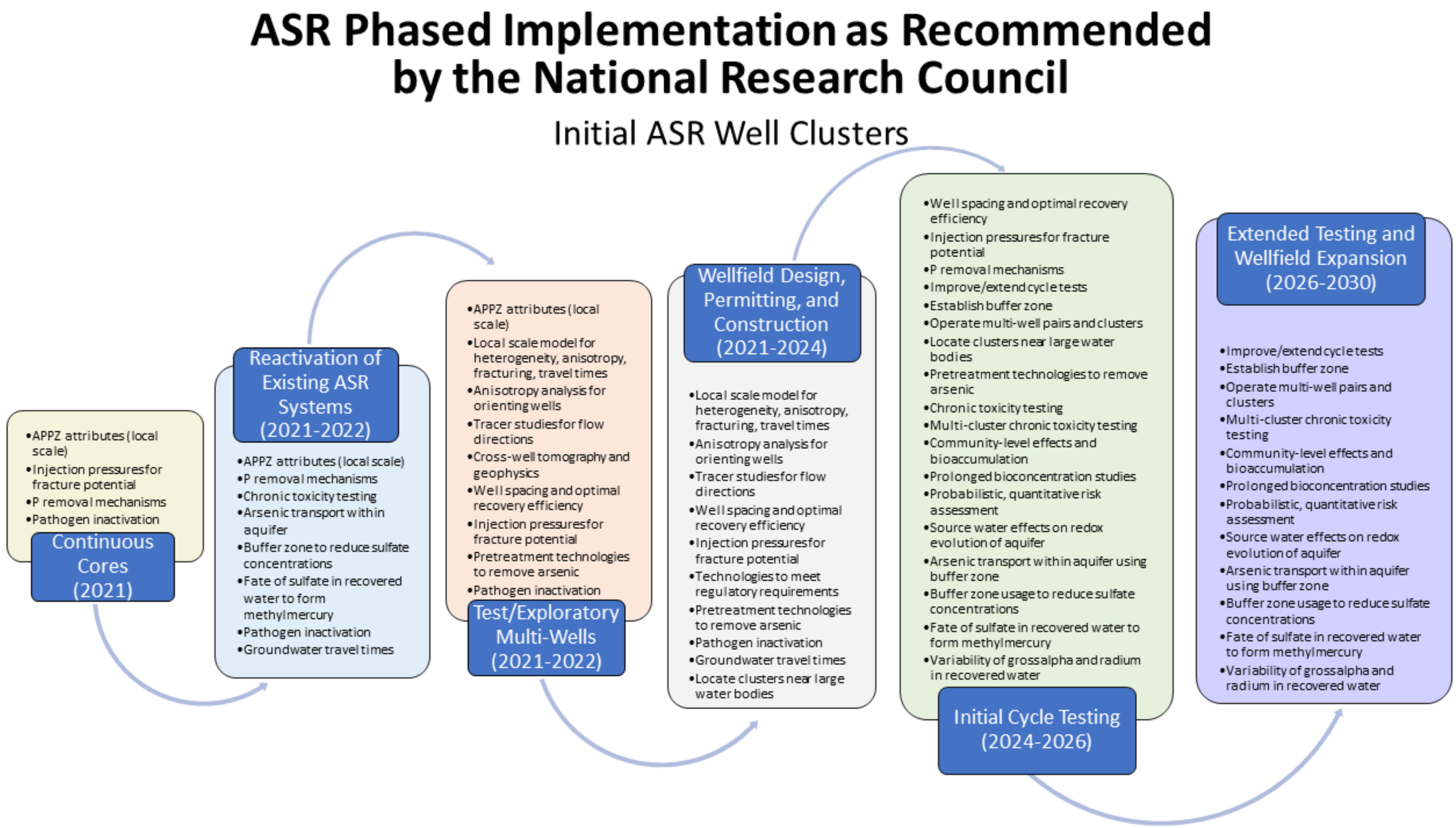


Figure 2-1. Phases of ASR project progression and proposed studies to address National Research Council comments.

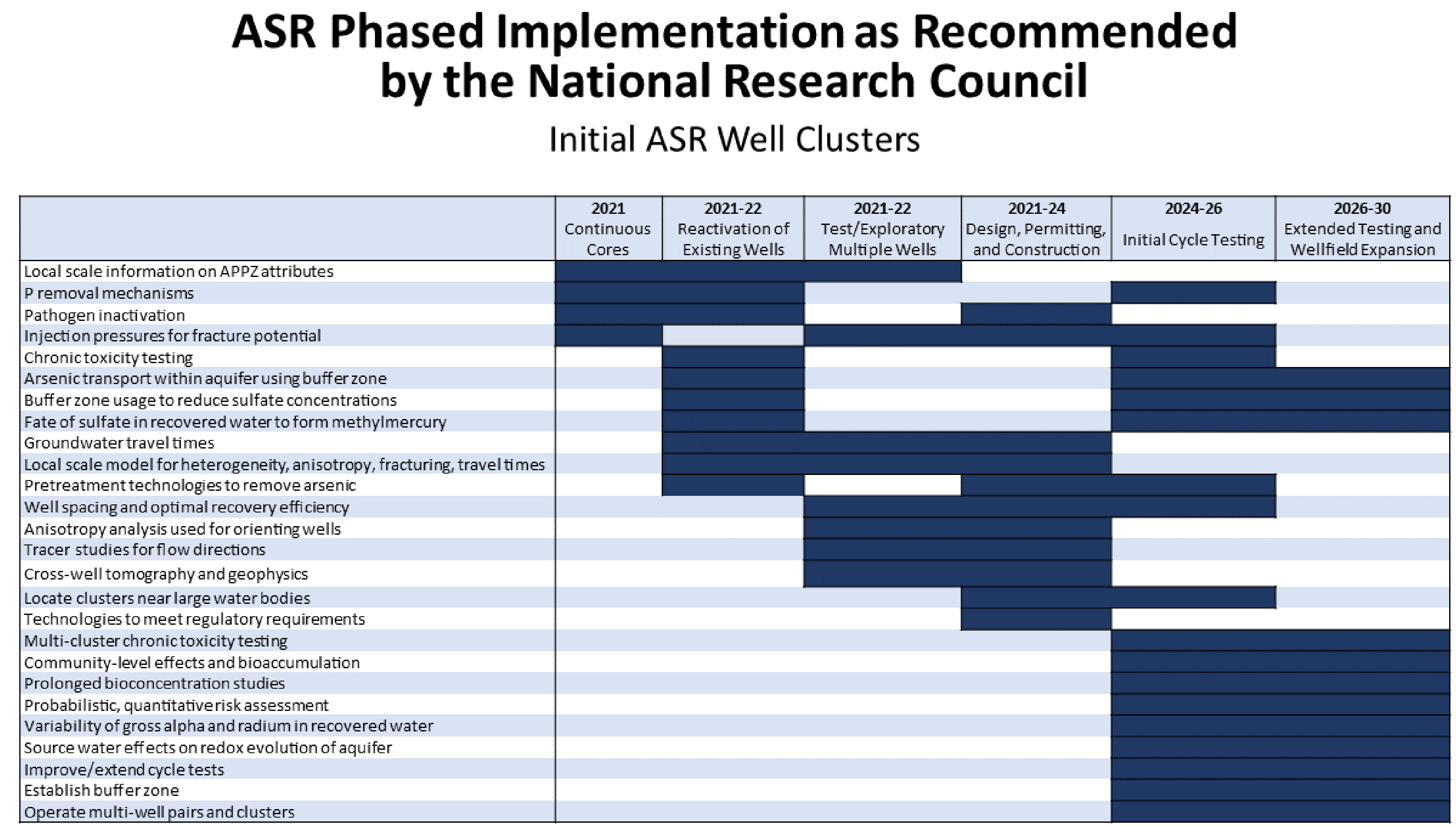


Figure 2-2. Proposed studies to address National Research Council comments during various phases of ASR implementation.

2.3 PROJECT REPORTING: ASR REPORT CARD

During implementation of the ASR Regional Study, efforts to monitor and document progress on addressing early recommendations (**Chapter 1**) took on the form of an annual ASR report card. The PRP recommended developing a similar report card to represent progress towards addressing NRC recommendations and additional recommendations offered in this ASR Science Plan. This method of tracking and visualizing progress will be useful not only to project managers but also to stakeholders. Descriptions of status details, anticipated timelines, links to reports, principal contractors, and points of contact could be included to improve communication and transparency. An example of a report card for the ASR Science Plan is presented in **Figure 2-3**. Progress has been made in some areas already, such as pathogen inactivation and nutrient reduction, as a result of recent studies by the USGS (e.g., Lisle 2020) and completion of preliminary design and treatment evaluations by Stantec Consulting Services Inc.

ASR Science Plan Report Card										
Date: October 2020	% Progress Towards Adressing the Topic									
	10	20	30	40	50	60	70	80	90	100
Local scale information on atributes of APPZ										
Research P removal mechanisms										
Reseach pathogen inactivation										
Anaysis of injection pressures for fracture potential										
Continue chronic toxicity testing										
Arsenic transport within aquifer using buffer zone										
Buffer zone usage to reduce sulfate concentrations										
Fate of sulftate in recovered water to form methylmercury										
Couple pathogen inactiation with groundwater travel times										
Local scale model for heterogeniety/anisotropy/fracturing/travel times										
Pretreatment technologies to remove arsenic										
Analysis of wellfield cluster for spacing and optimal recovery efficiency										
Anisotropy analysis used for orienting wells										
Tracer studies for flow directions										
Cross-well tomography and geophysics										
Locate clusters near large water bodies										
Examine technologies to meet regulatory requirements										
Multi-cluster chronic toxicity testing										
Examine community-level effects and bioaccumulation										
Prolonged bioconcentration studies										
Probabilistic, quantitative risk assessment										
Variability of gross alpha and radium in recovered water										
Examine source water effects on redox evolution of aquifer										
Improve/extend cycle tests										
Establish buffer zone										
Operate multi-well pairs and clusters										

Figure 2-3. Example ASR Science Plan report card.

2.4 ANNUAL ASR SCIENCE PLAN WORKSHOPS

Annual ASR Science Plan workshops will be conducted to discuss results of ongoing research and monitoring activities and to identify areas requiring further research and modeling efforts as the ASR program progresses. The public workshops will include federal and non-federal sponsors, PRP members, project and contract scientists, university and agency scientists, and various stakeholder groups. There will be an opportunity for the public to provide comments at each workshop. The workshops will provide open forums to discuss results to date and transparency in identifying future research, monitoring, and modeling needs.

2.5 PROJECT DATA MANAGEMENT

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

Research activities related to ASR and groundwater modeling are data intensive, including hydrologic, meteorologic, chemical, and biological data collected at a variety of spatial and temporal frequencies and extents. Users and providers of the data may include a diverse set of individuals and groups from academia, nongovernmental organizations, commercial institutions, and municipal, state, and federal agencies. Rich sets of legacy data on multiple aspects of the FAS have been collected by numerous groups. Ongoing data collection as part of specific short-term studies or long-term monitoring is planned or under way. The hydrologic and ecological modeling that is a core part of CERP will produce large amounts of model output.

The data emanating from these various activities will need to be organized, quality assured, maintained, and curated. Furthermore, the data must be accessible, discoverable, reviewable, and usable by individuals or groups, ideally within and beyond the CERP set of stakeholders. The PRP strongly recommends the SFWMD ASR team develop a comprehensive information management plan. Such a plan would ensure internal and external access to relevant data over the short and long term, facilitate data analyses and syntheses across multiple data types and sources, buffer against the potential turnover of key personnel, and increase transparency and communication to stakeholders as CERP is implemented and evaluated. In short, a well-planned and implemented information management system will make all aspects of CERP, including ASR, more likely to succeed.

Developing and implementing a comprehensive data management plan likely will require full-time information managers throughout the life of the project. Other complex, data-intensive projects such as the Long-Term Ecological Research Network, the Consortium of Universities for the Advancement of Hydrological Sciences, Inc., and the Ecological Society of America have developed functional information management and data registry systems that might serve as models. The plan should include multiple aspects of information management, including the following:

- Definition of data types; standardization of analytes (e.g., consistent reporting of dissolved nitrogen) and formats, ranging from raw data to metadata; and details of what data types are available and how they are characterized and organized
- An explicit data management plan, from the method of collecting and initially transferring data from the field into digital form to follow-up data flow, including QC, analysis, synthesis, and dissemination
- Agreements about which data and types will be centrally housed and which will be distributed among individual stakeholders
- Maintenance of database integrity, including QA, short- and long-term curation, archival, and data backup plans
- Description of the data access and sharing policy
- Description of limitations and disclaimers on data use
- Creation of an accessible environment for the retrieval of information
- Facilitation of linkages among diverse data sets
- Documentation of metadata for data interpretation and analysis
- Analysis of information management staffing needs

Plan for Data Storage, Management, and Public Access

ASR project data will be managed within an internet-accessible environment requiring a username and password for login. Upon receiving a username and password, individuals and groups from academia, nongovernmental organizations, commercial institutions, governmental agencies, and members of the public will be able to access the data. A combination of data management tools—primarily Data Access Storage and Retrieval (DASR), Morpho, and Metacat—will uniquely preserve all information generated by the implementation of each project component (**Figure 2-4**).

- DASR is an array of file servers used to manage file import and export, work-in-progress file sharing, and file staging for information archival in Morpho packages.
- Morpho is a metadata generation program, conforming to the Ecological Metadata Language specification. Information about people, sites, research methods, and data attributes are among the metadata created. Data are packaged with metadata in the same container. Morpho allows the user to create a local catalog of data and metadata that can be queried, edited, and viewed.
- Metacat is a flexible, open-source metadata catalog and data repository that targets scientific data, particularly from ecology and environmental science. Metacat is a generic XML database that allows storage, query, and retrieval of arbitrary XML documents without prior knowledge of the XML schema. Metacat is designed and implemented as a Java servlet application that uses a relational database management system to store XML and associated meta-level information.

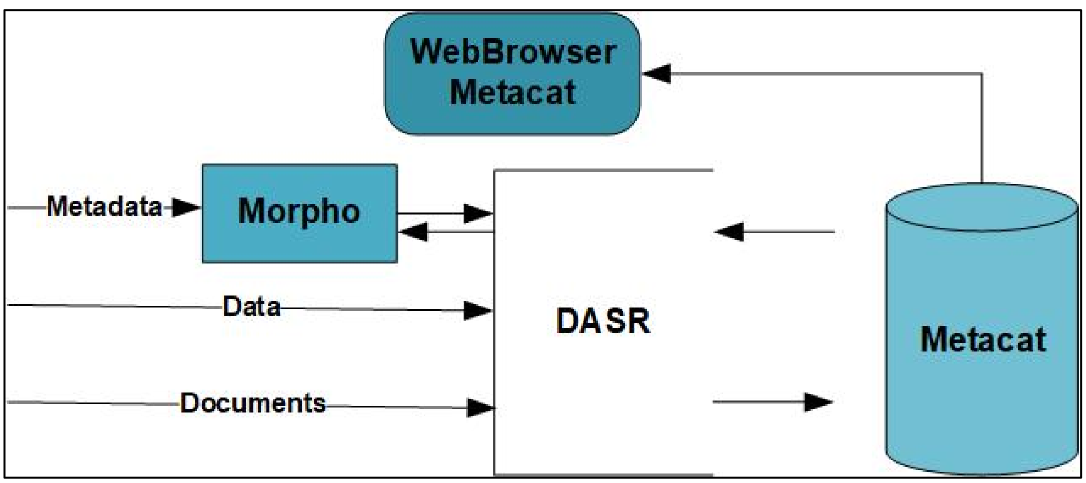


Figure 2-4. Data management tools to be used for ASR project data.

