Review of the Everglades Aquifer Storage and Recovery Regional Study

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Water Science and Technology Board

Division on Earth and Life Studies

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COMMITTEE TO REVIEW THE FLORIDA AQUIFER STORAGE AND RECOVERY REGIONAL STUDY TECHNICAL DATA REPORT

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This report was reviewed in draft form by individuals chosen for their breadth of perspectives and technical expertise in accordance with the procedures approved by the National Academies' Report Review Committee. The purpose of this independent review was to provide candid and critical comments to assist the institution in ensuring that its published report is scientifically credible and that it meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The reviewer comments and draft manuscript remain confidential to protect the deliberative process. We thank the following reviewers for their helpful suggestions, all of which were considered and many of which were wholly or partly incorporated in the final report: Jean Bahr, University of Wisconsin-Madison; Leonard Konikow (NAE), U.S. Geological Survey, Reston, VA; Wayne Landis, Western Washington University, Bellingham, WA; Mark McNeal, ASRus LLC, Tampa, FL; Madeline Schreiber, Virginia Polytechnic Institute and State University; Mark Stewart, University of South Florida, Tampa; Frank Stillinger (NAS), Princeton University, NJ; Joshua White, Lawrence Livermore National Laboratory, Livermore, CA; Marylynn Yates, University of California-Riverside.

Although these reviewers provided many constructive comments and suggestions, they were not asked to endorse the conclusions and recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Bonnie McCay, Rutgers University, New Brunswick, NJ and Wendy Graham, University of Florida. Appointed by the National Research Council (NRC), they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments received full consideration. Responsibility for the final content of this report rests entirely with the authoring committee and the NRC.

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Contents

Summary

The Florida Everglades, a unique aquatic ecosystem that supports a diversity of habitats and 67 threatened and endangered species, has been greatly altered over the past century by water management to support agricultural and urban development. The Comprehensive Everglades Restoration Plan (CERP), launched in 2000, is a joint effort led by the state and federal government to reverse the decline of the ecosystem. Increasing water storage is a critical component of the restoration, and the CERP included projects that would drill over 330 aquifer storage and recovery (ASR) wells to store up to 1.7 billion gallons per day in porous and permeable units in the Floridan aquifer system during wet periods for recovery during seasonal or longer-term dry periods.

To address uncertainties regarding regional effects of large-scale ASR implementation in the Everglades, the U.S. Army Corps of Engineers (USACE) and the South Florida Water Management District conducted an 11-year ASR Regional Study, focusing on the hydrogeology of the Floridan aquifer system, water quality changes during aquifer storage, possible ecological risks posed by recovered water, and the regional capacity for ASR implementation. At the request of the USACE, the National Research Council's Water Science and Technology Board convened a committee of experts to review the ASR Regional Study Technical Data Report (TDR) and assess progress reducing uncertainties related to full-scale CERP ASR implementation (see Box S-1). The committee was *not* asked to provide recommendations on the appropriate role of ASR in the CERP.

The ASR Regional Study, which included literature syntheses, laboratory testing, and field-scale experimentation primarily at two pilot ASR sites, represents a significant advancement in the understanding of large-scale ASR implementation in South Florida. The Regional Study improved the understanding of the hydrogeology of the Floridan aquifer system in southern Florida and used this information to develop a regional groundwater model. Through modeling simulations, the study concluded that the number of ASR wells that can be operated without significant regional effects on well pressure and groundwater heads is much lower (approximately 131 wells) than originally envisioned in the CERP. The study also examined subsurface geochemical changes and associated mechanisms that are likely to occur through water-rock interactions. The Regional Study TDR reported reductions in mercury and phosphorus in recovered water and initially elevated arsenic levels that become substantially reduced with additional cycles and storage. The Regional Study also examined pressures that could cause hydraulic fracturing and ranked components of ecological risk.

The committee agrees with the Regional Study findings that no "fatal flaws" have been discovered, but many uncertainties remain (see Chapter 2) that merit additional study before large-scale ASR should be implemented. The following represent the highest-priority uncertainties, considering their implications to CERP decision making.

BOX S-1
Statement of Task

The National Research Council was asked to convene a committee to review and evaluate the scientific methods, principles, and data that form the basis for the U.S. Army Corps of Engineers' ASR Regional Study Technical Data Report. The TDR is divided generally into the following four focus areas: (1) regional hydrogeological framework, (2) water quality changes during cycle testing, (3) groundwater flow simulations, and (4) ecotoxicology. The committee was tasked to assess progress toward the ASR Regional Study's stated goals "to reduce uncertainties related to full-scale CERP ASR implementation by conducting studies based on existing and newly acquired data, develop a regional groundwater model of the Floridan Aquifer System [FAS], and identify an appropriate magnitude of ASR capacity with minimal impact to the environment and existing users of the FAS." The committee was specifically tasked to review and comment on the following aspects:

- Validity of the data collection and interpretation methods,
- Integration of studies comprising the four focus areas mentioned above,
- Evaluation of scaling from pilot- to regional-scale application of ASR, and
- The adequacy and reliability of the study as a basis for future applications of ASR.

The committee also was asked to assess the scientific assumptions and logic on which the report's conclusions are based.

- **Operations to Maximize Recovery and Reduce Water Quality Impacts.** More research is needed to assess improvements in recovery efficiency and recovered water quality by establishing a freshwater buffer zone and maintaining it throughout subsequent cycle testing (termed a target storage volume approach). This approach could have major implications for the ecotoxicity of the recovered water if the proportion of native groundwater is substantially reduced. However, a larger buffer zone could create an expanded zone of near-term arsenic mobilization that is anticipated to attenuate over time. The use of well pairs or clusters should also be examined to improve recovery efficiencies and performance.
- **Ecotoxicology and Ecological Risk Assessment.** Some of the largest uncertainties remaining after the ASR Regional Study are associated with the ecological risks of ASR in the Everglades. The results of chronic toxicity testing and regional water quality modeling suggest some cause for concern and a need for further analysis considering longer storage times and greater recharge volumes, use of a target storage volume approach to improve recovered water quality, and more ASR sites. Ecotoxicological testing should be designed in light of the fact that water from ASR operations will primarily be recovered during dry, low-flow conditions. Research should also examine the impacts of calcium and hardness on soft-water areas of the Everglades. The ecological risk assessment should be probabilistic in nature and can be improved using advancements in quantitative methods drawn from other successful regional-scale assessments.
- **Understanding Phosphorus Reduction Potential.** Removal of phosphorus represents a key unexplored benefit of ASR, and more research is needed to examine the long-term rates and extents of subsurface phosphorus removal under various aquifer conditions.

- **Disinfection.** Disinfection permitting requirements were not uniformly achieved during the pilot studies due to high organic matter in the recharge water. Additional work is needed to develop appropriate pretreatment strategies without hindering subsurface biogeochemical processes that attenuate dissolved arsenic. Research on pathogen survival in groundwater has demonstrated inactivation in flow-through chambers at varying rates. However, substantial additional research is needed on a wider suite of pathogens under groundwater conditions, and this information needs to be coupled with an understanding of groundwater travel times and the locations of potential human exposures to determine the level of disinfection necessary to protect human health.
- **Cost and Performance of ASR Compared to Alternatives.** Decision makers are unlikely to support continued research on ASR without clear documentation of the potential benefits of ASR relative to other possible water storage alternatives. Thus, a comparative cost-benefit assessment for water storage alternatives, including integrated operation of ASR wells and surface storage reservoirs, is an important next step. Benefits should be assessed in terms of new water delivered to the Everglades, flood flow prevention, or water quality improvements. Such an analysis should document performance uncertainties, which may help prioritize research to inform future decision making.

These high-priority uncertainties can be resolved through research at a range of scales, from computer modeling and laboratory testing to continued pilot testing with expanded ecotoxicological testing to expansion of the current pilot sites. Although current uncertainties are too great to justify near-term implementation of ASR at a large scale in the Everglades, opportunities exist to target future phased implementation of ASR in a way that addresses critical uncertainties while providing some early restoration benefits. Until the uncertainties related to ecological effects are substantially resolved, any new ASR wells to be drilled should be sited adjacent to large water bodies with adequate mixing zones to minimize adverse ecological impacts.

1

Introduction

The Florida Everglades, a unique aquatic ecosystem that supports a diversity of habitats and 67 threatened and endangered species, has been greatly altered over the past century by water management to provide flood control, increase urban water supply, and enhance agricultural production. The remnant Everglades ecosystem now competes with urban and agricultural interests for available water and is impaired by contaminants from these two activities. The Comprehensive Everglades Restoration Plan (CERP), launched in 2000, is a joint effort led by the state and federal government to reverse the decline of the ecosystem. The CERP is designed to capture, store, and redistribute freshwater and to improve the quality, quantity, timing, and distribution of water flows. To "get the water right" and restore the Everglades, there is a critical need for new water storage because 130 years of canal drainage and water management have resulted in extensive losses of natural storage. Thus, in addition to surface reservoirs, the CERP included a project that would drill over 330 aquifer storage and recovery (ASR) wells (Figure 1-1). The CERP feasibility study proposed that up to 1.7 billion gallons per day could be stored in porous and permeable units in the Upper Floridan aquifer during wet periods for recovery during seasonal or longer-term dry periods.

ASR PILOTS TO ADDRESS UNCERTAINTIES

Although ASR technology has been employed successfully in Florida since 1983, concerns were expressed about this large-scale application of ASR in the Everglades. The South Florida Ecosystem Restoration Working Group's ASR Issue Team (1999) identified seven technical issues in need of further examination before ASR should move forward:

1. Suitability of prospective source waters considering spatial and temporal variability in water quality,
2. Characterization of the regional hydrogeology of the Upper Floridan aquifer,
3. Understanding the potential for rock fracturing,
4. Site and regional changes in head and patterns of groundwater flow,
5. Water quality changes during movement and storage in the aquifer,
6. Effects on mercury methylation and bioaccumulation in the Everglades ecosystem, and
7. The relationship between hydrogeologic properties and recovery and recharge volumes.

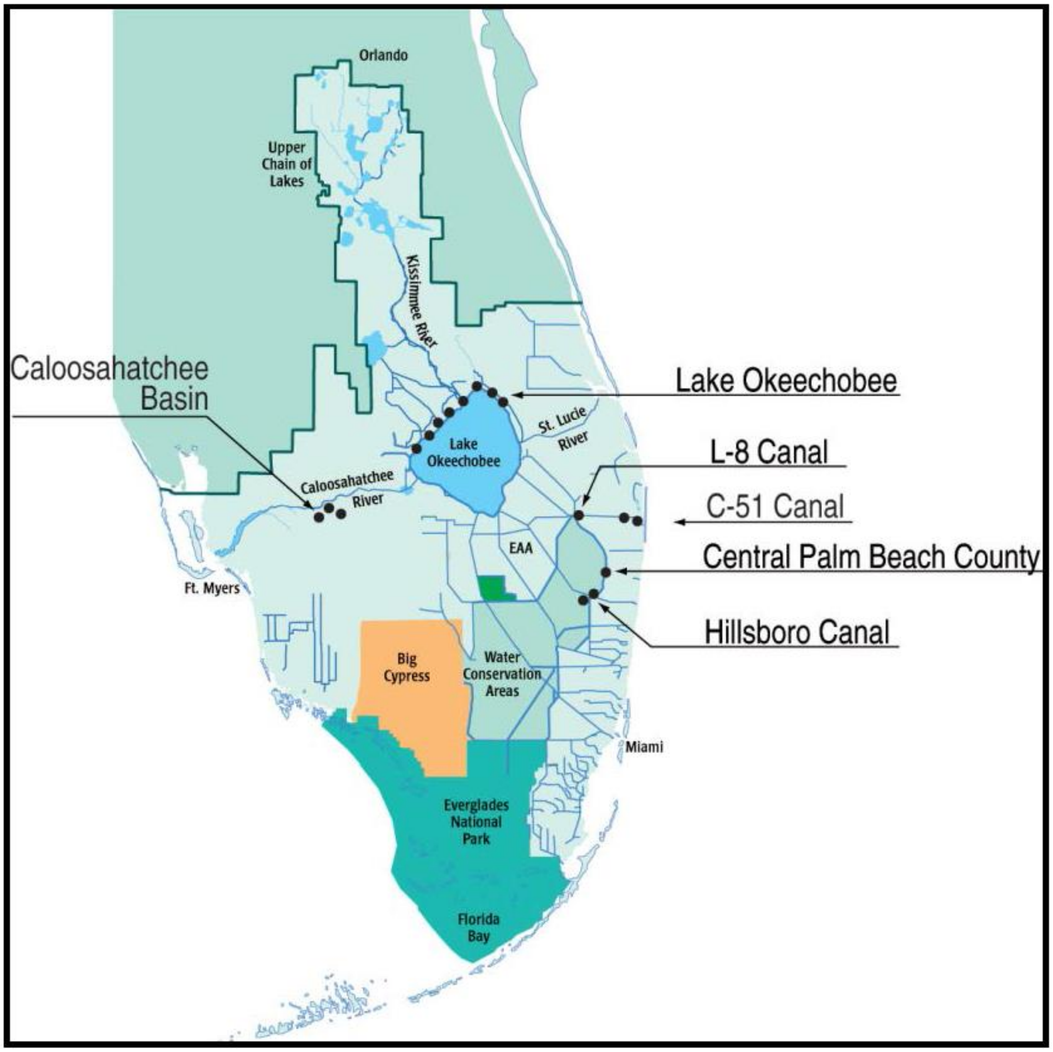

FIGURE 1-1 Generalized ASR well locations from the original CERP plan for 333 wells.
SOURCE: USACE and SFWMD (2014).