This data management system creates digital information packages encompassing the entire data lifecycle. Packages are composed of metadata as well as any file-type, digital data deliverable, in native format. The packages conform to Ecological Metadata Language standards and render the information keyword searchable. Once a package is generated and stored in Metacat, the information becomes accessible via web browser. Metacat and Morpho are primarily for metadata and ecological monitoring and research data. Morpho packages different data types, makes them searchable, and provides long-term data storage in the Metacat repository.

In addition to using Metacat for ecological monitoring and research data, the SFWMD will store ASR well data in the DBHYDRO database. DBHYDRO is the SFWMD's corporate environmental database for management of hydrologic, meteorological, hydrogeologic, and water quality data. The DBHYDRO browser allows users to search the DBHYDRO database, using one or more criteria, and generate a summary of the data from the available period of record. DBHYDRO users can select data sets of interest and have the time series data dynamically displayed in tables or graphs. ASR data stored in the DBHYDRO database will be referenced in the Morpho package with links to the DBHYDRO browser. Any data managed in repositories external to Metacat will be referenced with links to the external repository access interface for data retrieval.

2.6 ASR SCIENCE PLAN QUALITY ASSURANCE

Activities conducted under the ASR Science Plan are required to meet the applicable requirements of Chapter 62-160, Florida Administrative Code, known as the Quality Assurance (QA) Rule. The QA Rule, overseen by the FDEP, applies to many aspects of the ASR Science Plan studies: field activities (e.g., sample collection, sample preservation, field measurements, site evaluation); sample documentation, sample handling, storage, and shipment; laboratory activities (e.g., sample receipt, analysis, data verification, data validation); and other applicable activities that may affect data quality.

Additionally, the ASR Science Plan is being implemented as a component of CERP, which requires strict adherence to data collection and validation methods as well as QC verification and coordination. These QA policies and procedures are explicitly documented in CERP Guidance Memorandums and a Quality Assurance Systems Requirement manual that are maintained by the CERP Quality Assurance Oversight Team.

A separate document is being developed with guidance from the FDEP to address the QA objectives for the specific sample and/or data types that will be produced for this ASR Science Plan. The QA objectives for each sample and/or data type will describe the QA expectations and applicability of the QA Rule or other requirements to each sample and/or data type. This QA document is anticipated to be prepared in late 2021 and will be made available prior to the 2022 annual PRP workshop.

3 FUTURE CONSTRUCTION AND TESTING

3.1 NRC comment: More local-scale information is needed on the attributes of the APPZ, including a groundwater model to assess storage effects on the APPZ

Previous Investigations

The APPZ is situated in the middle of the FAS and has been identified in LOWRP as a high-potential zone for subsurface water storage. To date, the only ASR system completed and tested within the APPZ is the L-63N ASR system, which was constructed and cycle tested by the SFWMD in the 1980s. The original well construction and testing report is among the publications listed in **Appendix A**. A mechanical integrity test was conducted on the well in 2020, and it was determined to be viable and capable of being pumped at up to 10 million gallons per day. The 2020 mechanical integrity testing report is included in **Appendix C**.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

The APPZ tends to have a high transmissivity and a greater density of channel pores compared to the UFA. To improve recovery efficiency, ASR wells using the APPZ may require a one-way flow valve within the open hole. During the injection phase, fresh water would enter the entire thickness of the open hole. During recovery, the valve could be closed, and water would be pumped only from the upper part of the aquifer above the valve.

Proposed Plan for Future Studies

Continuous Cores (2021-2023)

The SFWMD contracted Huss Drilling, Inc. to collect continuous cores at multiple potential LOWRP ASR cluster sites that will fully penetrate the UFA and APPZ to depths of 2,000 feet below land surface. The cores will allow detailed examination of the continuous lithology of potential storage and confining zones and characterization of water quality at discrete intervals throughout the aquifer. The USGS will be contracted to perform a detailed analysis of mineralogy, porosity, fractures, and sedimentary fabrics on specific intervals of the cores that represent favorable targets for ASR storage. Additionally, geophysical logs will be conducted within the drilled borehole and will include optical borehole image, gamma-ray, caliper, resistivity, sonic, and temperature evaluations. Water quality samples will be collected during core drilling at 30-foot intervals beginning at 500 feet below land surface and analyzed for the following parameters:

- Chloride
- Alkalinity
- Arsenic
- Calcium
- Potassium
- Magnesium
- Sodium
- Silica
- Sulfate
- Total dissolved solids (TDS)
- Strontium

In addition to the analytes listed above, eight expanded water quality samples per corehole will be collected from the target storage zones. The samples will be analyzed for the parameters listed below, and the results will be used in a geochemical benchtop analysis.

- Total suspended solids
- Color
- Fluoride
- Carbonate alkalinity
- Bicarbonate alkalinity
- Iron
- Aluminum
- Copper
- Manganese
- Zinc
- Cadmium
- Selenium
- Total hardness
- Nitrate
- Phosphate
- Ammonia
- Hydrogen sulfide
- Total organic carbon
- Specific gravity or fluid density
- Total coliform
- Chloroform
- Bromodichloromethane
- Dibromochloromethane
- Bromoform
- Total trihalomethane
- Federal and/or state primary and secondary drinking water standards

The continuous cores also will yield mineralogic characterization of the strata to determine the potential for arsenic liberation during storage. Discrete core samples from the UFA and APPZ will be sent to a specialty laboratory for the following analyses:

- Porosity
- Vertical and horizontal hydraulic conductivity
- X-ray diffraction
- X-ray fluorescence
- Cation exchange capacity
- Acid insoluble residue
- Thin-section petrography
- Scanning electron microscope analysis

After collection of the continuous cores (3.5 inches in diameter), the borehole may be reamed to a wider diameter and converted into a monitoring well completed in the UFA, APPZ, or both. The cores will be stored at the USGS facility in Davie, Florida, where they will be slabbed, photographed, and evaluated for lithologic and other hydrogeologic attributes. A detailed work program for this effort is ongoing.

Reactivation of the L-63N ASR System (2022-2023)

Until recently, the L-63N ASR well completed in the APPZ had been inactive for more than 30 years. A design evaluation is under way to put the ASR well back into service after having successfully completed the mechanical integrity test in 2020 (**Appendix C**). Because this well was completed in the APPZ, it provides a local assessment of the attributes and efficiency of surface water storage in that zone. A continuous core is planned for collection near the ASR well to determine if additional ASR wells can be installed on the property. After the continuous core well is constructed, a local-scale groundwater model will be performed as part of the design process to determine how many additional ASR wells completed within the APPZ can be operated at the site. After construction of multiple wells at this location, it will be able to demonstrate the APPZ's potential for ASR.

3.2 NRC comment: Local-scale groundwater modeling should be undertaken to refine uncertainties about aquifer heterogeneity and anisotropy, travel times, and analysis of potential fracturing

Previous Investigations

The CERP ASR Regional Study used a spatially discretized, calibrated, three-dimensional (3D) groundwater model (SEAWAT; Guo and Langevin 2002) to determine the regional effects of large-scale ASR implementation. The smallest resolution cell size in the model was 2,000 feet, which was appropriate for a feasibility assessment of ASR on a South Florida-wide scale. During 2012, a local-scale model was conducted at the ASR pilot facilities, extracting data from the regional model and calibrating the smaller resolution grid to the responses in the surrounding monitoring wells during cycle testing.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

The SFWMD ASR team appears aware of the challenges of working with multi-scale groundwater models. Model scales are both spatial and temporal and may include large fluxes in water volumes over short periods. Bracketing extreme conditions in context of climate change (e.g., extreme drought or rainfall over extended periods) at all scales in all aquifers will be important as these possible future conditions will impact regional groundwater withdrawals and managed recharge activities. Equally important, tracking model uncertainty at all scales should be routine to inform the planning and adaptive management process.

A more specific modeling observation relates to impacts of surficial aquifer system heads on deeper aquifers. FAS modeling did not include the surficial aquifer system, which in most cases is not a major issue. However, the surficial aquifer system head is important because it impacts the heads in all underlying aquifers. In several USGS coastal plain MODFLOW models (e.g., the 17-layer model in North Carolina), the model sensitivity showed that the head in the uppermost aquifer (surficial or unconfined) was a dominant force in controlled heads in the deeper aquifers (Guo et al. 2015). Therefore, including surficial aquifer system heads under extreme drought or rainfall conditions is recommended while modeling the FAS.

The PRP suggests aquifer performance tests for anisotropy, flow zone analysis (maybe with packer testing), and cross-well seismic tomography to depict permeability away from the injection wells. Testing should be done in a way to understand aquifer heterogeneity and anisotropy and potential for fractures. Also, the PRP suggests the SFWMD ASR team explore various resistivity testing techniques (e.g., time domain) to characterize fluid movement in storage zones (with salinity contrast between native and injected water) before, during, and after cycle testing as these results can be useful in defining the extent of the freshwater buffer zone during operations.

Proposed Plan for Future Studies

Exploratory Wells at C-38S and C-38N (2021-2022)

The SFWMD applied for exploratory well construction permits at two potential ASR cluster locations along the C-38 Canal, just north of Lake Okeechobee. The locations are designated as sites 'A' and 'B' in **Figure 1-2**. The detailed configuration of the exploratory wells and additional monitoring well locations at C-38S and C-38N are presented in **Figure 3-1** and **Figure 3-2**, respectively. The 24-inch diameter test wells will be completed in the UFA and APPZ target storage zones. In addition to the tests wells, monitoring wells will be completed in the storage zones and overlying surficial aquifer system. After the wells are constructed, tracer tests may be conducted during the final well pump testing process. A short-term injection test may be requested to facilitate tracer testing. The orientation of the test wells and surrounding monitoring wells will provide an assessment of heterogeneity and anisotropy within both storage zones by use of tracer tests and geophysical surveys. Upon completion of the testing programs at both sites, a local-scale wellfield groundwater model will be constructed to determine the potential for additional wells at the sites, including evaluation of injection pressures to minimize the potential of fracturing the formations. The underground injection control permit applications for both sites are currently under review by the FDEP.

Local-scale Groundwater Wellfield Design Model (2022)

Data provided by the exploratory wells along the C-38 Canal will provide detailed local information to construct a groundwater model for the wellfield design. The model will be used to simulate interference effects from multiple active ASR wells, combined drawdown and head buildup effects, and potential water quality effects from underlying strata. Additionally, design engineers will use the model to determine the appropriate distances between ASR wells and monitoring wells, which will affect decisions on pump sizes, piping, and treatment facilities. The model also will be used to evaluate the effectiveness of a buffer zone to maximize recovery efficiency and prevent recovery of undesirable groundwater constituents.

Multi-scale Groundwater Model Development (2022-2025)

At this time, three phases of groundwater modeling are anticipated as the ASR program progresses:

- An early, wellfield-scale model will be used by design engineers to determine individual multi-wellfield size, well depth, spacing, monitoring well placement, pumping, treatment, and expansion components.
- After individual wellfield clusters are investigated and designed, a subregional model evaluation will be used to determine the impacts nearby well clusters might have on each other.
- After completion of exploratory wells at each proposed cluster location identified in LOWRP (**Figure 1-1**), a revised regional groundwater model will be used, updating the model prepared during the CERP ASR Regional Study.

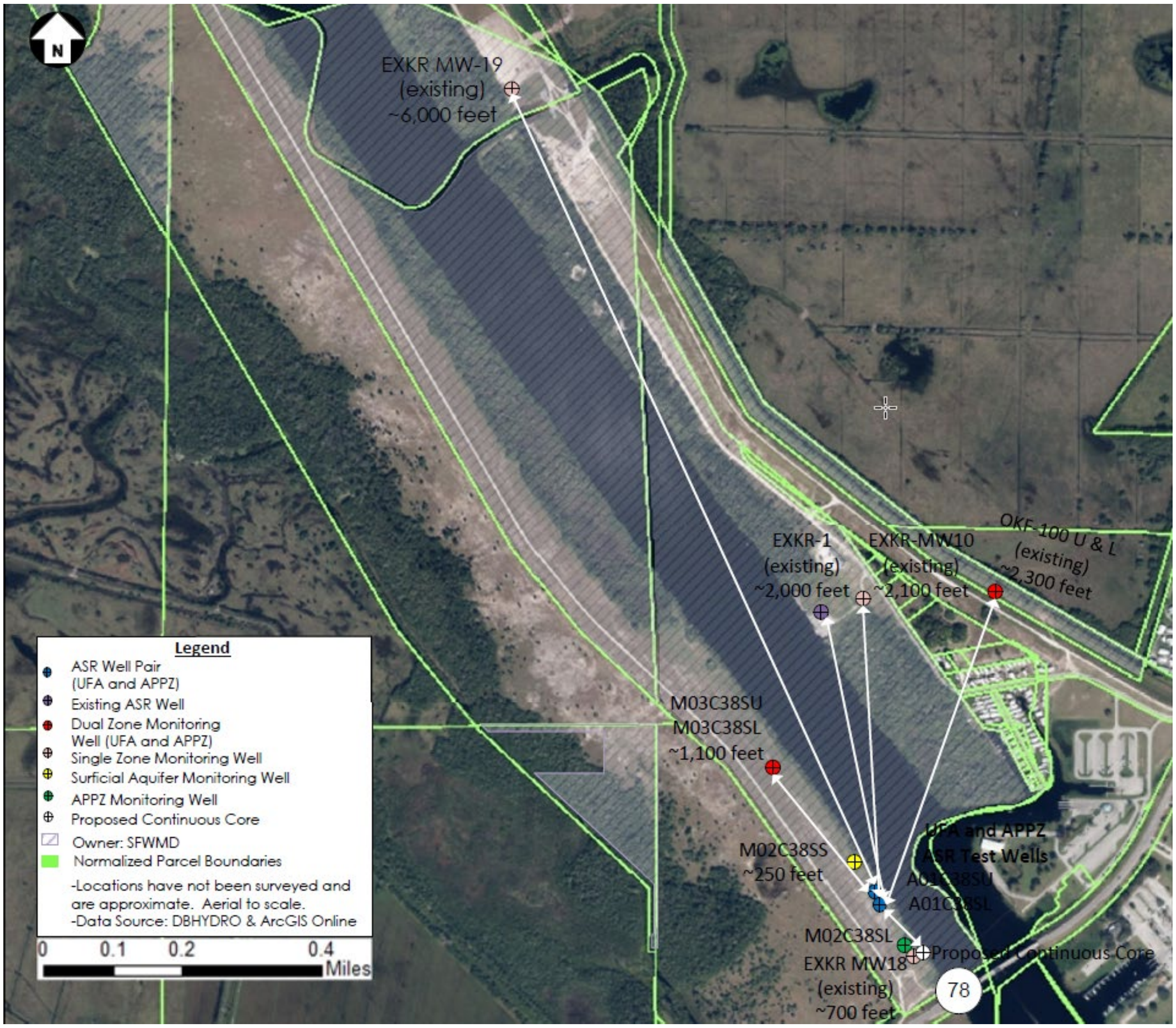


Figure 3-1. C-38S ASR test well and monitoring well layout.

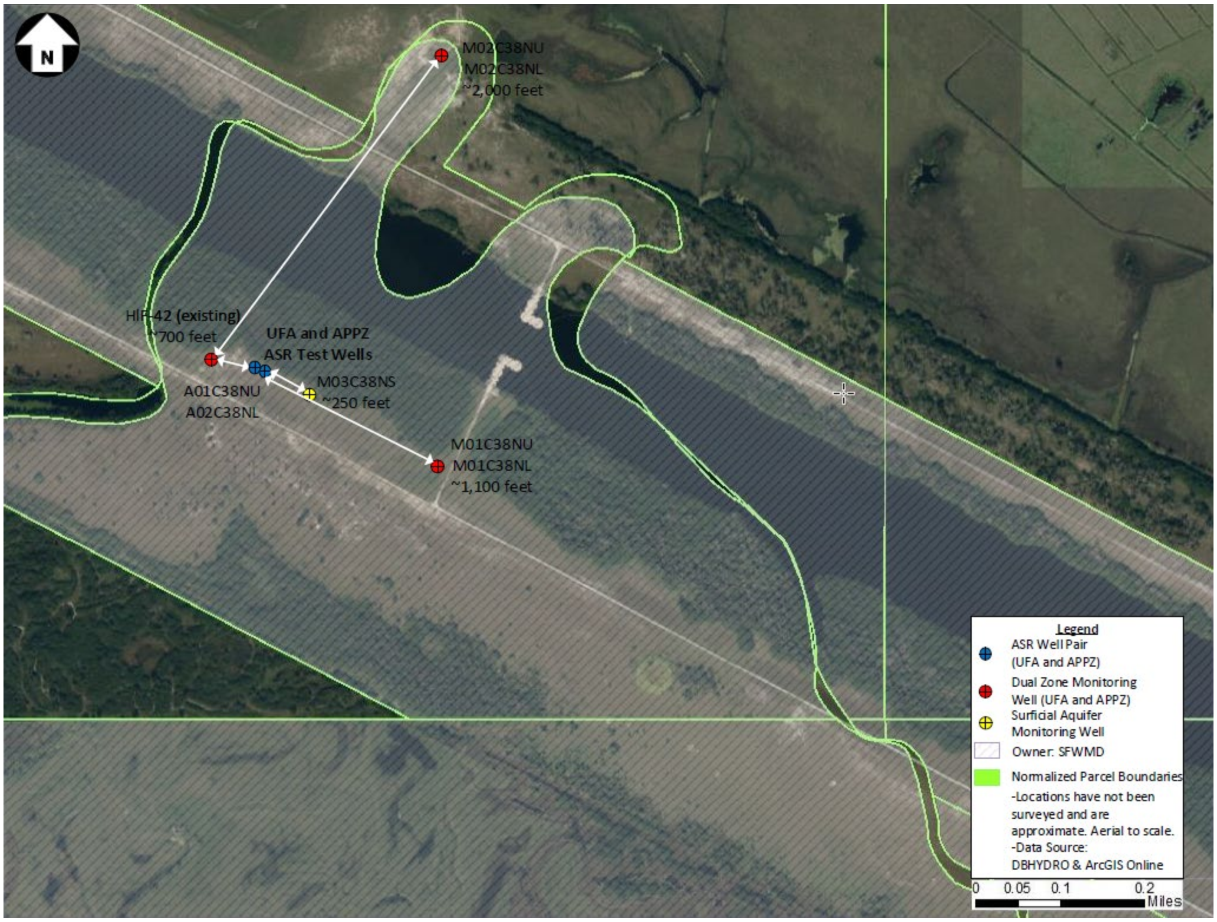


Figure 3-2. C-38N ASR test well and monitoring well layout.

3.3 NRC comment: The effects of aquifer anisotropy should be assessed, including the consideration of orienting recovery wells along the direction of preferential groundwater flow

Previous Investigations

Effects of aquifer anisotropy were evaluated during construction of the regional groundwater flow model for the CERP ASR Regional Study; however, the analysis was not used for orientation of multi-well configurations at the pilot ASR facilities. A local evaluation of anisotropy was performed during a pumping test at a new FAS wellfield in the City of Clewiston.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

The geometry of ASR well clusters has a significant impact on the potential recovery of stored water. One of the more effective geometries is the alignment of ASR in a linear mode in the down-gradient direction. This orientation may diverge from patterns of surface water bodies. In a gradient-oriented wellfield configuration, injected water commonly is captured at the terminus of the line before it can escape the effective capture radius of the system. This issue becomes more important as the natural flow gradient becomes greater. This alignment is particularly attractive in the case of continued injection during multiple or consecutive years of high-water conditions without annual recovery when some of the injected water could escape recapture as it moves with regional flow.

Proposed Plan for Future Studies

Exploratory Wells at C-38S and C-38N (2021-2022)

Pumping tests and tracer studies performed on the exploratory wells at the C-38S and C-38N sites will allow for assessment of aquifer anisotropy and heterogeneity at those locations. The effect of anisotropy can be integrated into a local-scale 3D groundwater model, which can be used to determine optimal locations for future ASR and monitoring wells during the design evaluations. Results of the exploratory well construction and testing will be documented in well completion reports.

3.4 NRC comment: Consider the use of tracer studies to determine hydraulic flow directions to properly orient/locate monitoring wells

Previous Investigations

To date, there have been no tracer studies conducted at the existing SFWMD ASR facilities.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

As noted in **Section 3.2**, the PRP suggests aquifer performance tests for anisotropy, flow zone analysis (maybe with packer testing), and cross-well seismic tomography to depict permeability away from the injection wells. Testing should be done in a way to understand aquifer heterogeneity and anisotropy and potential for fractures. Also, the PRP suggests the SFWMD ASR team explore various resistivity testing techniques (e.g., time domain) to characterize fluid movement in storage zones (with salinity contrast between native and injected) before, during, and after cycle testing as these results can be useful in defining the extent of the freshwater buffer zone during operations.

Proposed Plan for Future Studies

Tracer Studies at Exploratory Wells at C-38S and C-38N (2022-2023)

Tracer studies may be conducted at the C-38S and C-38N sites upon completion of the exploratory and monitoring wells. Tracer studies may comprise pumping out of the test wells or injecting into the wells for a brief period of time, depending on regulatory approval.

Wellfield-scale Groundwater Modeling (2022-2023)

Subsequent local-scale wellfield groundwater modeling will be performed during design.

3.5 NRC comment: Consider the use of cross-well seismic tomography and regional seismic evaluation to assess the effects of tectonic faults on well location and performance

Previous Investigations

Cross-well seismic tomography was conducted at the Hillsboro ASR system and Port Mayaca pilot project locations. The surveys helped delineate the vertical and lateral continuity of transmissive and confining zones within the FAS.

A subregional, two-dimensional (2D) marine seismic investigation was conducted within Lake Okeechobee to assess the regional continuity of the FAS beneath the lake. After completion of the CERP ASR Regional Study, a land-based 2D seismic reflection survey was conducted along the west bank of the C-38 Canal, near the proposed C-38S well cluster and at three other locations of interest to the ASR program. The survey report is provided in **Appendix D**. The seismic investigation successfully imaged the structural configuration of the FAS, including disturbed areas that might indicate fracturing.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

There is a significant potential role for applied geophysics regarding aquifer property characterization, especially at the wellfield scale. For example, 2D and 3D seismic surveys can provide information on storage zone integrity through identification of collapse zones that may be pathways for injectate to migrate vertically. These potential pathways, if present, could jeopardize the effectiveness of the ASR wells. Borehole geophysics such as vertical seismic profiles (VSPs), porosity-type logs, and ground-truthing through acquisition and hydrogeologic study of cores would inform seismic surveys and allow for improved post-processing to characterize subsurface properties in relation to ASR. Aquifer performance test data could be used to validate interpretive seismic results. Changes in water temperature could be used to ascertain whether these interpreted collapse zones are allowing upward fluid movement.

Proposed Plan for Future Studies

Exploratory Wells at C-38S and C-38N (2021-2022)

Cross-well seismic tomography and subregional seismic evaluation may be conducted at the C-38S and C-38N exploratory wells after they are constructed.

Land-based Seismic Geophysical Surveys (2022-2023)

Seismic surveys may be extended north of the previous survey area, toward the proposed C-38N well cluster, and at other sites under consideration for well clusters. Seismic surveys would be useful for comparative analyses between the well clusters. After cycle testing is conducted on the C-38S and C-38N clusters, the surveys may help determine optimal structural aspects of future cluster sites under consideration.

Additional Geophysical Surveys Under Consideration

Electrical Resistivity Tomography. Electrical resistivity is a geophysical exploration method that uses a pair of electrodes placed on the surface to pass currents through the ground. This process is referred to as electrical resistivity tomography (ERT) and may be conducted as 2D profiles or 3D volumes. It most often is conducted with surface electrode arrays but can be conducted with electrodes in one or more boreholes to conduct surface-to-borehole tomography or borehole-to-borehole tomography. ERT surveys commonly are used to map permeable zones of aquifers, map low-permeability confining units, identify fracture zones or faults, discriminate between saturated and unsaturated formations, and measure formation fluid conductivity as a proxy for water salinity. ERT works best to depths of a few hundred feet and has a practical limit of 500 to 750 feet. Below this depth, the resolution becomes low and the length of the required electrode arrays becomes too large for most applications. Other methods, such as electromagnetic induction, typically are more practical at greater depths.

Electromagnetic Induction. Electromagnetic induction (EM) is a family of geophysical methods that can accomplish many of the same objectives as ERT. EM methods commonly are used in groundwater studies when greater depths of investigation or more rapid data acquisition is needed. EM surveys fall into three broad categories: frequency domain EM, time domain EM, and magnetotellurics. Airborne frequency domain EM systems have been developed that can quickly survey hundreds of line miles per day with a typical exploration depth of a few hundred feet. Frequency domain EM methods have been supplanted in most groundwater studies by airborne time domain EM methods, which have better vertical resolution at the depths of concern for most groundwater studies. Typical exploration depths for time domain EM surveys are in the range of a few hundred feet to 1,000 to 2,000 feet. Time domain EM data typically are collected and interpreted as multicomponent (X, Y, and Z) data and interpreted in 3D. Unfortunately, the 3D component processing is arduous and beyond the budget of most groundwater studies. Time domain EM could be an attractive method to accomplish many objectives, though it will not work in highly developed areas. Magnetotellurics methods use natural, low-frequency EM signals generated in the upper atmosphere as a transmitter capable of producing lower-frequency EM energy than other methods. A modification of this method, the controlled-source audio frequency magnetotellurics method, uses a separate transmitter to add higher-frequency energy to extend the usable range to shallower depths. Magnetotellurics and controlled-source audio frequency magnetotellurics are most appropriate for deeper targets, in the range of several thousand feet.

Seismic Tomography. Seismic tomography describes a family of geophysical methods that image volumes of the subsurface from multiple angles to resolve the properties of the volume under investigation. Seismic tomography can be conducted using multiple source-receiver geometries, including borehole to borehole (cross-well seismic tomography), surface to borehole (VSPs), and surface to surface (full waveform inversion and specialized processing of traditional P-wave reflection). Each method has advantages and limitations, and each may play a different role in accomplishing the goals of groundwater studies. Cross-well seismic tomography is a variation of the seismic reflection method in which a string of geophones is placed in one or more boreholes and a seismic source is fired at various depths in an adjacent borehole. The method is particularly useful for producing high-resolution images of the data volume that can resolve layering, fractures, faults, and some formation fluid properties (water, gas, or air) in greater detail than can be achieved by most surface methods. While powerful, the method suffers from limitations of borehole spacing, generally limited by the strength of the seismic source that can be safely used in a borehole. However, the cross-well seismic tomography method can be modified to pair seismic source lines and geophone strings with the seismic source or the geophones on the surface with the other element in the borehole. This geometry generally is called a VSP. VSPs have the advantage of using stronger surface seismic sources or one or more lines of geophones on the surface that can greatly increase the volume of the subsurface that can be investigated. VSP data generally are higher resolution than typical surface seismic data, and the direct downhole seismic travel path provides accurate depth conversion for seismic data. VSP data can come close to the level of detail provided by cross-well seismic tomography, but over much larger subsurface volumes and at a much more practical cost.

Integration with Surface Seismic Surveys. Surface seismic reflection surveys can be conducted and processed in various ways to provide enhanced subsurface imaging. Collecting seismic data with three component geophones allows the data to be processed by full waveform inversion methods, which can create tomographic images of the subsurface with more detailed information on the distribution of lithology, rock integrity, and some formation fluid properties than standard surface reflection methods. This type of analysis is called amplitude versus offset and can be used to help identify fracture zones and faults. Amplitude versus offset may provide most of the data needed to resolve lithology, stratigraphy, fractures and faults, and some fluid formation properties.

3.6 NRC comment: Analysis of optimal wellfield cluster configurations and well spacing should be conducted to promote maximum recovery efficiency

Previous Investigations

The ASR pilot facilities constructed to date have been single well systems.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

Geometric ASR well arrangements that use triangles, double lines, or grids tend to trap native water between wells, thereby inducing mixing within the ASR storage zone. When operating a complex multi-well ASR system, it may be necessary to fully flush the ASR aquifer or zone between the first two wells, in the case of a triangle, before injection in the third well begins to avoid the mixing issue. This concept expands on typical buffer zone maintenance practices to improve recovery efficiency. The trapped water issue becomes more complex when using double lines or a grid. If the ASR storage zone has low TDS concentrations, there is no problem; however, as salinity in the ASR aquifer increases, the geometry problem becomes more acute. The trapped water issue can greatly reduce recovery efficiency.

In addition to well configurations, as new ASR wellfields are conceptualized, the PRP encourages consideration of hybrid approaches, including one or more of the following: bank filtration; aquifer storage, transfer, and recovery (i.e., recharge and recovery not using the same well); inter-aquifer transfer; wetland pre-treatment; or surface reservoirs. Hybrid approaches are advancing worldwide. A technical workshop focusing on emerging wellfield configurations and operational strategies would inform future decisions.

Proposed Plan for Future Studies

<u>Design Studies at C-38S and C-38N (2022-2023)</u>

Analysis of optimal wellfield cluster configurations will be accomplished through local-scale wellfield groundwater modeling after the exploratory wells are constructed and tested at the C-38S and C-38N sites.