The U.S. Army Corps of Engineers (USACE) and the South Florida Water Management District (SFWMD) originally planned five pilot studies (Figure 1-2) to address these concerns—three ASR pilot sites around Lake Okeechobee (Kissimmee River, Port Mayaca, and Moore Haven), one at the Hillsboro Canal, and one at the Caloosahatchee River. All pilots were authorized, but due to limitations in funding and poor site conditions at the Caloosahatchee River site, only two pilot sites (Kissimmee River and Hillsboro) were ultimately constructed. The Hillsboro and Kissimmee River ASR pilot studies (USACE and SFWMD, 2013) examined water quality changes, local hydrogeology, recharge and recovery performance, effects on hydraulic head and local groundwater flow, costs, and energy use at these two sites, each with a single ASR well and several monitoring wells. Additionally, surface water and groundwater quality measurements were conducted at the proposed Caloosahatchee River and Port Mayaca sites.

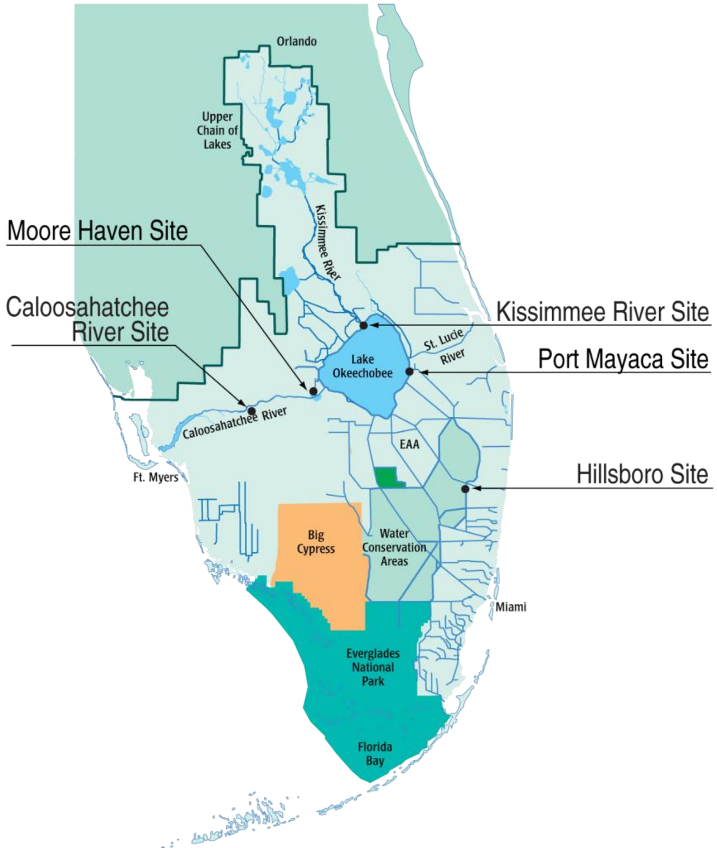

FIGURE 1-2 Locations of the five originally planned CERP ASR pilot projects. Ultimately, pilots were constructed only on the Kissimmee River and the Hillsboro sites because of funding limitations or poor site conditions.
SOURCE: USACE and SFWMD (2008).

After the National Research Council (NRC) Committee on the Restoration of the Greater Everglades Ecosystem held a workshop to examine plans for the two ASR pilot projects, NRC (2001) recommended additional research on regional science and water quality issues, including

- Aggregate hydraulic effects in a regional context,
- Performance under long (>1 year) recharge periods,
- Subsurface geochemical changes, and
- Ecotoxicological effects on downstream receptors.

To respond to these recommendations, the USACE, in cooperation with the SFWMD, launched the ASR Regional Study to complement the site-specific ASR pilot studies. The Regional Study was designed to address uncertainties concerning the feasibility of full-scale ASR implementation related to its effects on water levels, water quality, and biota and any outstanding issues (e.g., hydrogeology, geophysics) that could not be addressed by individual pilot projects. The ASR Regional Study included development of a regional groundwater model of the Floridan aquifer system, which was used to assess the technical feasibility of the proposed 333-well ASR system and, if infeasible, identify an appropriate magnitude of ASR capacity with minimal environmental impacts. NRC (2002) reviewed the proposed ASR Regional Study plan.

The $25 million ASR Regional Study began in 2003, and the results of the study are described in the ASR Regional Study Final Technical Data Report (TDR; USACE and SFWMD, 2014). The ASR Regional Study project consisted of four main focus areas:

- A hydrogeologic analysis to evaluate the regional extent of permeable storage zones, confining units, and groundwater quality in the Floridan aquifer system;
- Evaluation of water quality changes during ASR cycle testing;
- Groundwater flow simulations to evaluate the feasibility of regional-scale ASR, specifically locations and numbers of ASR wells that can be constructed without exceeding hydraulic and regulatory criteria; and
- An evaluation of the ecological risks of the recovered water.

COMMITTEE STATEMENT OF TASK

At the request of the USACE, the NRC's Water Science and Technology Board convened a committee of experts to review the ASR Regional Study TDR. The NRC was asked to assess progress toward the ASR Regional Study's stated goals "to reduce uncertainties related to full-scale CERP ASR implementation by conducting studies based on existing and newly acquired data, develop a regional groundwater model of the Floridan Aquifer System [FAS], and identify an appropriate magnitude of ASR capacity with minimal impact to the environment and existing users of the FAS." The committee was specifically tasked to review and comment on the following aspects:

- Validity of the data collection and interpretation methods,
- Integration of studies comprising the four focus areas mentioned above,
- Evaluation of scaling from pilot- to regional-scale application of ASR, and
- The adequacy and reliability of the study as a basis for future applications of ASR.

The committee also was asked to assess the scientific assumptions and logic on which the report's conclusions are based. The committee was *not* asked to provide recommendations on the appropriate role of ASR in the CERP.

The committee's report and its conclusions and recommendations are based on a review of the ASR Regional Study TDR, relevant technical literature, briefings and discussions at its December 11-12, 2014, meeting, and the experience and knowledge of the committee members in their fields of expertise. The committee did not review the Hillsboro and Kissimmee River pilot results (USACE and SFWMD, 2013) in detail. Additionally, the committee did not perform an in-depth review of the regional groundwater model developed for the Regional Study, because the USACE has its own review process[1] (USACE, 2012) and such involved analysis was beyond the scope of this 6-month study.

[1] The ASR Regional Study groundwater model was developed using the SEAWAT modeling code (Guo and Langevin, 2002). Both the bench-scale ASR model and the Phase II model calibration report were reviewed by the CERP Interagency Modeling Center (see TDR appendix E), and the Phase I calibration report received review comments at a 2008 interagency meeting (C. Murray, USACE, personal communication, 2015).

Chapter 2 of this NRC report discusses the progress made in the ASR Regional Study to address major uncertainties, any technical issues of concern, and remaining uncertainties. The report discusses the major uncertainties raised by the ASR Issue Team (1999) and many of the uncertainties raised by NRC (2001), organized by topic: hydrogeology, recharge and recovery, hydraulic fracturing potential, groundwater modeling, water quality, and ecological risk assessment. Integration across focus areas is also discussed.

Chapter 3 highlights the most pressing uncertainties that need to be resolved to inform policy decisions on the future role of ASR in the CERP and discusses possible strategies to address these issues.

2

Topic-Specific Reviews

The committee's review of the major components of the Aquifer Storage and Recovery (ASR) Regional Study—hydrogeology, recharge and recovery, hydraulic fracturing potential, ASR capacity, water quality, and ecological risk assessment—is presented in this chapter. The chapter focuses on how well the major uncertainties were addressed in each of these areas, whether data collection strategies were sound, and whether the findings were appropriate. Additionally, major unresolved uncertainties are discussed.

HYDROGEOLOGY

Hydrogeologic information on the nature of the permeable zones, the effectiveness of the confining units, and horizontal anisotropy is important to ASR system planning. Carbonate aquifers, such as found in the Floridan aquifer system, can have both diffuse flow through small pores and preferential flow through dissolution features and fractures. Preferential flow can allow migration of injected water farther than predicted and reduce recovery efficiency,[2] particularly in zones of high groundwater salinity. The extent and continuity of permeable zones is also important. If the permeable zone is discontinuous and/or its extent is limited, the response to injection will differ over the long term compared to that observed during short-term tests. The effectiveness of confining units that bound permeable zones reflects their hydraulic conductivity, thickness, and whether the confining units are crossed by permeable faults, fractures, or dissolution conduits. Loss of injected water through confining units can lower recovery efficiency as can mixing with underlying saline water during recovery. If microbial contaminants are injected or chemical contaminants mobilized through ASR, leaky confining units can result in contaminant movement to other aquifers. Horizontal anisotropy of hydraulic conductivity can impact predictions of hydraulic head change and migration of stored water.

Prior to the ASR Regional Study, the hydrostratigraphic description of the Floridan aquifer system suffered from inconsistencies and data gaps and potentiometric surface data were sparse. The ASR Regional Study aimed to reduce these uncertainties through efforts to synthesize existing data and new hydrogeologic investigations conducted in coordination with the U.S. Geological Survey (USGS).

[2] Recovery efficiency is defined as "the percentage of the water volume stored that is subsequently recovered while meeting a target water quality criterion in the recovered water" (Pyne, 2005). The target water quality criterion used for the ASR pilot study was 250 mg/L chloride, an Environmental Protection Agency (EPA) secondary maximum contaminant level (USACE and SFWMD, 2013). It is important to note that the definition is based on the *volume* of water injected and recovered within a single ASR cycle and does not reflect how much of that same water that is injected is recovered. In a low-salinity aquifer, recovery efficiency may exceed 100 percent.

Progress Addressing Uncertainties

Literature synthesis and a compilation of existing hydrogeologic data from over 700 wells produced a preliminary updated hydrogeologic framework for the Regional Study (Reese and Richardson, 2008). New hydrogeologic data were then collected to fill critical gaps in the hydrogeologic framework and to provide data to support the development of the regional groundwater flow model. Lithologic, geophysical, and hydrogeologic data (e.g., aquifer performance tests, packer tests, core permeability measurements) were collected using existing and new wells or well clusters drilled for the study. Water-level data were also collected across the region to characterize potential water storage zones. Additional hydrogeologic data collected included cross-well seismic tomography to map local permeability structures at the two pilot sites and seismic reflection profiles in Lake Okeechobee and canals.

The final hydrogeologic framework (Reese, 2014; summarized in Figure 2-1) indicates the presence of four major permeable zones within the Floridan aquifer system: the Upper Floridan aquifer, the Avon Park permeable zone (APPZ), the uppermost permeable zone of the Lower Floridan aquifer (LF1), and the Boulder Zone. Of the 30 ASR wells in South Florida completed in the Floridan aquifer system, most are completed in the Upper Floridan aquifer (Reese and Richardson, 2008). Borehole geophysical and flowmeter observations indicate that the Upper Floridan aquifer contains both diffuse and preferential flow (Reese and Cunningham, 2014; Reese and Richardson, 2008). Less information exists concerning the APPZ and LF1. Information on the characteristics of these aquifers is summarized by Reese and Richardson (2008).

The delineation of the APPZ is an important result of the synthesis. The APPZ, which contains multiple permeable zones, had previously been referred to as the Middle Floridan aquifer or had been considered part of the Upper or Lower Floridan aquifer (Reese and Cunningham, 2014; Reese and Richardson, 2008). Results from the Regional Study show that the APPZ is distinct from the Upper or Lower Floridan aquifers and a potential target for ASR. An ASR test well at the Taylor Creek Nubbin Slough site north of Lake Okeechobee intersected a low-salinity (<250 mg/L chloride), high-permeability zone near the top of the APPZ (CH2M Hill, 1989), although it is unknown whether this zone is regionally contiguous. The LF1 was not considered as an ASR target, although its exclusion was not explained in the Regional ASR Technical Data Report (TDR).

The distribution of total dissolved solids (TDS) modifies fluid density and thus affects flow patterns. Figures from the Final Groundwater Modeling Calibration Report (included as Appendix E of the TDR) suggest that TDS values are reasonably well characterized in the Upper Floridan aquifer, ranging from 500 to 5000 mg/L in the areas of potential ASR siting (see Figure 1-1). The TDR reports that the APPZ is generally more saline than the Upper Floridan aquifer in the region around Lake Okeechobee and shows a band of high TDS (5,000 to 20,000 mg/L) stretching west of the lake, although this band is based on limited data. TDS values in the LF1 and Boulder Zone are near to above seawater values from Lake Okeechobee to the south, although limited data in the LF1 make interpretation difficult.

As noted above, the effectiveness of confining units is an important consideration for ASR. In southeast Florida, the Upper Floridan aquifer is separated from the overlying Biscayne aquifer by fine-grained sediments within the Hawthorn Group, which form the intermediate confining unit (ICU; see Figure 2-1). These clays, fine-grained carbonate sediments, and silts provide good confinement. In southwest Florida, several permeable zones exist within the Hawthorn Group (termed the intermediate aquifer system), although aquifer tests indicate that the permeable zones are effectively separated by intervening fine-grained sediments (Reese and Richardson, 2008).

The Middle Floridan confining unit separates the Upper and Lower Floridan aquifers and contains the APPZ. Reese and Cunningham (2014) delineated middle semiconfining units 1 and 2 (Figure 2-1), which separate the Upper Floridan aquifer from the APPZ and the APPZ from LF1, respectively. These units consist of intervals of carbonate rock that are relatively less permeable and are described as semiconfining to leaky due to variable thicknesses and fracturing (Cunningham, 2014; Reese and Cunningham, 2014). Reese (2002) and Reese and

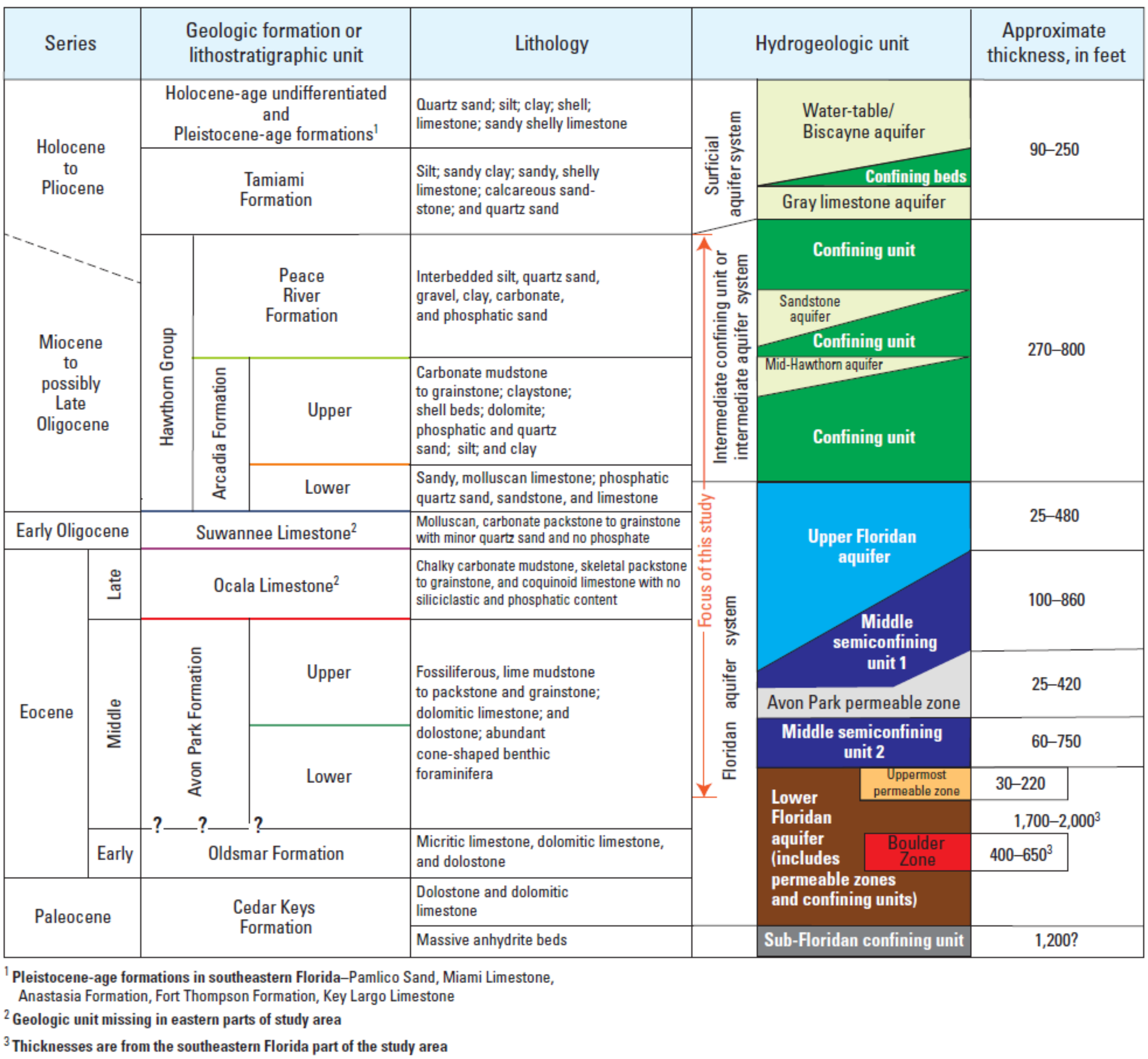

FIGURE 2-1 Regional hydrogeologic framework.
SOURCE: Reese and Cunningham (2014).

Alvarez-Zarikian (2007) reviewed aquifer test data from South Florida and found evidence for leaky behavior in the Upper Floridan aquifer attributed to leakage between permeable zones within the Upper Floridan aquifer or across the middle semiconfining unit 1; the overlying ICU is generally accepted to effectively prevent leakage (Reese, 2002). Hydraulic separation between LF1 and lower permeable zones, including the Boulder Zone, is also provided by intervals of lower-permeability carbonate rock.

The presence of cross-cutting faults, fractures, abandoned boreholes, or dissolution features can locally compromise confining layers. Large (200 to 300ft) depressions in the top of the Ocala limestone were observed along the northeastern and southwestern sides of Lake Okeechobee (Cunningham, 2014). In a Broward County study, Reese and Cunningham (2014) observed seismic sag structures and tentatively attribute these to collapse of karst caverns within or below the Lower Floridan aquifer. These seismic sag structures could decrease continuity of permeable zones. Associated faulting could allow vertical flow across the semiconfining layers within the Floridan aquifer system (Reese and Cunningham, 2014). Cunningham (2014) notes that vertical connections through the Floridan aquifer system were apparently responsible for migration of injected water from the Boulder Zone to LF1 in the city of Sunrise, Florida. In Broward County, the uppermost disturbance is within Miocene sediments of the Hawthorn Group (Cunningham, 2014; Reese and Cunningham, 2014), suggesting that these features could potentially affect the confinement provided by the ICU.

Mapping of surface lineaments was conducted as part of the regional-scale investigations. The Regional ASR TDR notes that surface lineaments may be related to fractures or faults that extend from the basement rocks to the land surface. Vertical tectonic fractures and faults may allow migration across confining and semiconfining units, although it is important to note that not all faults have high permeability.

The study of surface lineaments was also integrated with investigation of borehole fractures and existing aquifer performance test data to assess regional horizontal anisotropy (directional dependence) of hydraulic conductivity, a key parameter of the groundwater flow model. Although limited borehole data strongly suggest preferential flow in fractures with "distinct trends in fracture orientation," the surface lineaments do not directly correspond to data on flowing fractures within the aquifer (USACE and SFWMD, 2014). The borehole data were reported in the TDR to be too limited to support regional extrapolation of anisotropy in the groundwater flow model because most of the borehole fracture data came from a single well.

Uncertainties Remaining

Although uncertainties remain concerning the vertical distribution of hydraulic conductivity within permeable zones, horizontal anisotropy, and the effectiveness of confining layers, none of these preclude ASR. With the regional hydrogeologic framework established, future efforts at the local scale are needed to understand the variability in hydraulic connectivity within the Upper Floridan aquifer and the APPZ. Reese and Richardson (2008) report that transmissivity in the APPZ can range from 100,000 to 1,600,000 ft^2/d in Florida. Local leakage, transmissivity, and storativity values will control the response to injection and extraction (USACE and SFWMD, 2014). To evaluate many of the uncertainties at the local scale, including the nature and continuity of permeable zones, anisotropy, and confining unit effectiveness, longer-term tests will be needed with additional wells completed in the APPZ. Any future injection or withdrawal tests should use the tests to assess local flow and transport parameters including hydraulic conductivity, effective porosity, and dispersivity. These parameters can be used to construct local-scale models nested within the regional model to examine the migration of injected water during recharge and storage, including the potential for advective transport of solutes in the injected water based on the local hydraulic gradient.

The TDR's conclusion that data are insufficient to evaluate regional anisotropy is reasonable, and the uncertainty concerning regional anisotropy remains. On a regional scale, the groundwater flow and transport model provides a useful tool to evaluate whether anisotropy would significantly affect modeling conclusions. The regional model could be used to test the impact of reasonable horizontal anisotropy on the limiting factors (pump pressures and artesian pressure reduction) for ASR, although the effects of anisotropy will likely be more important at the local scale than the regional scale. Evaluation of anisotropy should be considered in any future additional pilot testing, with observation wells ideally located both along and perpendicular to the possible direction of preferential flow. Monitoring should include both hydraulic head and indicators of injected water (e.g., chloride and specific conductance can serve as useful indicators of fluid migration, if injected water salinity differs from native groundwater).

Monitoring of hydraulic head and tracers during future testing will also help to address uncertainty about migration patterns, flow rates, and the nature of permeable zones in the Upper Floridan aquifer and the APPZ. Cross-well seismic tomography, such as demonstrated at the Port Mayaca and Hillsboro ASR pilot sites, potentially helps to identify permeable zones and their continuity. Furthermore, repeat cross-well seismic tomography during cycle testing may be able to examine hydraulic head changes through time, and repeat cross-borehole monitoring of electrical resistivity might image migration of injected fluids (Minsley et al., 2011). Unfortunately, cycle testing could not be conducted at the Port Mayaca site to test the interpretations, and the cross-well tomography results at the Hillsboro site do not appear to have been incorporated into the interpretation of the cycle testing. Future application of cross-well tomography may be helpful to address hydrogeologic uncertainties at the local scale.

The observation of possible tectonic faults and seismic sag features and associated fractures in the Lake Okeechobee region should be carefully examined because these faults may affect confining-layer integrity. Improperly abandoned boreholes or poorly sealed wells should also be considered potential pathways for vertical migration through confining units. Transmission of pressure and migration of water across confining units should be evaluated during future pilot studies by monitoring hydraulic head and specific conductance (if distinct) within overlying or underlying permeable zones near testing sites. Monitoring in confining layers would be less helpful because transport across confining layers would likely be along the preferential flow paths.

RECHARGE AND RECOVERY

Among the seven major uncertainties identified by the 1999 ASR Issues Team was the relationship between hydrogeologic properties and ASR operational factors, such as recovery rates, recovery efficiency, and recharge and recovery volume in the context of urban, agricultural, and ecosystem needs. NRC (2001) identified several additional related concerns, including "studies to understand mixing of recharge water with saline groundwater," which affects recovery efficiency. Operational issues were examined at the two Comprehensive Everglades Restoration Plan (CERP) ASR pilot sites, with additional effort to learn from experiences at several utility ASR wells in Florida, some of which have been in operation for over 30 years.