3.7 NRC comment: Additional analysis of injection pressures on the propagation of fractures should be conducted, perhaps using step-rate tests that assess injectivity as a function of injection pressure

Previous Investigations

During construction of the ASR pilot projects and other CERP exploratory wells, conventional cores were collected and analyzed to assess rock strength and other physical properties of the FAS. The data were transformed and modeled to predict the potential for rock fracturing during injection. Those analyses were integrated into the regional groundwater model to use an operating wellhead pressure of 100 pounds per square inch as a limiting constraint on injection pressures and, ultimately, to reduce the number ASR wells that could be safely operated through CERP.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

Analysis indicated rock fracturing should not be a problem during normal operation of the regional ASR system. Results of the analysis seem conservative, especially above the UFA. There are improvements that could be realized in the analysis that likely would help evaluate the risk of unexpected movement of injected water.

Following the regional characterization of rock fracturing, minimal concern exists regarding fracturing through the overlying strata due to their modulus of elasticity; however, fracturing of the more brittle carbonate strata below the formation is a greater concern. Fracturing could increase the efficiency of injection or develop pathways for injectate migration and reduce recovery efficiency. To evaluate local fracturing during ASR, and as validation of previous fracture modeling, installation of a few high-sensitivity seismic geophones could provide a fracture monitoring strategy. The geophones also would provide data if collapse events occur.

Proposed Plan for Future Studies

Exploratory Wells at C-38S and C-38N (2021-2022)

Use of 100 pounds per square inch as a conservative limit for recharge (injection) pressure at individual wells should be sufficient to avoid inducing fractures. During construction of the exploratory wells, pumping tests will be conducted to ascertain the pumping effects on wells at varying distances to each other. The local-scale wellfield groundwater model should help determine distances between wells so as to not interfere significantly with each other. If the model indicates that collective pressures from multiple operational ASR wells within any one cluster are approaching the safe limit, downhole or high-sensitivity surface geophysics might be used to monitor the cumulative effects within a well cluster.

4 UNDERSTANDING PHOSPHORUS REDUCTION POTENTIAL

4.1 NRC comment: More research into long-term nutrient removal mechanisms and rates under varying aquifer conditions should be undertaken

Previous Investigations

During cycle testing at the KRASR system, observed nutrient concentrations were substantially reduced in recovered water compared to injected water. This effect had not been anticipated and has only been considered as a potential ancillary benefit of subsurface water storage. Subsequent desktop evaluations by the USACE indicated that processes of dilution, mineralogic uptake, or chemical transformation did not account for the extent of nutrient reduction.

Subsequently, the SFWMD contracted the USGS to assess a microbial component of nutrient uptake within the FAS. Results of the USGS evaluation on the uptake of nitrogen and phosphorus by subsurface biofilms were published in the peer-reviewed journal *Frontiers in Microbiology* in 2020 (Lisle 2020; **Appendix E**). The study indicated that microbial activity was capable of the observed nitrogen and phosphorus reduction.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

The PRP agrees that phosphorus removal during storage likely is caused by advective dilution, bacterial consumption, and most likely adsorption. The high potential for phosphorus to adsorb onto limestone has been demonstrated in laboratory tests (Price et al. 2010) and in shallow injection wells in the Florida Keys (Corbett et al. 2000). The precipitation of apatite is not anticipated to be a significant process based on the kinetics of the aquifer environment. Also, phosphorus can easily desorb from the bedrock with even small increases of chloride associated with saltwater intrusion (Flower et al. 2017), so monitoring of phosphorus with chloride concentrations during recovery is recommended.

The bioclogging column studies proposed by the USGS are a good step towards addressing the potential for phosphorus reduction. The PRP recommends geochemical modeling to assess the potential for phosphorus reduction and calcium carbonate dissolution/precipitation. The PRP understands the proposed testing is to be completed on cores and columns of FAS material collected from the exploratory borings in the UFA and APPZ. The PRP suggests similar testing be conducted for the water quality and microbial analyses during the injection, storage, and recovery phases of all ASR operations.

Proposed Plan for Future Studies

Continuous Cores (2021)

Scoping is under way for the USGS to conduct flow-through column experiments using portions of the continuous cores to document rates of native biofilm response to nutrient-laden surface water. This should further refine the rates and capacity for nutrient reduction and potential aquifer plugging from microbial biofilms during subsurface storage. The characterization may help estimate the maximum amount and duration of nutrient reduction if a "biomass plateau" is created within the aquifer during storage of nutrient-laden water.

The research infrastructure for the USGS bioclogging study will be used to conduct laboratory and field-based research related to the following:

- Determination of nutrient-holding capacities for specific storage zones at ASR facilities using established native biofilm communities grown on core material extracted from the same storage zones under study.
- Characterization of geochemical processes (e.g., changes in salinity between the recharged surface water and native groundwater) that influence nutrient adsorption/desorption rates from core materials.
- Characterization of biogeochemical processes (e.g., dissolved oxygen, oxidation-reduction potential, changes in salinity, carbonate dissolution) that influence rates of immobilization/mobilization of metals from core materials.
- Generation of biogeochemical data sets that will be used to refine existing models (e.g., Phosphorus Load Simulation Model) and develop new geochemical/reactive transport models for the fate and transport of nutrients, metals, and microorganisms.

Geochemical Modeling (2022-2023)

The primary objectives of the planned ASR geochemical program are to predict the quality of water recovered from ASR storage and to advance the physical, microbial, and geochemical understanding of ASR operations. Over 2 years, continuous cores will be obtained at up to four planned locations at the north end of Lake Okeechobee, extending to depths of approximately 2,000 feet below land surface. Approximately eight core sample segments, each about 1 foot long, will be selected from each corehole based on consideration of geophysical logs, photographs of each foot of core, field geologist notes, lithology, and packer test results. The segments will be sent to a core lab (Mineralogy, Inc. in Tulsa, Oklahoma) for detailed analysis using many different tests, resulting in a comprehensive lab report for each corehole. The report will enable a research geochemist to conduct a Geochemist's Workbench model analysis of the core data, relying on a comprehensive analysis of groundwater quality in each potential storage aquifer of interest, as determined from pump tests in the monitoring wells completed from each corehole. Recharge water quality and variability can be evaluated based on available data from each water source. Reasonable assumptions will be made regarding pre-treatment of the recharge water, mixing with native groundwater, and chemical reactions with the aquifer mineralogy.

Phosphorus Load Simulation Model (2022-2023)

In 2019, the SFWMD used the Phosphorus Load Simulation Model (a simple spreadsheet model) to estimate the reduction in phosphorus load to Lake Okeechobee due to implementation of LOWRP. The model indicated the ASR component would result in an annual phosphorus load reduction of approximately 4.1 metric tons. This estimate was conservatively computed based on the assumed volumetric recovery efficiency of the ASR, without recognition of a subsurface microbial or mineralogic uptake effect. Upon completion of the USGS column study (described above), the Phosphorus Load Simulation Model can be rerun to include documented rates and capacities of microbial phosphorus uptake.

Nutrient Monitoring During Cycle Testing (2024-2026)

When the new well clusters are constructed along the C-38 Canal and the KRASR well is operational, monitoring of phosphorus and nitrogen species will resume. A cycle testing monitoring program will be developed once the multi-well surface facilities are constructed. The monitoring plan will be reviewed by the PRP prior to submittal to the FDEP. During cycle testing, nutrient concentrations will be monitored in water recharged into the ASR well and at monitoring wells various distances away from the ASR well. The following variables will be tracked at each monitoring well, either by down-well sondes or at the wellheads:

- Temperature
- Salinity
- TDS
- pH
- Dissolved oxygen
- Oxidation-reduction potential

Additionally, to complement the data generated from the column studies previously described, (daily) grab samples may be collected for analyses of the following variables at the wellheads to generate a time series data set:

- Cations
- Anions
- Metals (including molybdenum)
- Nutrients
- Sulfates
- Sulfides
- Total carbon
- Dissolved organic carbon

Details of future studies beyond 2026 will be provided in subsequent updates of the ASR Science Plan as the ASR program progresses and additional information becomes available.

5 OPERATIONS TO MAXIMIZE RECOVERY

5.1 NRC comment: Improve/understand cycle tests to increase recovery efficiency

Previous Investigations

Cycle tests conducted on the KRASR pilot project indicated recovery efficiencies can be very high (>90%) if the ambient water quality in the UFA is moderately brackish, meeting surface water quality standards. Limited cycle testing conducted on the L-63N ASR well (completed in the APPZ) had relatively low (<20%) recovery efficiency due to highly brackish water and unusually high transmissivity within the storage zone (SFWMD and USACE 2013).

NRC and Peer-Review Panel Guidance

The NRC (2015) noted that additional work is needed to determine feasible recoveries in the UFA and APPZ at potential CERP ASR locations using a buffer zone maintenance approach and considering different storage periods.

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

As noted in **Section 3.6**, geometric ASR well arrangements that use triangles, double lines, or grids tend to trap native water between wells, thereby inducing mixing within the ASR storage zone. When operating a complex multi-well ASR system, it may be necessary to fully flush the ASR aquifer or zone between the first two wells, in the case of a triangle, before injection in the third well begins to avoid the mixing issue. This concept expands on typical buffer zone maintenance practices to improve recovery efficiency. The trapped water issue becomes more complex when using double lines or a grid. If the ASR storage zone has low TDS concentrations, there is no problem; however, as salinity in the ASR aquifer increases, the geometry problem becomes more acute. The trapped water issue can greatly reduce recovery efficiency.

There are concerns about water loss during recovery. Past studies of possible water recovery from long-term operating boulder zone injection wells showed poor results. Design modifications could be made to allow higher recoveries from these wells. The SFWMD ASR team should evaluate pros and cons of deep ASR wells based on surface water hydrologic modeling of extreme events.

Proposed Plan for Future Studies

Siting Evaluations for Multi-well Clusters (2020-2022)

In 2020, the SFWMD conducted well siting and constructability analyses on the proposed C-38S and C-38N cluster locations. The reports are provided in **Appendix F**. The evaluations indicated the ASR wells likely will be oriented in a relatively narrow, linear pattern within a limited right-of-way owned by the State (**Figure 5-1** and **Figure 5-2**). The limited available land at these sites will not allow construction of wellfields in patterns of triangles or double lines. However, use of a local-scale groundwater model may allow implementation of aquifer storage, transfer, and recovery and inter-aquifer transfer modes of operation for these systems to be considered.

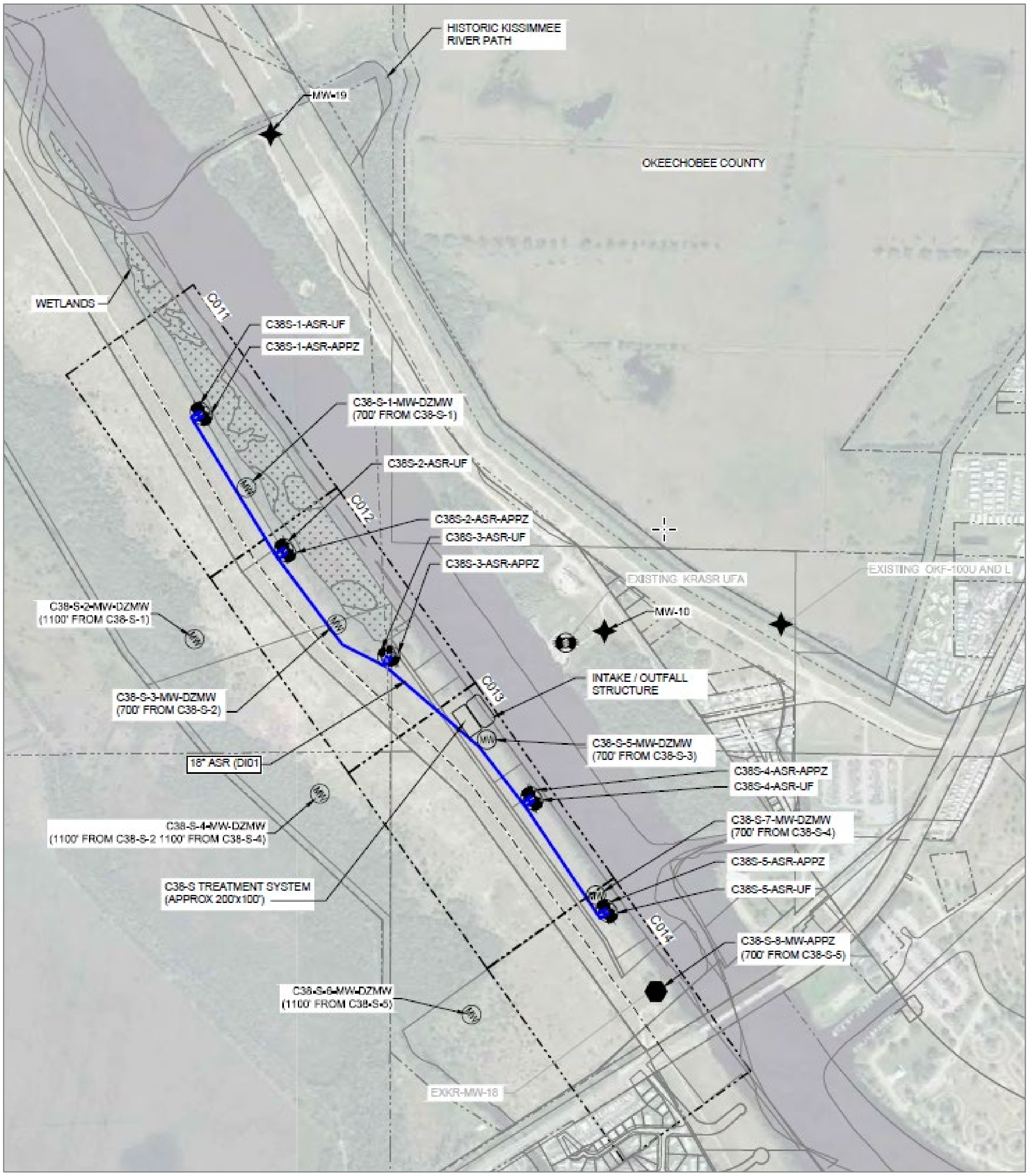


Figure 5-1. Conceptual layout of the C-38S ASR wellfield.