Progress Addressing Uncertainties

Each of the two pilot projects was designed with a single 5-million-gallon-per-day ASR well, completed in the Upper Floridan aquifer. Individual well recharge and recovery rates of 5 million gallons per day (MGD) were demonstrated to be viable at these two sites, although the Regional Study did not examine the capacity to achieve higher recharge or recovery rates. Additionally, the Regional Study did not examine the array of sites (5 to 10) recommended by the ASR Issue Team (1999), and therefore these findings cannot be projected on a regional basis.

A USGS study conducted outside of the ASR Regional Study (Reese and Alvarez-Zarikian, 2007) provides a useful synthesis of factors influencing ASR cycle test recovery efficiency based on 30 ASR wells completed in the Floridan aquifer system in southern Florida, although most of these wells were located along the east or west coasts. Out of 18 ASR wells with water recovery data, only 5 were reported to have achieved recoveries over 60 percent. Reese and Alvarez-Zarikian (2007) identified three aquifer properties—transmissivity above 30,000 square feet per day (ft^2/d), chloride concentration above 2,500 mg/L, and groundwater storage zone thickness above 150 feet—that were correlated with lower ASR well recovery efficiencies. The Regional Study included 12 sites where test wells or cores were drilled in the inland region of southern Florida to fill in missing hydrogeologic data (e.g., CH2M Hill, 2007a,b; Sunderland et al., 2011) and extensive data on transmissivity and salinity were compiled to calibrate the Regional Study groundwater model (USACE, 2011), but there is a surprising lack of synthesis in the ASR Regional Study TDR about the findings of this work as they relate to the potential for successful future siting of ASR wells with optimal recoveries.

The CERP ASR pilot projects examined the recovery efficiencies of the two ASR pilot wells, achieving 100 percent recovery at the Kissimmee River ASR site (150-281 mg/L chloride in the native groundwater) and 20-40 percent at the more brackish Hillsboro ASR site (2,293 mg/L chloride) (USACE and SFWMD, 2013). From these data, the Regional ASR Study Model assumes a 70 percent recovery efficiency region wide for the Upper Floridan aquifer, but this assumption likely underestimates recoveries achievable. Reese and Alvarez-Zarikian (2007) observed improved recoveries at sites that used a target storage volume approach, where a large volume of water is added to the well to form a freshwater buffer zone that is subsequently maintained throughout future recovery cycles. A buffer zone is essential for achieving acceptable recovery efficiency under brackish conditions and can be developed at the beginning of ASR operations through a single injection or more slowly over a series of operating cycles, as the mixing zone of saline and freshwater from one cycle becomes the buffer zone for the next (Pyne, 2015). The sum of the buffer zone volume and the recovered water volume is known as the target storage volume. Determining the appropriate initial volume of the buffer zone requires information from ASR operations and testing (sometimes obtained from existing wells when an ASR wellfield is being expanded), although existing ASR experiences in the Upper Floridan aquifer may be useful to inform the sizing of the target storage volume. There is some investment of resources (e.g., water, electricity) to form the buffer zone, and the initial injection of water is not factored into calculations of recovery efficiency. However, these investments are generally viewed as small relative to the increase in recovery and recovered water quality (particularly in areas with abundant wet-season surface-water flows and brackish aquifers for ASR storage). Wells completed in aquifers with high transmissivity or advective loss of stored water may not reach target recovery efficiencies (Pyne, 2005).

The design of the cycle testing program at the two CERP ASR pilot sites, while suitable for geochemical studies, was inappropriate to demonstrate high recovery efficiency. Only three or four cycles were conducted, during most of which the same volume recharged was recovered. This prevented the formation of an appropriate buffer zone around each ASR well. As a result, the methods of cycle testing introduced a substantial negative bias into conclusions regarding potential recovery efficiency as well as recovered water quality. For example, sulfate increases tend to occur toward the end of recovery if the same volume that is stored is recovered. If, instead, a buffer zone is initially formed and subsequently maintained around the well, the sulfate increase late in recovery should be substantially reduced.

Uncertainties Remaining

The work performed at the two pilot sites, while sound, did not fully address the uncertainties related to ASR recharge and recovery, particularly from a regional perspective. In part, this reflected budgetary constraints that reduced the number of sites to be investigated from five to two and time and budgetary constraints on the number of cycle tests conducted.

One of the remaining critical uncertainties is ASR recovery efficiency, as discussed in the previous section, which has important implications for the benefits of ASR region-wide. Initial recovery efficiencies are greater in low-salinity aquifers, such as at the Kissimmee River site, than more brackish aquifers. However, 30 years of ASR experience in Florida has demonstrated the ability to achieve high recovery efficiency in brackish aquifers. For example, at the Boynton Beach ASR site (chloride concentration 1,900 mg/L), cumulative recovery efficiency has been 63 percent, with higher efficiencies in later cycle tests (Reese and Alvarez-Zarikian, 2007). The Delray Beach site (chloride concentration 2,300 mg/L) attained 94 percent recovery using the target storage volume approach and minimal storage periods. With appropriate well development at the Hillsboro ASR site, the recovery efficiency can likely be significantly improved, although length of storage may impact recovery efficiency. Intervals of the APPZ with high transmissivity and salinity would be expected to have lower recovery efficiencies compared to the Upper Floridan aquifer.[3] Additional work is needed to determine the recoveries feasible in the Upper Floridan aquifer or the APPZ at potential CERP ASR locations using a target storage volume approach, considering different storage periods.

Continued study is also needed to determine the optimal well configuration for ASR to promote maximum recovery efficiency. Well clusters in brackish aquifers with closer horizontal spacing, rather than linear arrays of ASR wells spaced farther apart, are more conducive to rapidly developing a buffer zone and achieving higher recovery efficiency. If ASR moves

[3] The U.S. Army Corps of Engineers (USACE 2006) modeled transmissivities in the APPZ ranging from 100,000 ft^2/d to >500,000 ft^2/d. USACE (2011) reported total dissolved solids ranging from 1,000 to 20,000 mg/L in inland regions, with the highest total dissolved solids located west of Lake Okeechobee.

forward, the next implementation phase should include well clusters (approximately three to five wells) that could be used to address remaining uncertainties regarding pressure mounding and drawdown concerns, recovery efficiencies, and water quality. Transmissivity and salinity data gathered for the model calibration (USACE, 2011) would be helpful to identify areas and aquifers most conducive to high ASR recoveries when considering future phases of ASR implementation.

As mentioned in the ASR Issue Team report (1999), further investigation will be needed to understand the capacity of ASR to address the timing of storage and water supply needs of the environment and urban and agricultural users. The Regional Study TDR stated that this was beyond the scope of the Regional Study, but understanding the capacity for ASR to address flooding and drought needs over various climate conditions is essential to future decision making at both local and regional scales. In particular, there is a need to better understand how to maximize the benefits of ASR through integrated operation with surface reservoir storage. Many of the envisioned locations for ASR (Figure 1-1) are located near an existing or proposed surface storage reservoir. Both ASR pilot wells are sited near large surface storage reservoirs—the Kissimmee River ASR is approximately 8,000 feet from Lake Okeechobee and the Hillsboro ASR is located adjacent to the Site 1 impoundment, which is under construction. ASR wellfields often store much greater volumes of water than surface reservoirs, with greatly reduced losses due to evapotranspiration (NRC, 2005). However, ASR recharge and recovery rates are much lower than for surface reservoirs. Under integrated operations, surface reservoir elevations could be managed to maximize the capture of flood flows, steadily transferring water storage to ASR wells for subsequent recovery during dry periods, but additional modeling is needed to understand optimal designs and operations to maximize storage, flood control, and water delivery during drought to meet the needs of the environment and urban and agricultural users.

HYDRAULIC FRACTURING ANALYSIS

Injection of water during ASR changes the balance among stresses within the aquifer system in ways that could create new fractures or enlarge existing ones. These hydraulic fractures may serve as preferred-flow pathways that lead to uncontrolled migration of water during the recharge and storage phases of ASR and lower the recovery of stored freshwater. Increases in fluid pressure of 40 to 100 pounds per square inch (psi) are possible during the recharge phase of ASR, with the magnitude of the pressure change varying with recharge rate, well spacing, and aquifer permeability. A major goal of the ASR Regional Study was to assess whether these operational pressures were sufficiently high to induce hydraulic fracturing, thereby necessitating modifications to the design and operation of ASR. In addition to impairing ASR performance, creation of hydraulic fractures could violate state permitting requirements.[4]

[4] Rule 62-528.605 of the Florida Administrative Code on well construction standards for Class V underground injection wells states that "migration or mixing of fluids from aquifers of substantively different water quality (through the construction or use of a Class V well) shall be prevented by preserving the integrity of confining beds between these aquifers."

Progress Addressing Uncertainties

Uncertainties regarding the potential for hydraulic fracturing were addressed through two strategies: (1) a "desk-top study" comparing expected stresses encountered during ASR to literature-based estimates of critical stresses for rock-matrix failure and (2) analyses of the mechanical and elastic properties of core samples of Upper Floridan aquifer rock. The ASR Regional Study TDR reported that moderately low wellhead pressures (>95 psi with no added safety factor) can cause microfracturing of the Upper Floridan aquifer rock. Whether these microfractures (if created) could coalesce into larger fractures that would remain open under ASR operational pressures and capable of conducting groundwater flow was not assessed. Based on rock core analysis, the reported threshold wellhead pressures for rock-matrix failure at the well bore (>139 psi) and for shear fracturing (>>163 psi) were greater than those for microfracturing. These threshold wellhead pressures are also much higher than the pump pressures measured in the ASR studies (less than 66 psi during recharge), and the actual increases in pressure occurring in the aquifer due to ASR would be even lower than 66 psi as the water moves away from the well bore.

Based on these analyses, the ASR Regional Study TDR concluded that although the potential for hydraulic fracturing does exist, the probability of hydraulic fracturing can be kept low through appropriate wellfield design and operation during aquifer recharge. The TDR noted that operating ASR wells at pressures reported to cause hydraulic fracturing would require specialized piping and well casing that would substantially increase project costs. The ASR Regional Study TDR also concluded that if rock fracturing from excess fluid pressures were to occur, propagation of the fractures would occur vertically until arrested or would be redirected horizontally upon encountering the weaker lithology of the overlying Hawthorn Group.

There are several issues with these analyses, however, that call the results into question. First, the laboratory analysis of rock strength was conducted on intact core samples, whereas the aquifer likely contains preexisting fractures and open solution cavities. Second, the reported threshold pressures for hydraulic fracturing based on core samples did not consider the *in situ* compressive stress in the aquifer. Even if the formation has no tensile strength, regional compressive stress acts to prevent fractures from opening; hydraulic fractures open only when the induced pore pressure exceeds the least compressive stress. Compressive stress increases with depth, so hydraulic fracturing requires greater pressures in deeper wells. Fractures would propagate vertically because in Florida the smallest component of the stress tensor is horizontal (Zoback, 2010). Typically, analysis of the pressures required for hydraulic fracturing begins with a characterization of the state of stress in the aquifer, but regional stress was not considered in the quantitative analysis.

Uncertainties Remaining

Based on the lack of consideration of *in situ* stresses in the aquifer and other shortcomings of the analysis, many uncertainties remain regarding the true threshold wellhead pressures for hydraulic fracture initiation and propagation. A conventional analysis of hydraulic fracturing would likely find that the aquifer could withstand pumping pressures much greater than 66 psi, particularly in deeper wells. Thus, it seems unlikely that hydraulic fracturing would be a concern in this system under current operating pressures. However, additional analyses that consider existing in situ compressive stress and potential dilation of preexisting fractures would be needed to definitively confirm the committee's intuition. These tests might include step-rate well tests that assess injectivity as a function of injection pressure. If the potential for hydraulic fracturing at standard operating well pressures is determined, additional study would be warranted to assess whether upper and lower confining units would serve as fracture-propagation barriers.

GROUNDWATER FLOW MODELING AND OVERALL ASSESSMENT OF CAPACITY

The very large scale of the proposed network of ASR systems raises a number of questions about how ASR will impact Florida's groundwater system. Questions include: Could large-scale, regional implementation of ASR create pore pressures that are large enough to drive rock fracturing or require pressures that entail large energy costs? Could ASR pumping affect water quality at a regional scale? Could groundwater extraction during the recovery stage lower the artesian pressures within the Upper Floridan aquifer, making withdrawals more difficult for existing users of the Upper Floridan aquifer?[5] All of these uncertainties relate to the massive scale and cumulative effects of the proposed ASR system. Although these uncertainties cannot be addressed through the initial single-well pilot studies, they can be evaluated through application of hydrologic models. The hydrologic modeling conducted in support of the Regional Study was intended to address two major uncertainties: (1) the regional changes in groundwater heads, flow, and quality caused by implementation of ASR and (2) the characteristics of ASR well-cluster designs suitable for meeting performance metrics that quantify acceptable pump pressures, hydraulic-head impacts, and target aquifer storage and recovery volumes.

Progress Addressing Uncertainties

The hydrologic modeling and associated analyses were conducted in two phases. Phase I involved testing alternative models under steady-state conditions and at coarse spatial resolution to improve understanding of model sensitivities and to evaluate numerical schemes. Phase II involved construction of a transient-flow model at a much finer spatial resolution using the USGS code SEAWAT. Following its calibration against available data, the Phase II model was used in predictive mode to evaluate the regional groundwater-flow response to the 333-well ASR system proposed in the CERP and to test various ASR configurations in the context of predefined performance objectives. The model simulations considered well placement only on land that is currently in state ownership.

Results of the model simulations suggest that the Upper Floridan aquifer would be unable to sustain the pumping requirements of 333 5 MGD ASR wells. Model analysis suggests that pump pressure and Artesian Pressures Protection Area requirements can be maintained with a 131-well configuration: 94 ASR wells in the Upper Floridan aquifer and 37 ASR wells in the

[5] Martin and St. Lucie Counties, to the east of Lake Okeechobee, represent an Artesian Pressure Protection Area, where users depend upon artesian groundwater heads for water withdrawal. Permits for ASR systems in this area require that ASR wells not reduce artesian flow by more than 10 percent.

Avon Park Permeable Zone (Scenario 11). The TDR acknowledges that other designs may exist that would permit a greater number of ASR wells, but these were not identified. The TDR also presents maps of maximum hydraulic-head changes throughout South Florida as a result of this scenario.

This is an ambitious modeling effort that incorporates the complex hydrostratigraphic architecture of South Florida and is a useful first step toward understanding the regional effects of large-scale ASR implementation. The results described in the Regional Study TDR are generally consistent with observed hydraulic-head distribution and flow patterns in southern Florida, providing confidence that large-scale physical processes are generally well approximated. Nevertheless, the model calibration and verification periods are short (14 months and 10 months, respectively) and limited to comparison of measured and modeled hydraulic heads. Confidence in the model would have been increased by comparison of simulated and observed salinities. Moreover, agreement between measured and modeled hydraulic heads is poor at many locations (Nash-Sutcliffe Coefficient < 0.5; Appendix E of the TDR), suggesting that, while suitable for approximating groundwater flow patterns at the regional scale, the model cannot consistently resolve local-scale and subregional variations in the potentiometric surface in response to ASR. The Final Groundwater Model Calibration Report (Appendix E of the TDR) notes that pumping rates of existing wells were poorly constrained, and these pumping rates likely contributed to observed model error.

The Regional ASR TDR recognizes the importance that heterogeneity plays in governing flow and aquifer responses to natural and anthropogenic stresses. Karst aquifers, such as the Floridan aquifer system, exhibit considerable structured heterogeneity associated with preferential flow paths caused, for example, by bedding-plane dissolution. Karst aquifers present challenges for hydrogeologic modeling because flow along these preferred flow paths may be turbulent, particularly during periods of ASR pumping. Despite these limitations, previous work has established that an equivalent porous media approach, as used in the Regional ASR Study Model, can reasonably simulate the potentiometric surface of a karst aquifer at the regional scale (e.g., Abusaada and Sauter, 2013; Ghasemizadeh et al., 2012; Kuniansky, 2014; Scanlon et al., 2003). However, heterogeneities and non-Darcian flow could have greater impact on the local scale.

In the assessment of maximum ASR capacity, the performance measures used to identify suitable distributions of ASR wells may not be fully appropriate. In addition to the constraint to protect artesian flow in St. Lucie and Martin Counties, 100 psi was specified as the maximum permissible pump pressure based on a casing pressure test. This 100-psi threshold is greater than the 66 psi allowed under the Underground Injection Control permit and the 85 psi reported in Chapter 3 of the Regional ASR TDR as the pressure (with 10 percent safety factor) that could initiate microfracturing. If the lower pressure threshold was adopted as one of the performance criteria, it is possible that fewer than the 131 wells prescribed by Scenario 11 could be safely deployed. Model-computed pressures, as well as those measured during the pilot studies, were generally less than 66 psi, so lowering the pump-pressure threshold from 100 to 66 psi may not substantially alter the design of the acceptable ASR configuration. However, a Monte Carlo analysis of uncertainty of Scenario 11 reports that 11 out of 16 ASR sites failed to meet the 100-psi pump pressure in 90 percent of random scenarios. Thus, before accepting the TDR's conclusion on maximum ASR capacity, the numerical results should be reconsidered with respect to the 66-psi threshold and any revised analysis of hydraulic fracturing.

Remaining Uncertainties

There are several lines of investigation that could be taken to reduce uncertainty in modeled predictions of the groundwater-flow response to ASR and to inform ASR well-cluster design. Rather than continuing to refine the Regional Model, it may be more advantageous to shift the focus to application of local-scale flow and transport models to particular areas where ASR is planned, because local-scale models are more amenable to characterizing and simulating the heterogeneous and possibly anisotropic nature of the Floridan aquifer system. Based on the observations of preferential flow zones and bedding-plane dissolution in the Floridan aquifer system of South Florida, the possibility of turbulent flow conditions during ASR should be evaluated during cycle testing. Newer modeling approaches that are capable of simulating turbulent, non-Darcian flow in layers or in discrete pipe networks (see, for example, Shoemaker et al., 2008a, b) could be considered as an alternative to the equivalent porous-medium approach, although they would require estimation of the spatial distribution in permeability and considerable additional hydrogeologic characterization. This characterization is impractical at the scale covered by the Regional ASR Study Model but becomes tractable if small, discrete areas of planned ASR development are targeted and local-scale models are employed. Local-scale models would also improve estimates of groundwater velocities needed to evaluate microbial transport and to address other water quality effects (e.g., changing salinities, advective loss of the stored water), which are important concerns that could not be addressed through application of the Regional ASR Study Model.

WATER QUALITY

The plans for ASR at the large scale required for Everglades restoration raised questions about the suitability of the available surface water for injection, the geochemical effects of its injection into the Floridan aquifer system, and the quality of the water recovered after storage. Water quality concerns are driven by a combination of regulatory, ecological, and operational factors. Naturally elevated levels of turbidity, iron, and organic matter in surface water can affect ASR well operations upon injection, while surface-water-derived pathogens pose human health concerns if they are transported after injection to drinking water wells. In addition, water-rock interactions in the subsurface can leach arsenic, radium, and trace metals into injected water, causing possible ecological impacts when the recovered water is discharged into the environment. Subsurface mixing with native water can also impact recovered water quality. Thus, the ASR Regional Study examined the water quality changes and related geochemical processes associated with ASR.

Source Water Quality and Suitability for Recharge

Surface water quality can pose concerns for ASR system performance. For example, elevated levels of organic carbon and iron can spur biofilm growth that could clog the well bore, while turbidity could clog the aquifer pore space with inorganic particulates. Thus, evaluating the range of ASR recharge water quality is important to understand future treatment needs and related project costs.

The EPA has established Underground Injection Control regulations that are enforced by the state to protect underground sources of drinking water (defined by EPA as groundwater with TDS < 10,000 mg/L[6]) from contamination from injected waters. In general, regulators in the state have dealt with this circumstance by requiring that the injected water meet both the primary and secondary maximum contaminant limits (MCLs) for drinking water in Florida (Rule 62-528, F.A.C. Class V, Group 7). The Florida Department of Environmental Protection can provide water quality criteria exemptions for secondary standards, as were granted for the ASR pilot projects for iron or color. No drinking water wells were located within a 5-mile radius of either the Kissimmee River or Hillsboro ASR wells (J. Mirecki, USACE, personal communication, 2015; R. Verastro, South Florida Water Management District [SFWMD], personal communication, 2015), although the committee does not know if similar separation distances exist at other proposed CERP ASR sites. South of Lake Okeechobee, the Floridan aquifer system is generally too saline for potable use without treatment.

Progress Addressing Uncertainties

Surface water quality data were evaluated near four of the five original proposed ASR pilot project sites—Hillsboro, Caloosahatchee River, Port Mayaca, and Kissimmee River (see Figure 1-2). Uniform water quality sampling and analysis was not implemented in support of this effort. Instead, the Regional Study team used existing water quality data from the SFWMD DBHYDRO database from 2000 to 2014 and conducted some limited additional sampling for trace metals and anthropogenic organic compounds over 1 year at the Kissimmee River ASR site. The array of constituents monitored was extensive but the number of samples and the frequency and duration of sampling and analysis were inconsistent across the sites for both surface water and groundwater. For example, samples for color ranged over 14 years from 81 samples at the Caloosahatchee River site to 388 at the Kissimmee River site. Based on the low sampling frequency, the TDR noted that color "trends are not well-resolved" at the Caloosahatchee River site. Only the Kissimmee River site benefited from a comprehensive assessment of surface water over the approximately 14-year time frame, and these data cannot simply be extrapolated on a regional basis across the study area. Thus, collectively, the data provide a somewhat limited view of water quality for ASR recharge across the region.

Sampling at these four sites showed high but variable concentrations of iron, turbidity, and organic carbon (color)—in some cases exceeding EPA secondary criteria—that could pose constraints on ASR without additional treatment. When specific absorbance of light by the water matrix is high, the effectiveness of ultraviolet (UV) disinfection is compromised. High levels of color are strongly correlated with high UV absorbance, and the ASR Regional Study TDR reports that color in excess of 50 platinum-cobalt color units (PCU) can hinder the effectiveness of UV disinfection. At three of the four sites sampled, sufficient color to hinder UV disinfection (>50 PCU) was detected in approximately 75 percent or more of the surface water samples. Elevated turbidity was reported at the Port Mayaca site. Iron concentrations frequently exceeded the secondary MCLs at the Port Mayaca and Kissimmee River sites. Iron and turbidity are known to interfere with UV disinfection and may also contribute to well clogging. The ASR

[6] http://www.epa.gov/r5water/uic/glossary.htm.

pilot studies conducted at Kissimmee River and Hillsboro addressed these issues by gaining regulatory exemptions for color and iron and by providing media filtration and ultraviolet disinfection prior to injection. Future application of ASR is likely to require continued regulatory exemption for these constituents and additional attention to water quality treatment necessary to optimize operations.

Although the Regional ASR TDR did not report the concentrations of pathogens and indicator organisms in raw surface water at the ASR recharge sites, USACE and SFWMD (2013) reported that fecal coliform and enterococci concentrations—indicators of human pathogens—in source water averaged 55 colony-forming units (CFU)/100 mL and 207 CFU/mL, respectively. Even after filtration and ultraviolet disinfection, the recharge water commonly contained total coliform, enterococci, and *Clostridium perfringens*, with one detection each of *Escherichia coli, Giardia lamblia,* and *Cryptosporidium.*[7] USACE and SFWMD (2013) stated, "the UV systems as currently constructed and operated do not provide sufficient and consistent microbe inactivation given the range of recharge water compositions."

The Regional Study examined the survival of seven different microorganisms (including bacteria, protozoa, and viruses) in native groundwater through bench-scale experiments using waters of different salinities and temperatures (John and Rose, 2004, 2005) and found variable inactivation rates, ranging from 1 to 5 weeks for 2-log inactivation of enterococci to 1-4 months for *Cryptosporidium* and up to 7 months for *Giardia lamblia.* Field studies of two organisms in flow-through chambers determined higher inactivation rates for *E. coli* compared to fecal coliforms in the bench-scale studies, although comparable data for time to 2-log removal was not reported. Field testing of subsurface microbial attenuation surrounding ASR wells was precluded by regulatory constraints.

Uncertainties Remaining

The studies described in the ASR Regional Study TDR and supporting documents identify the inorganic contaminants in source water that may be of concern to ASR operations. However, more work is needed on a site-specific basis to understand the likely range of conditions and consider specific treatment strategies to address any operational or regulatory concerns. Bank filtration through sandy Lake Okeechobee sediments may be a cost-effective pretreatment option for recharge water at the Port Mayaca site, which has frequent high turbidity levels. This treatment technology is common in other parts of the world (Weiss et al., 2005) but is uncommon in Florida.