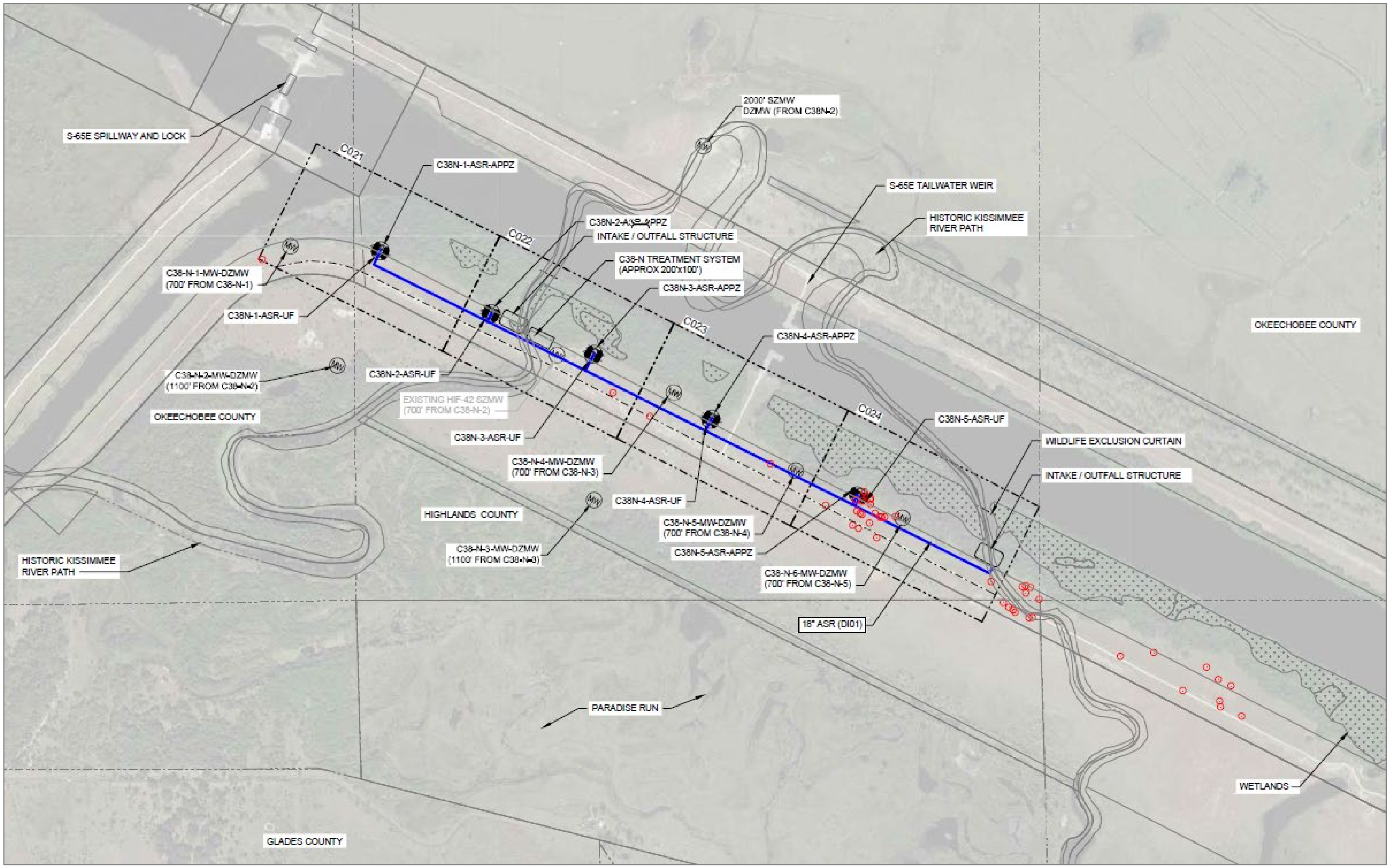


Figure 5-2. Conceptual layout of the C-38N ASR wellfield.

Cycle Testing (2024-2026)

To date, most cycle testing plans have centered around fully recovering the volume of water initially injected. While that approach is informative to quantify initial efficiencies of the system, it does not develop a buffer zone in an expedient manner. Future cycle testing plans at the wells along the C-38 Canal will be designed to allow recharge of an initial volume of water to form a buffer zone. Also, the APPZ is anticipated to contain higher salinity water than the UFA. Therefore, future ASR wells completed within the APPZ will need to be cycle tested with a long-term strategy to develop a buffer zone.

Consideration of Wells Completed Below the Underground Source of Drinking Water

The continuous core drilling program anticipates evaluating strata to depths of 2,000 feet below land surface. During these investigations, permeable material could be encountered at depths below the underground source of drinking water. If favorable storage zones are determined to exist below the underground source of drinking water, consideration will be given to using them as ASR wells.

5.2 NRC comment: Establish and maintain a freshwater buffer zone during cycle testing

Previous Investigations

Four test cycles conducted at the KRASR well from 2009 to 2013 resulted in recovery of a volume of water equal to or greater than the volume of water recharged. Thus, there was no development of a residual "bubble" of water left in the aquifer to create a buffer zone for subsequent cycles. Development of a buffer zone has been shown to improve recovery efficiencies as well as stabilize and neutralize non-conservative reactions such as arsenic mobilization. Recently, ASR systems across the country have indicated establishment and maintenance of a buffer zone storage volume from approximately 70 days of recharge is sufficient to improve recovery efficiency and minimize arsenic mobilization in brackish water (>3,000 milligrams per liter [mg/L] TDS) aquifers (Pyne 2005).

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

The concept of a buffer zone is most applicable to ASR systems that operate on an annual schedule to meet peak demand in public utility systems. Also, the buffer zone is a key factor in storage aquifers that contain brackish water because it increases the annual operational efficiency. Operational efficiency is commonly defined to include all water injected with a comparison of the water recovered to the goal TDS, including the water used to create the buffer zone. As it applies to ASR well systems, if the target aquifer is essentially fresh water, the use of a buffer zone is not essential. The wells will always have a high recovery efficiency because they exhibit the blended storage concept. In ASR wells located where brackish water occurs in the aquifer storage zone, a buffer zone is important, particularly if annual cycles of injection and recovery are anticipated (one injection and recovery period each year). A buffer zone is only effective if the storage aquifer rock has predominantly intergranular porosity. Where the transmissivity is very high and associated with channel pores (e.g., dual porosity), a buffer zone does not provide a clear operational advantage. The recovery efficiency will tend to remain low. In addition, as the salinity in the storage aquifer increases, the necessary buffer zone rises because more water needs to be displaced to prevent upward migration during rest/storage cycles. In the case of moderate- to high-salinity native groundwater, injection of more water than recovered is a common practice in order to create a buffer zone between the low- and high-quality water. Management of the volume and growth rate of the buffer zone could improve fouling issues, nitrogen and arsenic mobilization and transformation, and recovery efficiency.

Proposed Plan for Future Studies

Reactivation of the L-63N ASR Well (2022-2023)

The current efforts to reactivate the L-63N ASR well, completed in a highly brackish portion of the FAS, eventually will result in a request to initiate cycle testing in the permitting process. The proposed cycle testing program may include an initial period of recharge to establish and test the buffer zone concept. Future studies may determine if that mode of operation improves recovery efficiency and reduces arsenic mobilization.

5.3 NRC comment: Operate multi-well pairs and clusters to improve performance

Previous Investigations

To date, the ASR projects constructed at the Kissimmee River (KRASR), Hillsboro Canal, and L-63N Canal are single-well systems.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

The operation of well clusters is a good concept but requires special operational management. If a three-well cluster is used, only two wells can be used during the first injection cycle because if all three are used, a column of saline water (if present) may be trapped between the wells and cause extensive mixing and very poor recovery. The third well should be pumped only after the injection zone in that well is flushed of native water. This is not an issue where the aquifer water is close to fresh, but in brackish water systems, it is a major issue.

Proposed Plan for Future Studies

Exploratory Wells at C-38S and C-38N (2021-2022)

Operation of multi-well clusters at C-38S and C-38N is planned following completion of exploratory wells, design studies, and construction. The testing program will track the responses in monitoring wells installed at varying distances from the ASR wells as they are pumped.

Cycle Testing (2024-2026)

Inter-aquifer mixing and convergence of recharge water plumes will be addressed in the cycle testing plan. A local-scale groundwater model will be developed during design evaluations to estimate the size of recharge water plumes within the storage zone. The model will be calibrated to responses from the monitoring wells during the exploratory program and will be used to determine the volumes of water that should be recharged into the ASR wells during cycle testing to maximize recovery and minimize entrapment of poor-quality water between wells.

6 DISINFECTION/TREATMENT TECHNOLOGY

6.1 NRC comment: Examine treatment technologies to consistently meet regulatory requirements

Previous Investigations

During development of the CERP ASR pilot projects, evaluations were conducted that led to the decision to use combinations of filtration techniques and ultraviolet disinfection for the recharge water treatment process. At the Hillsboro ASR system, a series of 80-micron mechanical screens were coupled with two Amiad in-line ultraviolet chambers. At the KRASR system, a granular media filter coupled with three Amiad in-line ultraviolet chambers were employed. During cycle testing at both pilot systems, there were periods when the treatment systems were unable to fully reduce bacteria concentrations to applicable surface water quality standards.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

ASR wells are classified as Class V injection wells under the FDEP and United States Environmental Protection Agency underground injection control rules. The definition of an underground source of drinking water is any groundwater with a TDS concentration of 10,000 mg/L or less. Under the underground injection control rules, any water injected into an underground source of drinking water must meet all drinking water standards. This includes bacteria levels and many other parameters.

There are two potential strategies to meet these rules. The first is to treat the recharge water to meet all primary drinking standards and request exemptions for any secondary standard exceedances. This is the current direction the SFWMD and USACE are taking. Another approach would be to reclassify parts of the FAS (with buffers) to sole use as an ASR aquifer (with an aquifer exemption, as defined by the United States Environmental Protection Agency) and set appropriate standards that may exceed certain drinking water quality standards. Because the bacteria injected into the aquifer tend to die off rapidly and most arsenic and other regulated substances remain in the aquifer, the only water quality standards that would have to be met are those at the point of discharge back into the natural system. The “sole use” designation could save large amounts of capital and operating expenditures over the long term and would not pose any environmental risks.

Proposed Plan for Future Studies

Treatment Technology Evaluations (2020-2021)

In 2020, the SFWMD initiated a water treatment technology review to evaluate processes that could be used to meet regulatory requirements during water recharge and recovery. The processes under review included pressure and mechanical filtration, screens, exclusion barriers, membranes, cartridge filters, ion exchange, coagulation, chemical disinfection, pasteurization, oxidation, ultraviolet disinfection, ultrafiltration, and nanofiltration. Various combinations of those processes were systematically evaluated to determine the most optimal, efficient, and cost-effective configurations. The evaluations also included processes to protect ecologically sensitive species such as the manatee and to address concerns regarding fish entrainment. A draft copy of the report, which currently is under review, is included in **Appendix G**. A second phase of evaluation may be performed, including a short-term demonstration of the most optimal treatment processes concluded by the study. Based on the results of that second phase, the design of the well clusters along the C-38 Canal may be determined.

6.2 NRC comment: Develop appropriate pre-treatment strategies to attenuate arsenic mobilization

Previous Investigations

During cycle testing at the KRASR system, arsenic was mobilized within the UFA at distances greater than 1,000 feet from the ASR well, but not farther than 2,350 feet. Arsenic was recovered from the ASR well during the first test cycle but remained below the applicable surface water quality criteria during all subsequent test cycles. These results indicated arsenic mobilization was attenuated gradually as the aquifer matrix was subjected to repeated cycles of recharge and storage of fresh, minimally treated surface water.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

In hydrogeologic settings where arsenic is mobilized during ASR activities, the mechanisms of mobilization are understood well enough to employ pre-treatment mitigation measures. The PRP recommends the ASR team consider pre-treatment redox control of injected waters as it has been found effective in reducing arsenic concentrations. Redox control alternatives include use of reducing agents, membranes, catalytic oxygen removal, and degasification. The cost of such measures should be carefully analyzed to ascertain feasibility.

Investigations of water-rock interactions during ASR have focused on processes controlling a limited number of mobilized constituents. However, several metals besides arsenic, are mobilized during ASR, and while the concentrations do not exceed drinking water standards, their environmental effects are largely unknown. For all water quality analyses, the PRP suggests broad-spectrum hydrogeochemical analytical packages be used. These are cost-efficient, multi-method, multi-element analytical packages that provide robust information about constituents that may not be known concerns today. As scientific understanding continues, especially in the area of ecotoxicology, data within an expanded analyzed parameter list may become useful.

Based on results of ASR monitoring plans at each well and wellfield, a post-treatment action plan should be developed if the recovered water has high concentrations of arsenic, gross alpha activity, uranium, radium, or other constituents of concern.

Proposed Plan for Future Studies

Treatment Technology Evaluations (2020-2022)

As part of the ongoing treatment technology evaluation, a treatment process's ability to attenuate arsenic mobilization will be included in subsequent evaluation phases. A second phase of treatment technology evaluation is under development and likely will include demonstrations of multiple filtration and disinfection processes. Pilot system evaluation metrics probably will include chemical transformations that occur during treatment and might cause mobilization of undesirable constituents within the aquifer.

A comprehensive monitoring plan and QA/QC plan will be developed for each phase of the project. The primary and secondary drinking water standard analytes are included in the monitoring plan prepared for the first phase of the ASR program, continuous core drilling. Hydrogeochemical analytical packages will be analyzed to help model arsenic mobilization and other constituents.

Cycle Testing (2024-2026)

In addition to water treatment processes, the effects of using a buffer zone to minimize detrimental water quality effects (including constituents suggested by the PRP) in the aquifer will be evaluated during cycle testing. Details of future studies beyond 2026 will be provided in subsequent updates of the ASR Science Plan as the ASR program progresses and additional information becomes available.

6.3 NRC comment: Continue research on subsurface pathogen inactivation using a wider array of pathogens

Previous Investigations

Studies conducted to date by the USGS at the KRASR pilot project have shown that microbial indicator species remain viable for up to 90 days when subjected to anaerobic, aphotic conditions within the FAS. Pathogens used for previous studies have included *Escherichia coli* and MS2 (bacteriophage). In Open-File Report 2014-1011 (Lisle 2014), the USGS documented *E. coli* and *Pseudomonas aeruginosa* were naturally attenuated/inactivated after being subjected to water from the UFA. The number of organisms experienced an average log-3 reduction after 30 to 90 days. The report and subsequent publication in the *Journal of Applied Microbiology* (Lisle 2014) are included in **Appendix H**.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

Research by the USGS on microorganism die-off and fate of nutrients (e.g., Lisle 2014, 2020) should be continued with the purpose of addressing the NRC (2015) uncertainties related to water quality, nutrient reduction potential, and pathogens.

Proposed Plan for Future Studies

Pathogen Inactivation Studies (2020-2022)

The USGS recently performed additional pathogen inactivation studies utilizing the same experimental methodology as Lisle (2014) examining enterovirus and cryptosporidium. The work likely will be published in 2022. Previous studies provide documentation that surface pathogenic organisms do not persist in deep, saline, anoxic, aphotic aquifers. The studies confirm that disinfection pre-treatment processes at the surface may not be necessary.

Continuous Cores (2021)

Scoping is under way for the USGS to use segments of the continuous cores to conduct flow-through experiments documenting microbial response from sediment extracted from within deep aquifer conditions.

6.4 NRC comment: Couple pathogen inactivation studies to groundwater travel times and distances using local-scale groundwater modeling

Previous Investigations

As noted in **Section 6.3**, studies conducted to date by the USGS at the KRASR pilot project have shown that microbial indicator species (bacterial and viral) remain viable for up to 90 days when subjected to anaerobic, aphotic conditions within the FAS.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

USGS work should continue as planned to address the NRC (2015) uncertainties related to water quality, nutrient reduction potential, and pathogens.