The persistence of bacteria, protozoa, and viruses after treatment and their fate in the subsurface remain important uncertainties that need to be addressed to determine the appropriate extent of treatment necessary to protect public health and satisfy regulatory requirements. UV disinfection did not provide the anticipated removal, likely due to periods of high color and associated UV absorbance. The capital and operating costs for UV disinfection are substantial and may be more so if designed for the lower UV absorbance observed in testing. Thus, questions remain about whether natural processes could provide sufficient inactivation to reduce

[7] The EPA drinking water MCLs for microbial contaminants are primarily based on treatment performance (e.g., percent removal), but the total coliform MCL specifies that no more than 5 percent of samples in any month show detectable total coliforms (including fecal coliform).

the permit-required level of treatment or even eliminate the need for disinfection. The Florida Department of Environmental Protection (FDEP) has recently issued a Water Quality Criteria Exemption for total coliform bacteria for an ASR well in the City of West Palm Beach in recognition of the natural attenuation that occurs underground relative to the travel time necessary before the groundwater flows beyond the property boundary. The ASR Regional Study examined the inactivation rates of several microorganisms under laboratory conditions and two organisms in flow-through chambers in the field, but much more information is needed before such an exemption should be considered in the CERP to ensure that any current or potential future private or public water supply wells are not put at risk from ASR under reduced disinfection requirements. Specifically, more research is needed at the ASR sites to document inactivation rates for a wider range of organisms under field conditions and to compare these to groundwater flow rates and potential exposure points to assess risk to human health.

From a regulatory perspective, if public water systems[8] that use groundwater are located in the vicinity of future ASR wells, more work may be required to assess compliance with the EPA's Long-Term-2-Enhanced Surface Water Treatment Rule (LT2ESWTR). If the ASR wellhead disinfection system does not meet the minimum requirements of this rule—removal or inactivation of *Cryptosporidium* ooysts ranging from 99.9 to 99.997 percent, depending on sampling survey results (EPA, 2006)—a zone of "groundwater under the direct influence of surface water" (GWUDI; Chaudhry et al., 2009; Chin and Qi, 2000; Jacangelo and Rodriguez, 2001) may need to be established in the vicinity of the ASR well. Any public water systems that use groundwater located in this zone would need to add treatment to meet the requirements of the LT2ESWTR. Thus, locations of public water systems, the requirements of the LT2ESWTR, and the implications of a GWUDI zone need to be determined and considered in future ASR disinfection design.

Arsenic

ASR has the potential to mobilize arsenic in the subsurface when oxygen-rich surface waters oxidize pyrite, a common mineral in limestone in the Floridan aquifer system, and liberate arsenic bound within the pyrite structure (Arthur and Cowart, 2001; Mirecki et al., 2013). Because arsenic is toxic to humans and aquatic life, the extent and conditions of arsenic mobilization were major uncertainties for ASR in the CERP (ASR Issue Team, 1999). In 2006, the EPA lowered the drinking water standard for arsenic from 50 to 10 parts per billion (ppb), raising additional concerns about whether this new standard could be achieved in ASR. The State of Florida also has a Class III surface water criterion of 50 ppb arsenic. A letter from EPA to FDEP in 2013 (provided as Appendix A of the TDR) clarified that if ASR wells are anticipated to mobilize arsenic, permits are required to specify conditions to minimize mobilization, limit the spatial extent of contamination, and, if necessary to protect human health, restrict access to contaminated groundwater.

[8] Public water systems are defined by EPA as providing water for human consumption to at least 25 persons or at least 15 service connections (see http://water.epa.gov/infrastructure/drinkingwater/pws/index.cfm).

Progress Addressing Uncertainties

Significant progress was made in understanding the geochemical reactions responsible for the mobilization and sequestration of arsenic at the Kissimmee River ASR pilot site (Mirecki et al., 2013; USACE and SFWMD, 2013). Sampling was more limited at the Hillsboro ASR site. The pilot results suggest that repeated ASR cycles reduce arsenic concentrations in ASR recovery water. Both sites showed large increases in arsenic in the ASR well during the first cycle, with concentrations in recovery water exceeding 100 ppb at the Hillsboro site and 70 ppb at Kissimmee River, as the oxygenated water interacted with newly exposed pyrite. Subsequent cycles produced much smaller increases in the ASR well, with recovery water concentrations all below 10 ppb arsenic. Nearby monitoring wells showed increased concentrations after ASR recharge events, but those concentrations steadily declined over the course of storage.

Mirecki et al. (2013) concluded that ferric iron and organic carbon in the recharge water stimulated microbial activity that reestablished sulfate-reducing conditions over time in the subsurface, causing dissolved arsenic to coprecipitate with iron sulfide minerals. Data from the first cycle test at the Kissimmee River site demonstrated a sharp drop in dissolved oxygen and a steady decline in oxygen reduction potential after recharge ceased and the water was stored in the aquifer for 4 weeks (USACE and SFWMD, 2014). In cycle tests 3 and 4 at Kissimmee River, when recharge periods exceeded 170 days, arsenic concentrations were not monitored in the ASR well during storage, but elevated arsenic concentrations (above 10 ppb) were observed in groundwater monitoring wells located 350 and 1,100 feet away from the ASR well for up to 300 days. The Hillsboro site, which had shorter recharge and storage periods, did not show the same long-term elevated concentrations at monitoring wells. Mirecki et al. (2013) reported that sequestration of arsenic in the Upper Floridan aquifer appears to be dependent on ASR recharge water containing sufficient iron and organic carbon with low concentrations of other more energetically favorable electron acceptors, such as manganese and nitrate, which would delay the return of sulfate-reducing redox conditions in the storage zone.

Uncertainties Remaining

Some uncertainties remain regarding arsenic mobilization in future ASR implementation, considering differences in surface water chemistry across the region. For example, surface water at the Hillsboro site has much lower iron levels than the Kissimmee River and Port Mayaca sites. The Caloosahatchee site, which had very limited sampling of these constituents, indicates further variation in iron concentration and much lower levels of organic carbon. Port Mayaca surface water showed a significant seasonal variation in iron concentration, with much higher iron concentrations (up to 7,100 mg/L) than the other three ASR sites sampled. If ASR is to be implemented in the CERP, more research is needed to understand the impacts of different water qualities on long-term redox evolution of the aquifer and the effect on arsenic mobilization and sequestration. It would also be important to understand how far arsenic is likely to be transported within the aquifer over extended cycles (>1 year) and how the use of a target storage volume approach (where a freshwater buffer zone is established that is not recovered in subsequent pumping) affects arsenic transport and sequestration. A target storage volume approach could initially increase arsenic transport in the subsurface, which could pose regulatory concerns, particularly if the ASR wells are located in the vicinity of other drinking water wells, although arsenic concentrations are anticipated to attenuate with storage time.

Sulfate and Mercury

A key uncertainty identified by the ASR Issue Team (1999) was the potential for ASR to increase mercury and methylmercury in the Everglades. Mechanisms considered included enhanced methylation of mercury in the subsurface and increased mercury and sulfate discharged from groundwater into the ecosystem.

Progress Addressing Uncertainties

The Regional ASR TDR presents a rational case for negligible mercury and methylmercury loading in wetlands from recovered ASR water. Sampling at 24 wells (completed in the Floridan aquifer system and the Biscayne and surficial aquifers) showed that groundwater contains very low levels of mercury and methylmercury (<1 ng/L, with the lowest levels in the Floridan aquifer system). Therefore, ASR is unlikely to provide a significant additional mercury load to the Everglades ecosystem (Krabbenhoft et al., 2007). Based on laboratory experiments, Krabbenhoft et al. (2007) also concluded that increased ecosystem loading of methylmercury formed during ASR storage is unlikely because of extensive mercury sorption to the aquifer material. Field sampling confirmed these findings, as ASR pilot testing showed “no significant difference” in mercury and methylmercury concentrations at Hillsboro and a statistically significant reduction at the Kissimmee River site. The ASR Regional Study TDR identified three possible mechanisms that could explain the observed decreases in mercury during ASR storage: (1) dilution, (2) sorption to aquifer solids, and (3) coprecipitation as a solid sulfide. The conclusions with regard to decreases in mercury and methylmercury concentrations are reasonable for the conditions studied.

Another major uncertainty regarding the potential for ASR to enhance mercury methylation in the Everglades ecosystem involves increased sulfate loading to surface waters from ASR recovery water. The TDR presents sulfate concentration data from Upper Floridan aquifer and APPZ well samples taken across the region. These samples show substantially higher concentrations of sulfate than typical Everglades surface waters, with the lowest concentrations located north of Lake Okeechobee and the highest concentrations to the southwest and southeast. Maximum sulfate concentrations in surface waters at the four ASR test sites ranged from 38 to 83 mg/L, with median concentrations ranging from 11 to 30 mg/L sulfate. In contrast, mean sulfate concentrations of 446 mg/L in the Upper Floridan aquifer and 662 mg/L in the APPZ were reported, indicating the potential for sulfate loading in the ecosystem from recovered ASR water. Although sulfate concentrations throughout the Kissimmee River and Hillsboro ASR cycle tests were not reported, other cycle test data from ASR wells completed in the Upper Floridan aquifer (USACE and SFWMD, 2014, Appendix C) showed minimal changes in sulfate concentrations during storage but increasing sulfate in the recovery phase, as an increasing proportion of native groundwater was withdrawn during recovery. USACE and SFWMD (2013) state that at the end of the Kissimmee River ASR cycle test 4, sulfate concentrations were approximately half the concentration in native groundwater.

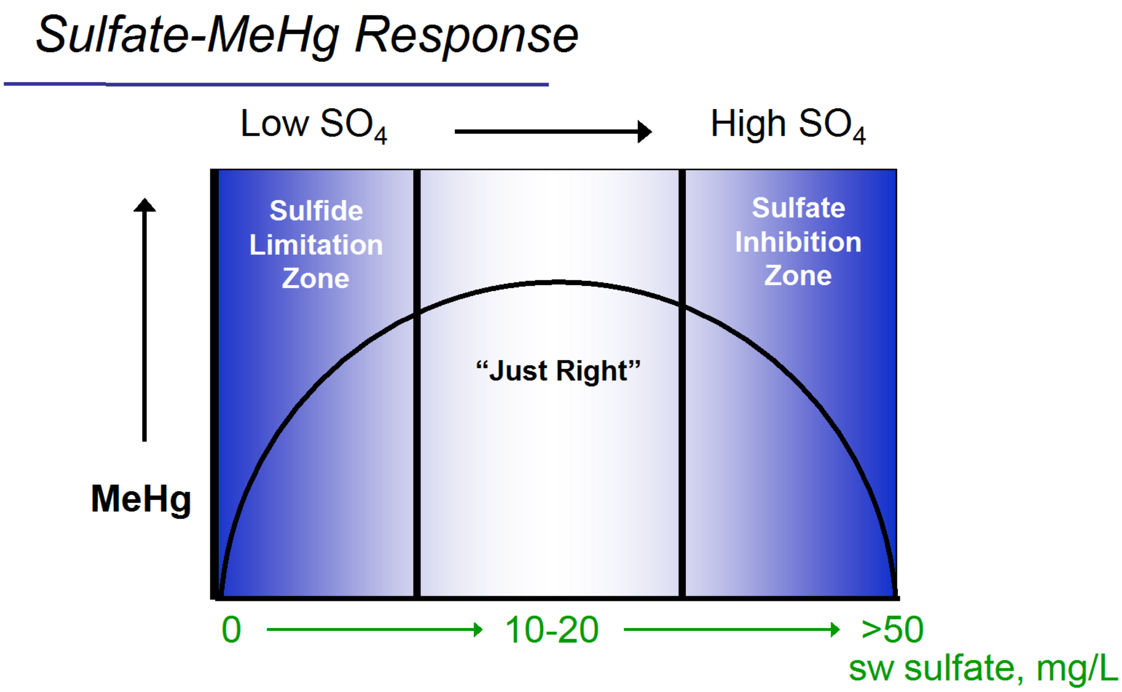

FIGURE 2-2 A simplified conceptual diagram showing the methylation of mercury in response to varying surface water (sw) sulfate concentrations. At low concentrations of sulfate, increasing sulfate leads to increasing methylation. At higher sulfate (and sulfide) concentrations, methylation is inhibited. This figure does not consider additional factors associated with dissolved organic matter (Graham et al., 2013). SOURCE: Modified from Gilmour et al. (2009).