Proposed Plan for Future Studies

Continuing USGS Studies of Pathogen Inactivation (2021)

USGS studies on pathogen inactivation are anticipated to be completed by the end of 2021 and result in a peer-reviewed journal publication by 2022. The results likely will determine conservative inactivation rates of a broad range of pathogens when subjected to conditions within the FAS. Those rates can be coupled with a local-scale groundwater model used for wellfield design to estimate zones within the aquifer where pathogens are likely to be active and where they are not.

Exploratory Wells at C-38S and C-38N (2021-2022)

Pathogen inactivation time and travel distance studies are anticipated to be done with local-scale groundwater models during wellfield design after the exploratory well pairs and associated monitoring wells are installed and tested, so the effects of aquifer anisotropy and heterogeneity can be assessed.

Bacteriophage Tracer Study (2024-2026)

To characterize the fate and transport of microorganisms during a cycle test, a bacteriophage tracer study may be conducted where a known concentration of bacteriophage is added to the recharge water. Samples will be collected from select monitoring wells to estimate the bacteriophage's movement and attenuation via adsorption during the recharge and storage phases of the cycle test. The recovered water may be sampled for the presence of bacteriophage to estimate the survival of these surrogates for microbial pathogens during storage in different zones of the UFA. Performance of this type of study will require underground injection control regulatory review and approval. Results of the evaluation may be coupled with groundwater models to estimate transport mechanisms, travel times, and travel distances of pathogens within the aquifer during recharge. Details of studies beyond 2026 will be provided in subsequent updates of the ASR Science Plan as the ASR program progresses and additional information becomes available.

7 ECOTOXICOLOGY AND ECOLOGICAL RISK ASSESSMENT

7.1 NRC comment: Locate ASR systems adjacent to large water bodies to allow for adequate mixing zones

Previous Investigations

To date, the ASR systems constructed by the SFWMD are located along the Kissimmee River (KRASR), the Hillsboro Canal, and the L-63N Canal. The systems were constructed along canals that convey large quantities of water during wet periods and offer substantial capacity for mixing with receiving water in the canal. National Pollutant Discharge Elimination System permits were obtained to allow for mixing zones of recovered water within the receiving water bodies.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

The primary avenues for impacts to fish at operational ASR facilities are thermal alterations to receiving waters and impingement/entrainment of early life stages of various species.

A warm plume in winter and/or a cool plume in summer may alter the spawning timing of some species in the vicinity of recovered water discharge. Table 8-7 of the ASR Regional Study Final Technical Data Report (SFWMD and USACE 2015) showed a qualitative risk associated with these effects but no mitigation strategy. ASR review should explore quantified risks and mitigation strategies, which need to be considered when discharge of recovered water is likely. ASR recovery probably would occur during low flows throughout the spring spawning period. Warm, highly oxygenated water being released in the winter is likely to attract species such as blue tilapia into the area and displace some cool season spawners such as largemouth bass and black crappie. Quantifying likely outcomes based on possible plume sizes and relative impact on system-level recruitment may be warranted. Tempering recovered water for temperature in addition to ensuring good oxygenation may be a desirable mitigation strategy if thermal effects are deemed detrimental.

As noted in Section 10.6 of the CERP Final Technical Data Report for the Kissimmee River ASR pilot project (SFWMD and USACE 2013), impingement and entrainment can be mitigated by intake design as well as the timing and diffusion of withdrawals during recovery. The testing of these alternatives offers an opportunity for adaptive management by monitoring for the presence of vulnerable organisms during recharge and recovery operations and considering altered withdrawal regimes if needed.

The SFWMD and USACE (2015) noted that oxygenated recovery water could attract fish during low ambient oxygen conditions and pose a kill risk if there was a sudden withdrawal of the oxygenated recovery water. This risk should be low at sites like KRASR if the recovery water is discharged during low-flow augmentation. Low oxygen concentrations in the lower Kissimmee River and canals typically occur during high stages when recharge/withdrawal activities most likely would be occurring, as opposed to discharge of recovered water. The PRP recommends having a site-specific monitoring protocol in place for this possibility.

Proposed Plan for Future Studies

Well Siting Evaluation and Exploratory Well Construction (2020-2022)

In 2020, the SFWMD conducted well siting and constructability analyses on the proposed C-38S and C-38N cluster locations (**Appendix F**). The results of these evaluations indicated that siting future well clusters along larger canals would be optimal for design of recharge and recovery components. Construction of exploratory wells at both cluster locations is expected to occur through 2022.

Mixing/Dilution/Dispersion Design Evaluations and Models (2023)

After construction of the exploratory wells along the C-38 Canal, design evaluations of the recharge (intake) and recovery (discharge outfall) structures will begin. Intake structures will be designed to minimize the potential for impingement and entrainment. Outfall structures will be designed to reduce undesirable physical and chemical impacts to the receiving water body. During design evaluations, mixing models will determine optimal ranges of recovered water volumes and dispersion durations to the receiving water body during dry, cool periods that minimize the thermal effects to biota.

Ecological Responses (2024-2026)

One possible impact highlighted during review of ASR studies is the potential for spawning season disruptions due to temperature alterations. Black crappie is an important commercial species that spawns in Lake Okeechobee; therefore, it can be a subject of long-term monitoring. Size-class distributions of black crappie are monitored annually in Lake Okeechobee, and monitoring could be expanded to include Kissimmee River locations. Long-term monitoring efforts could include electrofishing or trawl sampling during spawning at upstream and downstream locations as well as fry sampling post-spawn. Details of future studies beyond 2026 will be provided in subsequent updates of the ASR Science Plan as the ASR program progresses and additional information becomes available.

7.2 NRC comment: Additional bench-scale chronic toxicity testing using recovered water from multiple ASR sites should be performed, including changes in hardness and how that affects toxicity to sensitive aquatic species

Previous Investigations

Acute and chronic bench-scale toxicity tests were conducted at the Hillsboro and KRASR pilot facilities during the first two recharge and recovery test cycles to evaluate the aquatic toxicity and bioconcentration potential of source water prior to storage and of recovered water, using recharge (source), recovered, and laboratory (control) water treatments (SFWMD and USACE 2013). The recovery periods during test cycles 1 and 2 were relatively brief, lasting 39 days and 66 days, respectively.

The bench-scale toxicity tests were as follows:

- 96-hour chronic growth test with *Selenastrum capricornutum* (green algae)
- 7-day *Ceriodaphnia dubia* (water flea) chronic static-renewal toxicity
- 7-day *Pimephales promelas* (fathead minnow) static-renewal chronic embryo-larval survival and teratogenicity tests
- 21-day *Daphnia magna* (water flea) chronic static-renewal survival and reproduction test
- 96-hour frog embryo survival, malformations, and growth tests
- 96-hour *Ceriodaphnia dubia* (water flea) and *Cyprinella leedsi* (bannerfin shiner) survival tests

NRC Review Panel Guidance

The NRC (2015) noted that additional bench-scale chronic toxicity tests should be performed under a variety of conditions using recovered water from multiple ASR sites, considering longer storage times, greater storage volumes, and buffer zone formation, which could improve water quality and decrease toxic effects. Additional attention should be given to examining changes in water hardness in recovered waters and how that affects the toxicity to sensitive aquatic invertebrates.

Proposed Plan for Future Studies

Future toxicity testing approaches will be based on results of previous studies specifically addressing uncertainties related to the spatial and temporal scale of ASR discharges. Using previously selected organisms (and possibly other types of organisms) and standard toxicity tests used in the KRASR pilot study (SFWMD and USACE 2013), additional bench-scale chronic toxicity tests can be conducted under a variety of conditions with recovered water from multiple ASR sites. These tests may consider longer storage times, greater storage volumes, and buffer zone formation, which could improve water quality and decrease toxic effects. Studies can be designed to investigate primary sources of toxicity (e.g., sulfide). The tests also can determine how changes in water hardness in recovered waters affect the toxicity to sensitive aquatic invertebrate species. Initial modeling revealed the hardness of recovered water is likely to be higher than the receiving waters, thus potentially affecting sensitive aquatic species of plants, invertebrates, and periphyton in the Kissimmee River, Lake Okeechobee, and the Greater Everglades ecosystems. Tests can be conducted with varied ratios of recharge and recovered water from multiple ASR locations.

Because recovery of stored water can result in substantial changes to surface water chemistry, the quality of recovered water with longer storage times and larger storage volumes needs to be understood. Once the implications of storage on water quality characteristics have been determined, additional modeling can be conducted at local and regional scales to evaluate downstream effects under more realistic water quality assumptions. Additional toxicity and bioaccumulation tests can be conducted before ASR is implemented at a larger scale. The Lake Okeechobee Environment Model will be updated with the most recent water quality and sediment data before being used to assess the fate of recovered water within and downstream of the lake. Modeling also can include updates to new Kissimmee River flow targets and ASR configurations. If updated operations and configurations result in different temporal or spatial discharge patterns, then newer hydrologic modeling can better inform bench-scale toxicity tests (in terms of dilution levels and exposures times), local and downstream dilution factors, and eventually the overall ecological risk assessment. The goal is to use hydrologic modeling prior to exposure studies to refine treatment designs.

Baseline Testing from Exploratory Wells (2021-2022)

For toxicity testing, initial application of UFA water from the exploratory wells could provide a baseline of an organism's toxicity, growth, and survival responses. Assessing any changes in these responses (e.g., increased toxicity, decreased growth) that occur with exposure to recovery water would be helpful when the system is in operation. For reference, these response parameters in tests using groundwater from the aquifer may differ from those observed in the recovered water, which is critical to understand when comparing toxicity responses later in the process.

7.3 NRC comment: Continue chronic toxicity testing at points of discharge using larger, longer storage and recovery volumes

Previous Investigations

Chronic toxicity testing using an on-site mobile bioconcentration laboratory with a flow-through distribution system was conducted at the KRASR system (SFWMD and USACE 2013). The mobile laboratory was designed to be as flexible as possible to allow on-site testing of aquatic organisms of different sizes under variable conditions (e.g., exposure time, water quality conditions) using recovered and source waters. Additionally, the laboratory allowed flow-through access to source and recovered water in unlimited volumes. Fish and mussels were exposed to source water under flow-through conditions for 28 days to evaluate bioconcentration of selected trace metals and radium.

NRC Review Panel Guidance

The NRC (2015) noted that toxicity and bioconcentration of arsenic and trace metals likely would differ with a buffer zone approach, and more study is needed on the water quality and ecotoxicological effects under these conditions, including rigorous bench-scale chronic toxicity tests and *in situ* testing over extended time periods.

Proposed Plan for Future Studies

Additional toxicity and bioaccumulation studies focused on arsenic and other select trace metals can be developed with laboratory/mesocosm or *in situ* field approaches to determine longer-term impacts on relevant bioindicators (e.g., mussels). The tests can be completed at multiple wells to examine differences in local groundwater chemistry during the recovery process and effects of storage duration and recovery volume.

7.4 NRC comment: Examine the *in situ* and community-level impacts of recovered water hardness on soft-water areas of the Everglades, considering bioaccumulation and potential shifts in community composition

Previous Investigations

Hydrologic and water quality modeling was conducted to assess the ecological impacts of ASR considering several different well placement scenarios in the Lake Okeechobee basin (SFWMD and USACE 2013). Water quality data inputs were based on an assessment of UFA groundwater quality at the KRASR site, SFWMD surface water quality data, and KRASR recovered water quality. Water quality modeling using the Lake Okeechobee Environment Model showed ASR induced notable increases in sulfate concentrations, hardness, and chloride concentrations, particularly during long ASR recovery events (during dry periods, when lake level would be at low stage), in a multidecadal simulation. However, the model considered several excessively conservative scenarios that are of limited usefulness, except to illustrate worst-case scenarios.

NRC and Peer-Review Panel Guidance

The NRC (2015) commented that potential ecological impacts from increased water hardness should be examined at different ASR locations and discharge points. There is evidence that calcium and elevated mineral content have significant impacts on wetland plant communities, with documented impacts on the diversity of periphyton communities in the Everglades (Harvey and McCormick 2009, Swift and Nicholas 1987) and implications for fish species and food webs (Williams and Trexler 2006).

The PRP noted more research is needed into the ecological and ecotoxicological impacts of discharging ASR recovered water to the Kissimmee River, Lake Okeechobee, the Greater Everglades, and canals (Arthur et al. 2020; **Appendix B**).

Proposed Plan for Future Studies

Because past hydrologic modeling considered several conservative scenarios that are of limited use for this application, additional modeling with updated hydrologic models and the Lake Okeechobee Environment Model can be performed to test the effect of recovered water on the downstream soft-water areas of the Greater Everglades, especially in the Arthur R. Marshall Loxahatchee National Wildlife Refuge and northern water conservation areas. Based on the outcomes of these updated modeling scenarios, a set of bioaccumulation laboratory and mesocosm experiments can be designed. These experiments could examine representative organisms from different trophic levels and effects of exposure to water of different mineral concentration treatments (e.g., calcium, magnesium).

Designs of future studies regarding the impacts of water hardness on community-level responses will be informed by multiple lines of evidence, including an updated Lake Okeechobee Environment Model, existing scientific literature, an existing ASR ecotoxicity database, and environmental tolerances of species of concern. Additionally, a conceptual site model to communicate potential interactions between the alteration of exposures (due to varying water hardness) and receptors (i.e., species of concern) will be developed.

7.5 NRC comment: Prolonged *in situ* bioconcentration studies should be conducted using mussels, periphyton, and/or algal communities

Previous Investigations

Bioconcentration tests were conducted at the KRASR system using freshwater mussels (*Elliptio buckleyi*) and bluegills. The studies were conducted during test cycle 1, for a period of 28 days, using mixtures of ASR recovered water and receiving/recharge water (Kissimmee River) at percentages of 100% recovered water, 100% receiving/recharge water, and a 50/50 blend of both waters. Laboratory control water prepared with reverse osmosis water was used to ensure the testing conditions were adequate for the test species. Additionally, *in situ* bioconcentration studies were conducted using freshwater mussels (*E. buckleyi*) at four locations in the receiving water (Kissimmee River) during cycle test 2, for a period of 69 days. Two stations were directly in the mixing zone of the discharged recovered water, and the other two stations were upstream and downstream of the KRASR point of discharge. The objective of these tests was to evaluate the potential bioaccumulation of metals and radionuclides in the tissues of mussels and bluegills.

NRC Review Panel Guidance

The NRC (2015) noted that results from the laboratory bioconcentration studies suggest additional *in situ* bioconcentration tests are needed, ideally in conjunction with community composition analyses to simultaneously monitor bioconcentration and community-level responses. In addition to using caged mussels, bioconcentration studies using periphyton and/or algae are recommended because of their importance to trophic transfer in food webs. Different spatial and temporal contexts should be considered, and more prolonged bioconcentration tests (>69 days) are needed. If significant accumulation occurs in mussels, periphyton, and/or algae, then tissue concentrations should be interpreted in light of invertebrate health and the health of organisms that consume them (e.g., predators, grazers). These findings, and the interdependence of species and trophic guilds, could influence the regional scaling of the risk analysis.