In the Regional Study, the Lake Okeechobee Environment Model (Jin et al., 2007) was used to examine the impact of various ASR configurations on the sulfate concentrations in Lake Okeechobee. A simulation of 200 ASR wells (scenario ALT2V; likely an overestimate of what is feasible based on the groundwater modeling analysis) showed increases in peak sulfate concentrations in the lake to 75 mg/L from a baseline of approximately 50 mg/L, with these increases lasting several years in the reported simulation. Given that mercury methylation is likely already inhibited in the lake due to high sulfate concentrations (Figure 2-2), the ASR Regional Study TDR concludes that increased mercury methylation in Lake Okeechobee is a low risk. This finding is reasonable for the lake as a whole, because increased sulfate above 10 to 20 mg/L should not increase mercury methylation. The TDR acknowledges moderate uncertainty in this estimate, considering that there could be some locations within the lake with lower sulfate concentrations that are prone to increased mercury methylation under certain hydrologic conditions. The Everglades Landscape Model was used to simulate a worst-case scenario of extended ASR discharge of elevated sulfate concentrations and their impacts on sulfate concentrations in the Everglades. The model results show that, in this worst-case scenario, additional sulfate loading does occur but the concentration increases tend to be fairly low (<5 mg/L difference in scenarios, ALT2V or ALT4V).

Uncertainties Remaining

A major unresolved uncertainty relates to the actual concentrations of sulfate in ASR recovery water upon long-term ASR operations. Some analyses performed for this study (ALT2V, ALT4V) assumed sulfate concentrations in recovery water increased over time from typical surface water concentrations to those found in groundwater, while some more conservative analyses (ALT2C, ALT3C, ALT4C) assumed only native groundwater was recovered. Depending on how ASR recharge and recovery operations are managed, however, sulfate concentrations in recovered water could be much lower than these assumptions, particularly if an initial buffer zone is established and subsequently maintained. Thus, more work is needed to assess the effects of buffer zones and long-term ASR operations and storage on recovered water quality to better understand the downstream impacts.

The Regional Study provided some preliminary modeling to explore how increased sulfate could affect mercury methylation in Lake Okeechobee and the Everglades, but uncertainties remain. The Regional Study describes the impact of ASR-derived sulfate as “minimal” relative to other sources (e.g., agriculture), but small (<5 mg/L) shifts in sulfate have the potential to significantly increase mercury methylation if those areas are sulfate limited (Gabriel et al., 2014; see also Figure 2-2). For example, the area in western Water Conservation Area 3A projected by the Regional Study simulations to experience the greatest increases in sulfate concentrations under worst-case conditions (Figure 8-18 in USACE and SFWMD, 2014) is a region that Sheidt and Kalla (2007) reported to have low sulfate concentrations. The Regional Study correctly notes that increasing sulfate may inhibit methylation in some areas (e.g., Lake Okeechobee) while increasing it in others (e.g., Everglades), but no information is provided to document the relative change in methylation potential over time across the Everglades with ASR. More work is needed to model the anticipated changes in mercury methylation with increased sulfate loading in the Everglades, considering a range of probable ASR implementation and operational scenarios. Additionally, further study on temporal and spatial variability in sulfate and mercury methylation dynamics in Lake Okeechobee is warranted.

With regard to the fate of mercury in the subsurface, the laboratory experiments using crushed aquifer rock are useful to demonstrate the concept of subsurface mercury removal, but the results cannot be quantitatively extrapolated to actual well operation. Although ASR test data similarly showed a decline in mercury in recovered water compared to surface water, the Regional ASR TDR recommended further study on the mechanisms of mercury sequestration “before results from the current test wells can be extrapolated to other locations with any degree of certainty.” It is likely that water-surface interactions could vary from well to well based on native groundwater quality, aquifer and confining-unit characteristics, and ASR operational conditions.

Phosphorus

Phosphorus is a major contaminant in the Everglades ecosystem, which developed under oligotrophic (low-nutrient) conditions. Phosphorus inputs from many decades of agricultural activities have altered the remnant ecosystem, reducing the density and extent of periphyton communities (a key component of the food chain) and replacing areas of sawgrass with dense stands of cattail (NRC, 2012). A 1992 Consent Decree[9] ultimately led to the development of a 10 ppb-phosphorus criterion for the Everglades Protection Area and large state expenditures on water quality treatment and source control. Today, water quality remains a major constraint for moving new water into the remnant Everglades, because without additional treatment systems the added water could lead to a violation of the Consent Decree. Phosphorus in ASR recovered water was not initially a major uncertainty for ASR, although the ASR Issue Team (1999) recommended additional research to document the significant reduction of nitrogen and phosphorus that had been observed at some ASR facilities.

Progress Addressing Uncertainties

Cycle testing at Kissimmee River showed statistically significant reductions in phosphorus during storage (see Figure 2-3). Observed decreases during storage suggest that reductions in phosphorus concentrations occurred as a result of mineral precipitation, sorption, or biological uptake (Corbett et al., 2000; Price et al., 2010). Phosphorus concentrations at the Hillsboro pilot site were also reduced in the recovery water, although the results were not statistically significant. Limited sampling and problems with sample collection at the Hillsboro site limit the conclusions that can be drawn from this site.

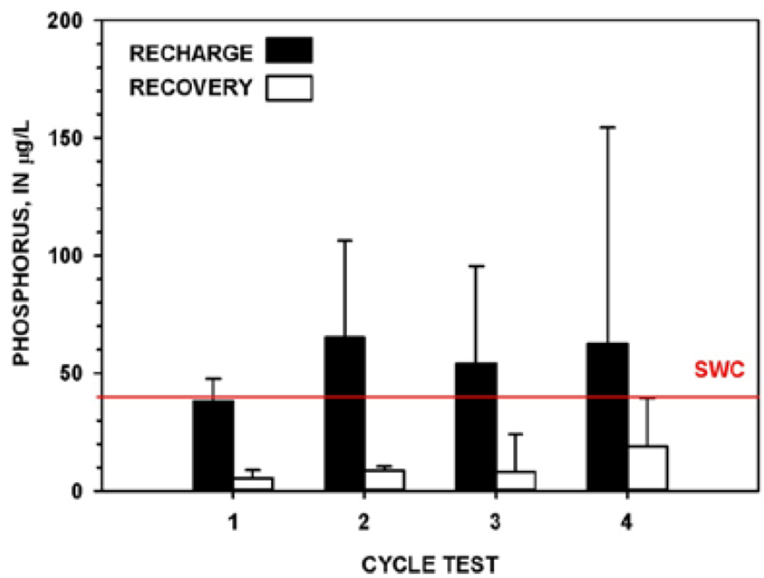

FIGURE 2-3 Phosphorus concentrations at the Kissimmee River ASR well during cycle testing. Error bars represent one standard deviation. The surface water criterion (SWC; 40 ppb) for Lake Okeechobee is shown as a red line.
SOURCE: USACE and SFWMD (2014).

[9] United States v. SFWMD, 847 F. Supp. 1567 (S.D. Fla. 1992).

Uncertainties Remaining

More research is needed to understand the mechanisms of subsurface phosphorus removal during ASR recharge and storage and how phosphorus sequestration is likely to vary over time. More study could determine if the upward trend in phosphorus in recovered water seen over the four cycles at Kissimmee River (Figure 2-3) would continue. Bench-scale experiments could be designed to examine these mechanisms to provide insight into the potential for phosphorus reduction in ASR. If long-term phosphorus removal could be documented and the mechanisms understood, water quality improvement could be considered an additional project benefit. If substantial long-term phosphorus removal is documented, the feasibility of siting ASR wells south of Lake Okeechobee might be considered to provide both storage and phosphorus treatment to the remnant Everglades. Phosphorus removal via ASR north of Lake Okeechobee could help expedite the timeframe for reaching water quality targets in the lake, but it would not impact phosphorus loads to the Everglades in at least the next few decades, given the large reservoir of legacy phosphorus in the lake.

Carbonate Solubility

One original ASR uncertainty involved changes in the aquifer matrix caused by dissolution. Although NRC (2001) largely focused this question toward understanding the liberation of trace metals, arsenic, and other ions from the rock matrix, dissolution of the limestone itself could alter aquifer properties. The calcite saturation indices of water samples showed that calcite dissolution would be expected throughout the storage zone: 1,100 feet away from the ASR well, during the recharge phase, and even during the storage phase 200 to 300 days into the cycle. During recovery, nearly all saturation indices became positive.

Although the ASR Regional Study TDR states that limestone dissolution is beneficial from an operational perspective, no analysis was conducted to suggest how much dissolution is likely over the long term and how dissolution might affect aquifer conditions over the long term. Other ASR systems in Florida may have data on changing transmissivity over repeated recharge and recovery cycles to reduce this uncertainty. Additionally, calculations could be performed using geochemical modeling (e.g., PHREEQ) to determine whether the amount of calcium carbonate dissolution has a significant effect on the overall porosity of the aquifer over long-term operations.

Gross Alpha Radioactivity and Radium Isotopes

A review of ASR water quality data in South Florida showed “pronounced spatial variations” in gross alpha activities (a measurement of alpha decay from uranium and its daughter products, including radium-226 and -228) with several instances of exceedance of the federal MCL of 15 picocuries/L (Appendix C of USACE and SFWMD, 2014). Elevated gross alpha activities are attributed to high-phosphate-containing lithologies in the lower Hawthorn Group (see Figure 2-1) and are commonly observed in southwest Florida (e.g., Lee and Collier Counties). The ASR pilot studies detected only one exceedance of the gross alpha MCL during cycle testing (detected at the Kissimmee River ASR site). However, given the known spatial variability, substantial uncertainty remains regarding gross alpha and radium activities in other locations across the Everglades ecosystem. Site-specific sampling would be warranted at any future proposed ASR site.

ECOTOXICOLOGY AND ECOLOGICAL RISK ASSESSMENT

Broad-scale use of ASR in South Florida has the potential to provide several important environmental benefits that include providing freshwater to the Everglades, decreasing current freshwater losses and impacts to coastal estuaries, and removal and sequestration of phosphorus from stored water in the subsurface environment. However, these possible benefits need to be compared to potential environmental risks related to the water quality of the recovered water and its ecological effects when discharged into the environment. Possible hazards of ASR in South Florida include mobilization of arsenic from pyrite in the storage zones, release of sulfur in recovered waters that could promote methylation of mercury in receiving surface waters, and toxicity of recovered waters to aquatic plants and animals.

Progress Addressing Uncertainties

To address these possible issues, the USACE, SFWMD, U.S. Fish and Wildlife Service, and others conducted a multiyear ecotoxicology and risk-assessment study based on ASR well placement in the Lake Okeechobee basin. The study included a standard suite of acute and chronic laboratory toxicity tests, ranging from 96-hour to 21-day tests, using recovered water samples from all four cycles of the Kissimmee River ASR pilot. The only detected toxicological effect was on the reproduction of *Ceriodaphnia dubia* (the water flea), which was observed in the middle of or late in the recovery cycles. Laboratory- and field-based bioconcentration tests were also conducted using fish and mussels, and both types of tests revealed evidence of accumulation of several elements, including arsenic. Some native mussels were also collected to assess their tissue concentrations, but data collected were insufficient to definitively link observed patterns of tissue concentrations to ASR recovery water. Additional field tests on ASR impacts to periphyton abundance and community composition were also not definitive because of limited testing and variable responses among the test sites. No toxicological effects were observed at the Hillsboro ASR site, although only limited toxicity tests required for permitting were performed.

Subsequent 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 (from 100 to 200 wells, with placement either entirely in the Upper Floridan aquifer or including the APPZ and Boulder Zone). Water quality data inputs were based on an assessment of groundwater quality in the Upper Floridan aquifer at the Kissimmee River site, SFWMD surface water quality data, and Kissimmee River ASR recovered water quality. Water quality modeling using the Lake Okeechobee Environment Model showed ASR-induced changes in phosphorus, sulfate, chloride, and dissolved oxygen in Lake Okeechobee in a multidecadal simulation. Changes in phosphorus concentrations were negligible, considering the vast reservoir of adsorbed phosphorus in the lake, but notable increases in sulfate, hardness, and chloride concentrations were observed, particularly during long ASR recovery events (when the lake would be at low levels during drought conditions). As the number of wells increases, so does the potential for moderate or high risks of adverse effects in Lake Okeechobee and in downstream receiving waters, including the Everglades ecosystem. However, as discussed previously in this chapter (see “Sulfate” and “Mercury”), the model considered several excessively conservative scenarios that are of limited usefulness, except to illuminate worst-case scenarios. Under a target storage volume approach, the influence of background groundwater on recovered water quality is minimized. Because the Kissimmee River ASR pilot did not develop a buffer zone, the recovered water quality data and the results of the “variable” water quality scenarios (that trend from surface water quality to background water quality) likely exaggerate the water quality effects in ASR wells that use a target storage volume approach. Additionally, risks of mercury methylation could be managed by halting ASR recovery based on sulfate concentrations rather than chloride concentrations, but such operational controls were not considered in the TDR.