Proposed Plan for Future Studies

Bioconcentration Studies (2023-2026)

During operation of the LOWRP ASR wells, periods of recovery may last several months and possibly up to 1 year. Therefore, longer (>69 days) *in situ* exposure studies using periphyton, caged mussels (*E. buckleyi*), Florida apple snails, and black crappie fish will be conducted at stations upstream of C-38N and downstream of C-38S and C-38N, in the mixing zone of the recovered water, to study bioconcentrations and community-level (in case of periphyton) responses to recovered water. The studies will be conducted before construction for baseline data and during operation of ASR facilities.

Periphyton are a multifaceted group of cyanobacteria, algae, protozoa, and organic debris, dominated by phototrophic microorganisms attached to submerged surfaces in most aquatic ecosystems. Periphyton are a fundamental part of the Everglades (and other ecosystems) food web as the primary food source for small consumers, including fish and invertebrates (Azim et al. 2005, Gaiser 2009). Periphyton can remove toxic substances, nutrients, and metals from water and consequently can be very useful in ecotoxicological studies. Periphytometers can be deployed along a transect, with the control sites positioned north of the proposed C-38N ASR facility, and several other sites positioned between C-38S and C-38N, south of the C-38S ASR facility, and extending into Lake Okeechobee (receiving water body), with the total number of sites dependent on the final study design. Multiple sampling events can occur before, during, and after the exposure period to examine the effects of recovered ASR water on this crucial food web component.

The Florida apple snail also is an important component of the Everglades food web. It is the sole food source for the federally endangered snail kite, and an important dietary component of other birds, fish, reptiles, and mammals (Sharfstein and Steinman 2001). Apple snails, as with other molluscan species, are promising bioindicators and biomonitors and have been used to assess the impacts of heavy metals in aquatic ecosystems. As part of the ecotoxicology testing and bioaccumulation studies for the ASR Science Plan, apple snails will be one of the representative receptors monitored for an assortment of heavy metals within the receiving water bodies. Sampling can be conducted at the same locations as the periphyton studies.

Florida shiny spike mussels (*E. buckleyi*) can be deployed in cages at the same locations, with setup and methodologies similar to those used during the KRASR cycle 2 *in situ* pilot study (SFWMD and USACE 2013), to capture bioconcentration responses to longer exposures (>69 days).

Paradise Run is proposed for wetland restoration as part of LOWRP (**Figure 1-1**). Discharging recovered ASR water into the wetland could provide an opportunity to conduct bioconcentration tests (*in situ* and utilizing existing and constructed mesocosm facilities) with existing wetland flora and fauna and monitor community-level responses to varying recovery water dilution (with source water) scenarios.

Designs of future studies will be informed by existing scientific literature, an existing ASR ecotoxicity database, ecological risk assessment data, and updated exposure models.

7.6 NRC comment: A refined ecological risk assessment, probabilistic in nature, should be conducted using robust data from multiple sites and modernized quantitative methods

Previous Investigations

The ecological risk assessment conducted for the ASR Regional Study Final Technical Data Report (SFWMD and USACE 2015) followed the United States Environmental Protection Agency's (1998) guidance on ecological risk assessment studies. The methodology involved determining a series of chemical and physical stressors and receptors and evaluating the likelihood of their encountering via a conceptual model.

NRC and Peer-Review Panel Guidance

The NRC (2015) noted that future approaches to a regional ecological risk assessment should draw from extensive recent literature that builds upon the United States Environmental Protection Agency's (1998) early guidance document, which provides robust quantitative risk assessment approaches to other complex regional issues. By clarifying particular attributes of specific entities (e.g., the number of bluegill reproducing in a receiving stream) that could be adversely affected by regional ASR, risk-assessment models could generate explicit probabilities of various outcomes (Suter et al. 2005). The risk assessment should provide clear guidance based on these probabilities of risk for different ASR scenarios and a quantitative evaluation of the inherent uncertainties associated with these conclusions.

The PRP (Arthur et al. 2020; **Appendix B**) also had concerns regarding the timing of discharges to the ecosystem, which will be driven by what volume of recharge and recovery is realized and how that can work with the Lake Okeechobee operating schedule. The PRP suggested a population-level approach to modeling impacts on fish populations and communities, as described in Suter et al. (2005).

Proposed Plan for Future Studies

The quantitative ecological risk assessment will incorporate all chemical, toxicity, bioaccumulation, and other data collected throughout the project (past and future studies) and available through relevant peer-reviewed literature into a comprehensive assessment to define the suitable receptor (e.g., periphyton, aquatic invertebrates, fish, amphibians) attributes based on the conditions expected in the modeled ecosystems. By combining relevant and updated information from research and studies in literature with extensive feedback from stakeholders, agencies, and experts from academia and the PRP, the most appropriate quantitative ecological risk assessment model approach will be determined. Feedback from the Ecological Risk Assessment Working Group will be needed to determine which receptors, ecosystems, and population variables are most important to consider as part of the risk assessment. The Working Group consists of SFWMD and USACE representatives as well as external subject matter experts representing a range of stakeholder interests. The Working Group will be tasked with the cooperative development of a comprehensive ecological risk assessment work plan. The work plan will follow guidance from the United States Environmental Protection Agency and provide a detailed strategy to complete the ecological risk assessment process (i.e., problem formulation, risk analysis, and risk characterization). The problem formulation step will incorporate much of the data collected in support of the original ecological risk assessment, including more quantitative analyses of the data. The work plan also will include a data gaps analysis and new data collection study plans to fill the data gaps identified by the Working Group.

Based on this information and feedback received from the Working Group, appropriate models will be selected to assess and predict interactions of the ASR operations and surrounding ecosystems. The risk assessment endpoints will be based on receptor populations and will be predictive and probabilistic in nature, using the expected operational parameters of the wells.

8 WATER QUALITY

8.1 NRC comment: More research is needed to understand the impacts of different source water qualities on the long-term redox evolution of the aquifer and its effect on arsenic mobilization

Previous Investigations

Numerous studies have been conducted on the geochemical aspects of the FAS associated with arsenic mobilization. Findings have been published in peer-reviewed publications and agency documents, including Petkewich et al. (2004), Mirecki (2004, 2006), Mirecki et al. (2013), SFWMD and USACE (2013), and Geddes et al. (2018).

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

As noted in **Section 6.2**, investigations of water-rock interactions during ASR have focused on processes controlling a limited number of mobilized constituents. However, several metals besides arsenic are mobilized during ASR, and while the concentrations do not exceed drinking water standards, their environmental effects are largely unknown. For all water quality analyses, the PRP suggests broad-spectrum hydrogeochemical analytical packages be used. These are cost-efficient, multi-method, multi-element analytical packages that provide robust information about constituents that may not be known concerns today. As scientific understanding continues, especially in the area of ecotoxicology, data within an expanded analyzed parameter list may become useful.

Work on ASR geochemical processes is central to understanding mobilization and/or fixation of chemicals of concern. Geochemical investigations by the USACE should continue to be supported, including recommended isotopic fractionation studies. The PRP recommends a future ASR plan include more water chemistry measurements related to monitoring recovered ASR waters. Routine determination of isotopic ratios of nitrogen, arsenic, oxygen, hydrogen, and sulfur measurements over time should assist in understanding the microbial processes responsible for fixation and mobilization.

Proposed Plan for Future Studies

Sampling and Analysis of Surface Water and Groundwater for Redox-sensitive Constituents and Isotopic Fractionation (2024-2026)

The redox condition of surface water and groundwater is defined by systematic quantification of terminal electron accepting processes; i.e., the dissolved constituents that accept electrons as the water quality evolves from oxic (surface water) to reduced (native groundwater). There are routine geochemical analyses (dissolved oxygen, nitrate, iron, manganese, sulfate/sulfide, and methane) that, as a collective, are used to quantify the redox condition. However, all constituents must be analyzed in each water sample obtained during cycle testing to completely characterize the redox environment. For example, transition metal analyses, at parts per billion detection levels, must be included with redox-sensitive species. These metals (e.g., molybdenum, vanadium, arsenic) occur in sulfide minerals in FAS lithologies and are released during pyrite oxidation.

Many South Florida monitoring wells have stable isotope analyses of native FAS groundwater. The SFWMD's Regional Floridan Groundwater Monitoring program has developed a groundwater quality characterization database for all aquifers in the FAS. These data will serve as a basis for the use of stable isotopes in mixing studies. A comprehensive redox sensitivity monitoring program to occur during cycle testing can be prepared following geochemical benchtop modeling studies and findings from the exploratory well sampling program. The monitoring program will include analyses for species of arsenic, radionuclides, molybdenum, vanadium, and other constituents based on the benchtop studies that could be mobilized during changes in redox potential during recharge, storage, and recovery.

8.2 NRC comment: Determine how far arsenic can be transported within the aquifer using extended (>1 year) cycles and development of a buffer zone

Previous Investigations

The largest test cycle (#4) at the KRASR pilot project consisted of 7 months of recharge (at 5 million gallons per day), followed by nearly 1 year of storage and 6 months of recovery. There was no buffer zone within the aquifer prior to this cycle. During the cycle, arsenic concentrations increased to approximately 50 parts per billion at a monitoring well 1,100 feet from the ASR well. There was no detectable trend of arsenic in monitoring wells 2,560 and 4,200 feet from the ASR well.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

Management of the volume and rate of growth of the buffer zone could assist in improvement of fouling issues, nitrogen and arsenic mobilization and transformation, and recovery efficiency. Investigating clustering of ASR wells could be helpful in increasing the extent of the freshwater buffer zone in the aquifer and reducing arsenic mobilization.

Proposed Plan for Future Studies

Cycle Testing (2024-2026)

The cycle testing plan will incorporate longer duration, larger volume recharge and storage phases. Typical cycle tests eventually will span multiple years.

Preliminary designs of proposed ASR systems at C-38S and C-38N include monitoring wells on both sides of the Kissimmee River. The proposed ASR system at C-38S is adjacent to the existing KRASR system and incorporates existing monitoring wells into a new system design. Thus, the monitoring wellfield at both ASR systems will enable detection of recharged surface water at greater distances than was possible during cycle testing at the KRASR site.

Although cycle testing schedules have not been developed yet, a guiding paradigm for cycle testing at the LOWRP ASR systems is that onset of recharge and recovery will be tied to lake levels. Although wet season recharge and dry season recovery occur on annual schedules, LOWRP ASR systems will have greater operational flexibility due to conjunctive use of the wetland attenuation feature. Greater operational flexibility will allow for longer duration, larger volume recharge and storage phases.

Buffer zone development can be readily incorporated into the cycle testing plans at the proposed LOWRP ASR systems. In fresher portions of the UFA, the buffer zone will be characterized by non-conservative constituents such as carbonate alkalinity or sulfate, rather than chloride. In brackish portions of the UFA, buffer zone composition will be based on contrasting chloride concentrations between native groundwater and recharged water, which will supplement the non-conservative constituents. In the APPZ, buffer zone development will be controlled to a greater extent by aquifer characteristics due to fracture permeability.

8.3 NRC comment: Determine how development of a buffer zone can reduce sulfate concentrations in recovered water, or determine limits on recovery based on sulfate concentrations

Previous Investigations

As noted in **Section 5.2**, the four test cycles conducted at the KRASR project resulted in recovery of a volume of water equal to or greater than the volume of water recharged. Thus, there was no development of a residual “bubble” of water left in the aquifer to create a buffer zone for subsequent cycles. Development of a buffer zone has been shown to improve recovery efficiencies, stabilize and neutralize non-conservative geochemical reactions taking place within the subsurface, and reduce concentrations of metals recovered during later cycles.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

Sulfate loading can enhance methylmercury production in the Everglades (Orem et al. 2011). As sulfate concentrations have been found to be higher in recovered ASR waters compared to the receiving water body, the PRP recommends monitoring sulfate in recovered waters and investigating the effects of added sulfate to receiving wetlands, canals, and Lake Okeechobee in relation to methylmercury production in water, soils, and biota in those areas. The potential need for post-treatment or dilution of high sulfate concentrations in the recovered water should be considered because of sulfate’s reactivity with mercury species in the Everglades.

Proposed Plan for Future Studies

Cycle Testing (2024-2026)

At the KRASR site, even though native UFA water is fresh, sulfate concentrations (approximately 180 to 200 mg/L) exceed those in Kissimmee River surface water (approximately 20 to 40 mg/L). Cycle testing at KRASR (2010 to 2014) was largely exploratory because it was the first ASR system with a capacity of 5 million gallons per day located in an interior location. Now that water quality patterns are reasonably well understood at the scale of a single system, LOWRP ASR systems will provide the opportunity to characterize trends at a subregional scale. This includes strategies to reduce recovered volumes during successive cycles, enabling development and characterization of buffer zones in the aquifer, at locations having different groundwater quality characteristics. Buffer zone composition is a mixture of native groundwater diluted by recharge water. Progressive development of a buffer zone with lower sulfate concentrations, coupled with larger volume recharge phases will minimize sulfate discharge into surface water environments. A comprehensive monitoring program to occur during cycle testing can be prepared following geochemical benchtop modeling studies and findings from the exploratory well sampling program. Details of future studies beyond 2026 will be provided in subsequent updates of the ASR Science Plan as the ASR program progresses and additional information becomes available.

8.4 NRC comment: Further modeling on the fate of sulfate in recovered water should be conducted, along with additional study on the temporal and spatial variability of sulfate and mercury methylation in Lake Okeechobee

Previous Investigations

Results from ASR pilot studies indicated mercury and methylmercury concentrations declined to the minimum detection limit (well below regulatory criteria) during the storage phase of ASR cycle testing. There was no evidence of increased mercury methylation during ASR cycle testing. However, the potential impacts of sulfate and other water quality constituents (e.g., iron, dissolved organic matter) on mercury methylation and bioaccumulation in downstream waters were not investigated.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

The PRP is concerned that non-methylated mercury may be introduced into downstream waters and recommends that recovered waters be analyzed for total mercury as well as sulfate due to sulfate's connection with mercury methylation (Orem et al. 2011). Results from previous studies are encouraging in that methylmercury concentrations are low in the FAS and in recovered ASR waters (SFWMD and USACE 2013). However, microbial sulfate reduction under anoxic conditions has been found to enhance mercury methylation, the most toxic form of mercury that bioaccumulates in the food chain (Gilmour et al. 2011). As noted in **Section 8.3**, sulfate loading can enhance methylmercury production in the Everglades (Orem et al. 2011). As sulfate concentrations have been found to be higher in recovered ASR waters compared to the receiving water body, the PRP recommends monitoring sulfate in recovered waters and investigating the effects of added sulfate to receiving wetlands, canals, and Lake Okeechobee in relation to methylmercury production in water, soils, and biota in those areas. The potential need for post-treatment or dilution of high sulfate concentrations in the recovered water should be considered because of sulfate's reactivity with mercury species in the Everglades.

Proposed Plan for Future Studies

Lake Okeechobee Environment Model (2022-2024)

The Lake Okeechobee Environment Model can be updated with the newest water quality and sediment data to assess the fate of recovered water within and downstream of Lake Okeechobee. Modeling may include updates for new Kissimmee River flow targets and ASR configurations. If updated operations and configurations result in different temporal or spatial discharge patterns, then newer hydrologic modeling can be used to improve bench-scale toxicity tests, local and downstream dilution factors, and eventually the overall ecological risk assessment. Results from the modeling efforts can inform chronic toxicity testing, in terms of dilution levels or/and exposures times.

Cycle Testing (2024-2026)

A more effective method of limiting sulfate discharge in recharge water is to develop a buffer zone with a lower sulfate concentration, so that a greater fraction of naturally occurring sulfate remains in the aquifer. This is an operational optimization that can be tested over a few cycles, during which some fraction of recharged water remains in the aquifer. Additional modeling should focus on sulfate trends in the aquifer, which are simpler to execute compared to regional surface water quality simulations. However, increased sulfate in surface water systems could be a focus of the ecological risk assessment.

Additional Studies

The following additional studies may be conducted:

- Laboratory incubation of sediment cores taken from downstream of proposed ASR wells with recovered water and marsh water to obtain a series of sulfate concentrations from low (2 mg/L) to high (30 to 40 mg/L)
- Mesocosm experiments at a site downstream of the proposed ASR wells to examine mercury methylation rates and various sulfate dosing treatments under ambient environmental conditions
- Monitoring of water quality parameters along impacted areas of proposed ASR well discharges to understand relationships between recovered water constituents (e.g., sulfate, iron, dissolved organic matter) and methylmercury production and bioaccumulation in fish
- Modeling of wetland responses to mercury methylation from recovered water discharges with existing sulfate, iron, dissolved organic matter, and methylmercury data (water and mosquitofish) from South Florida wetlands

8.5 NRC comment: More understanding on the spatial variability of gross alpha and radium at future ASR locations should be addressed during longer-term testing

Previous Investigations

Radium isotopes (Ra^{224} and Ra^{226}) are one of the few constituents not released through water-rock interactions during cycle testing. Instead, radium appears in recovered water as the result of mixing with native groundwater. The source of radium in native UFA groundwater samples from southwestern coastal areas of Florida is the uranium (U^{238}) decay series (Ra^{226}) and thorium (Th^{232}) decay series (Ra^{224}). High concentrations of uranium and thorium occur in highly insoluble, detrital phosphate minerals at the base of Hawthorn Formation sediments, particularly in southwestern Florida coastal counties. Alpha-recoil during uranium and thorium decay creates minute crystal defects in phosphate minerals, through which radium is released to groundwater. Both radium isotopes remain dissolved as a divalent ion in native groundwater and may exceed drinking water standards in some areas.

Peer-Review Panel Guidance

The following guidance was provided by the PRP in its 2020 report (Arthur et al. 2020; **Appendix B**).

Elevated concentrations of gross alpha and radium have been observed in water collected from some ASR systems in southwestern Florida. Water recovered from the KRASR system did not indicate concentrations of these constituents above background levels. However, due to the high degree of variability in concentrations observed regionally, monitoring of these constituents at future ASR locations is warranted.

Proposed Plan for Future Studies

Baseline Condition Monitoring (2022-2024)

Ambient groundwater samples may be collected at existing and exploratory locations proposed for ASR clusters, if recommended by the SFWMD ASR team, to establish specific baseline conditions.

Cycle Testing (2024-2026)

Generally, radium isotope analyses are merited when the gross alpha measurements meet or exceed the drinking water standard (15 picocuries per liter) in native groundwater samples. As a routine part of native groundwater quality characterization at proposed exploratory boreholes, gross alpha and radium isotope analyses should be included as part of the analytical suite. If gross alpha and radium isotope analyses meet or exceed their respective drinking water standards in native groundwater, then cycle testing strategies must include an option to minimize radium in recovered water. Because radium shows conservative behavior (except in groundwaters having very high sulfate concentrations), radium mitigation would be best accomplished through buffer zone development, leaving radium as it occurs naturally in the aquifer. Details of future studies beyond 2026 will be provided in subsequent updates of the ASR Science Plan as the ASR program progresses and additional information becomes available.

9 PLANNING-LEVEL COST ESTIMATE AND ASR WELL COST-BENEFIT ANALYSIS

9.1 PLANNING-LEVEL COST ESTIMATE FOR THE ASR SCIENCE PLAN

Planning-level cost estimates were prepared for the research activities described within this ASR Science Plan (**Table 9-1**). The cost estimates are based on recently conducted studies for other projects and programs within the SFWMD and are for planning purposes. The estimates are subject to change and will be updated annually as the ASR program progresses.

9.2 ASR WELL PROGRAM COST-BENEFIT ANALYSIS

The NRC (2015) review recommended analyses be undertaken to compare capital and long-term operating costs of ASR to other storage alternatives. “These analyses should consider existing uncertainties related to recovery efficiency, disinfection technology required, and the potential for gravity (artesian) flow of water recovered from ASR wells. Decision makers are unlikely to support continued research on ASR without clear documentation of potential benefits of ASR relative to other possible alternatives” (NRC 2015). As the ASR program is implemented and augmented with results from the ASR Science Plan studies, a thorough analysis of the capital, operational, and maintenance costs of ASR will be conducted. The ASR cost-benefit analysis most likely will be performed in 2023 when the treatment technology evaluation is completed and integrated into the well cluster surface facilities design. Costs can be evaluated by comparing the environmental, ecologic, and water supply benefits provided by the technology to the benefits of potential alternatives. The ASR program cost-benefit analysis will be presented during the annual progress review public workshops and in future updates of the ASR Science Plan.

Table 9-1. Planning-level costs estimates for the 2021 ASR Science Plan.

Research Activity	Estimated Cost by Fiscal Year					Total Cost
	FY21	FY22	FY23	FY24	FY25	
Future Construction and Testing (Chapter 3)						
Seismic/Geophysical Evaluation		$270,000	$200,000			$470,000
Fracture Porosity Assessment	$64,572	$200,024	$159,738	$25,944		$450,278
Geochemical Benchtop Modeling		$25,000				$25,000
Optical Borehole Image Logging	$30,287	$60,000	$60,000	$60,000		$210,287
						$1,155,565
Understanding Phosphorus Reduction Potential (Chapter 4)						
Nutrient Column Studies (Bioclogging)	$280,028	$187,098				$467,126
						$467,126
Operations to Maximize Recovery (Chapter 5)						
Mixing Zone/Dispersion Model (Recovery)		$60,000				$60,000
						$60,000
Disinfection/Treatment Technology (Chapter 6)						
Pathogen Inactivation Support Risk Assessment		$50,000	$50,000	$50,000	$50,000	$200,000
						$200,000
Ecotoxicology and Ecological Risk Assessment (Chapter 7)						
Risk Assessment	$55,000	$75,000	$75,000	$130,000	$130,000	$465,000
Bench-Scale and Mesocosm Chronic Toxicity and Bioaccumulation Studies	$10,000	$400,000	$80,000	$80,000	$80,000	$650,000
Bioaccumulation Assessment Field Studies	$10,000	$215,000	$300,000	$300,000	$300,000	$1,125,000
Modeling	$15,000	$235,000		$75,000	$100,000	$425,000
						$2,665,000
Water Quality (Chapter 8)						
Enhanced Monitoring During Cycle Testing		$100,000	$200,000	$200,000	$100,000	$600,000
Sulfate/Methylmercury Studies		$200,000	$300,000	$250,000		$750,000
Gross Alpha/Radium Monitoring		$50,000	$50,000	$50,000		$150,000
						$1,500,000
ASR Peer-Review Panel						
Scientific Panel	$45,000	$45,000	$45,000	$45,000	$45,000	$225,000
Quality Assurance/Data Management Systems	$45,000	$45,000				$90,000
						$315,000
Total by Fiscal Year	**$554,887**	**$2,217,122**	**$1,519,738**	**$1,265,944**	**$805,000**	**$6,362,691***

* This is a planning-level cost estimate and does not include contingency. Cost is based on 2021 dollars and does not include future inflation escalation. Each cost estimate will be finalized upon detailed scoping of each task. Cost information was assembled by SFWMD staff based on best available information.

REFERENCES

Arthur, J.D., R. Hyle, T.M. Missimer, R.M. Price, and S.B. Upchurch. 2020. Aquifer storage and recovery peer review panel final report. Submitted to the South Florida Water Management District, West Palm Beach, FL. November 12, 2020. 25 pp.

Azim, M.E., M.C. Verdegem, A.A. van Dam, and M.C. Beveridge. 2005. Periphyton: ecology, exploitation and management. CABI.

Corbett, D.R., L. Kump, K. Dillon, W. Burnett, and J. Chanton. 2000. Fate of wastewater-borne nutrients under low discharge conditions in the subsurface of the Florida Keys, USA. Marine Chemistry 69(1-2):99-115.

Flower, H., M. Rains, D. Lewis, J.Z. Zhang, and R. Price. 2017. Saltwater intrusion as potential driver of phosphorus release from limestone bedrock in a coastal aquifer. Estuarine, Coastal and Shelf Science 184:166-176.

Gaiser, E. 2009. Periphyton as an indicator of restoration in the Florida Everglades. Ecological Indicators 9(6):S37-S45.

Geddes, E., S. Coonts, and B. Collins. 2018. Geochemistry of the Upper Floridan aquifer and Avon Park permeable zone within the South Florida Water Management District. Technical Publication WS-47. South Florida Water Management District, West Palm Beach, FL.

Gilmour, C.C., D.A. Elias, A.M. Kucken, S.D. Brown, A.V. Palumbo, C.W. Schadt, and J.D. Wall. 2011. Sulfate-reducing bacterium *Desulfovibrio desulfuricans* ND132 as a model for understanding bacterial mercury methylation. Applied and Environmental Microbiology 77(12):3,938-3,951.

Guo, W. and C.D. Langevin. 2002. User’s Guide to SEAWAT: A Computer Program for Simulation of Three-Dimensional Variable-Density Ground-Water Flow. Techniques of Water-Resources Investigations 6-A7. United States Geological Survey, Tallahassee, FL.

Guo, W., K. Coulibaly, and R.G. Maliva. 2015. Simulated effects of aquifer heterogeneity on ASR system performance. Environmental Earth Sciences 73:7,803-7,809.

Harvey, J.W. and P.V. McCormick. 2009. Groundwater’s significance to changing hydrology, water chemistry, and biological communities of a floodplain ecosystem, Everglades, South Florida, USA. Hydrogeology Journal 17(1):185-201.

Lisle, J.T. 2014. Survival of bacterial indicators and the functional diversity of native microbial communities in the Floridan aquifer system, South Florida. United States Geological Survey Open-File Report 2014-1011. 70 pp.

Lisle, J.T. 2020. Nutrient removal and uptake by native planktonic and biofilm bacterial communities in an anaerobic aquifer. Frontiers in Microbiology 11(1765). 13 pp.

Mirecki, J.E. 2004. Water-quality changes during cycle tests at aquifer storage recovery (ASR) systems of South Florida. United States Army Engineer Research and Development Center Technical Report ERDC-TR-04-8. 56 pp.

Mirecki, J.E. 2006. Geochemical modeling of water quality changes during ASR cycle tests: Phase I – Geochemical models using existing data. United States Army Engineer Research and Development Center Technical Report ERDC/EL-TR-06-8. 66 pp.

Mirecki, J.E., M.W. Bennett, and M.C. López-Baláez. 2013. Arsenic control during aquifer storage and recovery cycle tests in the Floridan aquifer. Groundwater 51(4):539-549.

National Research Council. 2015. Review of the Everglades Aquifer Storage and Recovery Regional Study. The National Academies Press, Washington, D.C. 68 pp.

Orem, W., C. Gilmour, D. Axelrad, D. Krabbenhoft, D. Scheidt, P. Kalla, and G. Aiken. 2011. Sulfur in the South Florida ecosystem: Distribution, sources, biogeochemistry, impacts, and management for restoration. Critical Reviews in Environmental Science and Technology 41(S1):249-288.

Petkewich, M.D., D.L. Parkhurst, K.J. Conlon, B.G. Campbell, and J.E. Mirecki. 2004. Hydrologic and geochemical evaluation of aquifer storage recovery in the Santee Limestone/Black Mingo Aquifer, Charleston, South Carolina, 1998-2002. United States Geological Survey Scientific Investigations Report 2004-5046. 92 pp.

Price, R.M., M.R. Savabi, J.L. Jolicoeur, and S. Roy. 2010. Adsorption and desorption of phosphate on limestone in experiments simulating seawater intrusion. Applied Geochemistry 25(7):1,085-1,091.

Pyne, D.G. 2005. Aquifer Storage and Recovery: A Guide to Groundwater Recharge Through Wells. Second edition. Gainesville, FL. 608 pp.

SFWMD and USACE. 2013. Central and Southern Florida Project Comprehensive Everglades Restoration Plan Aquifer Storage and Recovery Pilot Project Final Technical Data Report. South Florida Water Management District, West Palm Beach, FL, and United States Army Corps of Engineers, Jacksonville, FL. December 2013. https://www.sfwmd.gov/sites/default/files/documents/Main%20Report_Final_2013.pdf.

SFWMD and USACE. 2015. Central & South Florida Comprehensive Everglades Restoration Plan Final Regional Aquifer Storage and Recovery Technical Data Report. South Florida Water Management District, West Palm Beach, FL, and United States Army Corps of Engineers, Jacksonville, FL. May 2015. https://www.saj.usace.army.mil/Portals/44/docs/Environmental/ASR%20Regional%20Study/Final_Report/ASR_RegionalStudy_Final_2015.pdf.pdf.

Sharfstein, B. and A.D. Steinman. 2001. Growth and survival of the Florida apple snail (*Pomacea paludosa*) fed 3 naturally occurring macrophyte assemblages. Journal of North American Benthological Society 20:84-95.

Suter II, G.W., T. Vermeire, W.R. Munns Jr., and J. Sekizawa. 2005. An integrated framework for health and ecological risk assessment. Toxicology and Applied Pharmacology 207(2):611-616.

Swift, D.R. and R.B. Nicholas. 1987. Periphyton and water quality relationships in the Everglades Water Conservation Areas, 1978-1982. Environmental Sciences Division, Resource Planning Department, South Florida Water Management District, West Palm Beach, FL.

United States Environmental Protection Agency. 1998. Guidelines for Ecological Risk Assessment. EPA/630/R-95/002F. 188 pp.

USACE and SFWMD. 1999. Central and Southern Florida Project Comprehensive Review Study Final Integrated Feasibility Report and Programmatic Environmental Impact Statement. United States Army Corps of Engineers, Jacksonville, FL, and South Florida Water Management District, West Palm Beach, FL. April 1999.

USACE and SFWMD. 2020. Comprehensive Everglades Restoration Plan, Lake Okeechobee Watershed Restoration Project: Final Integrated Project Implementation Report and Environmental Impact Statement. United States Army Corps of Engineers, Jacksonville, FL, and South Florida Water Management District, West Palm Beach, FL. August 2020.

Williams, A.J. and J.C. Trexler. 2006. A preliminary analysis of the correlation of food-web characteristics with hydrology and nutrient gradients in the southern Everglades. Hydrobiologia 569(1):493-504.