Based on the toxicological results and water quality modeling, an environmental risk assessment was conducted in the ASR Regional Study based on four different well-placement scenarios. The risk-assessment approach was not probabilistic in nature and did not incorporate modernized quantitative techniques (e.g., Bayesian models) that have been developed for other regional-scale risk assessments. The largest near-field ecological risks were reported to be associated with chronic toxicity, arsenic bioconcentration, impacts to water clarity, and impingement or entrainment of larval fish. Moderate mid-field risks were reported for adverse impacts on mercury methylation, and far-field water quality effects include ecological impacts from increases in hardness. However, the results are based on limited sampling and lack of appropriate buffer zone development in the ASR wells, which limits the usefulness of the findings for regional ecological risk assessment. The quantitative shortcomings of the risk assessment itself also limit confidence in the findings.

The TDR concluded that the number, placement, and operational conditions of ASR wells influence the extent of ecological risk at a regional scale. The report also concluded that ASR systems should be ideally located adjacent to large flowing water bodies to allow for sufficient mixing zones and compliance with discharge permits. Despite the limitations of the current risk assessment, the committee supports this conclusion and suggests that any deviation from this be subjected to additional scrutiny because of the increased potential for adverse effects to local freshwater communities.

The Regional Study TDR concluded that use of a modest number of appropriately placed ASR wells will have low-to-moderate adverse effects on aquatic organisms and ecosystems. However, because the work raised several uncertainties, the committee judges that the findings are not yet conclusive enough to suggest that ASR is environmentally safe on a regional scale in south Florida. A more detailed understanding of potential toxicity, especially under chronic exposure and *in situ* conditions, is needed before incorporating ASR at a regional scale. This additional testing will reduce uncertainties associated with potential hazards to aquatic biota and significantly improve public perception and trust that broad-scale ASR is safe for protection of freshwater resources.

Uncertainties Remaining

The recovery of stored water can result in substantial changes to surface water chemistry, and significant uncertainty remains about the magnitude of those changes under probable ASR scenarios and the resulting effects to aquatic life at local and regional scales. Thus, an improved understanding of the quality of recovered water is needed, with longer storage times and larger storage volumes and considering a target storage volume approach (assuming such an approach is feasible under regulatory constraints for arsenic). Once the water quality implications of these operational conditions have been determined, additional modeling should be conducted to evaluate likely downstream effects under more realistic water quality assumptions, and additional toxicity and bioaccumulation testing should be conducted to resolve remaining uncertainties before ASR is implemented at a large scale.

Laboratory-scale testing of recovered water from the Kissimmee River ASR pilot facility revealed repeated chronic toxicity to *Ceriodaphnia dubia* reproduction in multiple separate tests and at middle and late stages of recovery. Because results of chronic toxicity tests are typically more ecologically meaningful than acute toxicity results, these findings raise significant uncertainty about the toxicity of recovered water, and the specific toxic constituents within the recovered water under expected operational conditions, that need to be resolved. The report suggests that these chronic toxicity results may have been an anomalous artifact, but, given that the adverse effect was replicated on at least five occasions, these outcomes should not be dismissed. 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.

In addition to bench-scale analyses, *in situ* testing should be expanded at different temporal and spatial scales to better understand the risks of recovered waters to freshwater communities. The committee agrees with the conclusion in the Regional Study ASR TDR that the community-based data provided are currently limited and not statistically robust. To better evaluate community-level impacts (i.e., benthos, periphyton, zooplankton, and fish), more *in situ* tests are recommended across spatial (e.g., upstream, within, and below mixing zones in different ecological settings) and temporal contexts (e.g., before and after experimental designs during different seasonal recovery contexts, under low-flow conditions, and during different periods during recovery). These studies should consider both bioaccumulation as well as potential shifts in community composition in response to ASR operations.

The ASR Regional Study TDR concluded that current bioconcentration tests were also largely inconclusive but indicated accumulation of elements such as arsenic in freshwater mussels. These initial results suggest that additional *in situ* bioconcentration tests are needed, ideally in conjunction with the aforementioned community composition analyses so that bioconcentration and community-level responses can be monitored simultaneously. In addition to using caged mussels, bioconcentration studies using periphyton and/or aufwuchs are recommended because of their importance to trophic transfer in food webs. As before, different spatial and temporal contexts should be considered, and more prolonged bioconcentration tests (i.e., beyond 69 days) are needed. If significant accumulation occurs in mussels and periphyton or aufwuchs, 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.

Additionally, the regional risk assessment is primarily based on ecotoxicological results from a single facility at Kissimmee River and was not regional in nature. In order to address uncertainties associated with scaling from Lake Okeechobee to a regional assessment of South Florida, additional sites for ecotoxicological testing should be examined. Potential ecological impacts from increased water hardness should also be examined, particularly to the northern water conservation areas and the Arthur R. Marshall Loxahatchee National Wildlife Refuge, for different ASR locations and discharge points. As summarized by NRC (2010), 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), with implications for fish species and food webs (Williams and Trexler, 2006).

Finally, future approaches to a regional ecological risk assessment should draw from extensive recent literature that builds upon EPA's (1998) early guidance document, providing robust quantitative risk assessment approaches to other complex regional issues (Bartolo et al., 2012; Bayliss et al., 2012; Landis and Thomas, 2009; Moares et al., 2002; Obery and Landis, 2002; Walker et al., 2001; Wiegers et al., 1998). The Regional Study ecological risk assessment relies heavily on the early EPA (1998) guidelines which were originally intended to define the risk of single chemicals to single receptor species (Landis, 2005). Applying these early techniques to understand how ASR operations could affect diverse receptors across a spatially heterogeneous landscape is inadequate for identifying risk in such a complex system. A central problem with the current approach is that it is not probabilistic in nature, does not provide a modern quantitative uncertainty analysis and description (Landis, 2005; NRC, 2009), and relies on qualitative rankings of risk (minimal to high) without a transparent underlying quantitative basis for these rankings. By clarifying particular attributes of specific entities (e.g., the number of bluegill sunfish reproducing in a receiving stream) that could be adversely affected by regional ASR (Suter et al., 2005), risk-assessment models could be used to generate explicit probabilities of various outcomes. In the end, the risk assessment should provide clear guidance based on these probabilities about the risks of different ASR scenarios and a quantitative evaluation of the inherent uncertainties associated with these conclusions.

COSTS AND BENEFITS OF WATER STORAGE ALTERNATIVES

One uncertainty that was not identified by either the ASR Issue Team (1999) or NRC (2001) is the economics of ASR relative to other water storage and water management options. This information is critical to management decisions on possible future roles for ASR in the CERP. SFWMD and USACE (2013) provided detailed data on the capital and operating costs of the two pilot studies, including power, labor, and materials costs for each ASR cycle. In 2007, the SFWMD published an investigation of the economics of various water supply and water management technologies (CDM, 2007), and although the report documents capital costs per million-gallons-per-day well capacity based on a number of ASR projects in Florida, it offers little clarity on comparative costs. Additional analysis is needed to compare the capital and long-term operating costs of ASR to other storage alternatives. The pilot studies and information from similar ASR investigations nationwide should be used to examine long-term ASR costs, and these costs should be compared to the storage benefits (e.g., volume of ASR water delivered to the Everglades, reduction in high-volume flows to the northern estuaries) under various simulated climate scenarios. These analyses should consider existing uncertainties related to recovery efficiency, disinfection technology required, and the potential for gravity flow of water recovered from ASR wells. The results could then be compared against similar analyses of new surface storage alternatives to estimate costs per volume of water delivered to the Everglades for various water storage alternatives. Project managers stated that cost-benefit analyses were not considered in the ASR Regional Study because they are a required part of any future CERP feasibility study. However, a clear demonstration of costs and benefits is needed if decision makers are to continue to support further research to resolve critical ASR uncertainties in the near term.

INTEGRATION AMONG STUDY TOPICS

The major components of the ASR Regional Study included

1. Hydrogeologic and geophysical characterization,
2. Geotechnical analysis,
3. Water quality evaluation,
4. Microbial-fate assessment,
5. Hydrogeologic simulation modeling, and
6. Ecological risk assessment.

Because these components address interrelated phenomena, the overall approach of the ASR Regional Study was intended to be integrative in nature such that the components of the study informed and drew from one another. The complexity of the Regional Study, which necessitated contributions from numerous personnel with disparate scientific expertise, posed a formidable challenge to integrating across topics.

The two components of the ASR Regional Study that were perhaps integrated most successfully and to greatest benefit were the hydrogeologic characterization and the groundwater-flow modeling. In particular, an extensive field campaign yielded quantitative estimates of aquifer properties and well-delineated hydrostratigraphic units that were requisite to development of a regional model for groundwater flow. Results of the groundwater modeling revealed that less than half of the originally planned 333 ASR wells were feasible if performance measures and constraints were to be met. This critical piece of information was, in turn, used in another facet of the study to better inform simulations of the effects of ASR operations on the water quality of Lake Okeechobee.

In a few instances, there were too few data and too little knowledge exchanged across major study initiatives. For example, the analysis of microbial fate within the Floridan aquifer system was based largely on measurements of microbial inactivation rates. Inactivation rates are necessary, but insufficient, for approximating the distances in which live, pathogenic microbes could penetrate into the aquifer during the recharge and storage phases of ASR. The analysis could have been strengthened by integrating data on inactivation rates with groundwater flow rates to estimate the areal extent of groundwater degradation resulting from introduction of pathogen-containing waters during ASR operations. Additionally, the wellhead pressure performance measure used in the predictive groundwater simulations did not appear fully informed by the operational permitting constraints of the pilot studies. If greater exchange of data and findings among the study tasks were promoted, it is unlikely that the key findings of the ASR Regional Study would have changed significantly, although support for some conclusions could have been strengthened.

3

Looking Forward

The Aquifer Storage and Recovery (ASR) Regional Study resolved many uncertainties about large-scale application of ASR in South Florida and developed tools and an impressive knowledge base to support future ASR projects, if implemented, but the research identified several new questions, and some key uncertainties remain. This chapter presents the committee's assessment of the highest-priority uncertainties that need to be resolved before large-scale implementation of ASR is considered. These uncertainties could be addressed across a range of scales, from continued operation and cycle testing of existing pilot project wells to an incremental adaptive management approach (NRC, 2007, 2008), where a few ASR well clusters are constructed and operated to provide some restoration benefits while building knowledge and resolving critical uncertainties to inform future project implementation.

HIGH-PRIORITY RESEARCH NEEDS

Chapter 2 identified many remaining uncertainties. This section reflects the committee's judgment on the highest-priority uncertainties, considering their implications to Comprehensive Everglades Restoration Plan decision making. These uncertainties are discussed in more detail in Chapter 2, but summarized here. The following are *not* listed in rank order but are organized by topic.

Operations to Maximize Recovery and Reduce Water Quality Impacts

As discussed in Chapter 2, the ASR pilot operations were appropriate to examine possible geochemical changes occurring in groundwater during storage and to limit the spatial extent of arsenic transport, but they were inappropriate to explore maximum well recoveries. Most or all of the injected water was removed without initial formation of a buffer zone, thereby lowering the recovery efficiencies compared with what could likely be achieved under a target storage volume approach. More research is needed at the Hillsboro site, where only 30 percent recovery was documented, to determine whether improvements in recovery can be achieved when a buffer zone is established prior to cycle testing and maintained throughout the subsequent cycle testing. The use of well clusters should also be examined to improve recovery efficiencies and performance. This approach will have major implications for the ecotoxicity of the recovered water, because the proportion of native groundwater will be substantially reduced. However, a larger buffer zone could create an expanded zone of near-term arsenic mobilization that is anticipated to attenuate over time.

Ecotoxicology and Ecological Risk Assessment

Some of the largest uncertainties remaining after the ASR Regional Study are associated with the ecological risks of using recovered ASR water in the Everglades. The results of chronic toxicity testing to date suggest some cause for concern and a need for further analysis considering longer storage times and greater recharge volumes, as well as more sites. Current *in situ* bioconcentration tests and assessment of community composition are not adequate to draw conclusions or for informing a robust and probabilistic risk assessment. Lack of a fully developed buffer zone presents a key limitation in the interpretation of the existing results. Recovered water quality and the resulting ecotoxicological impacts are likely to be quite different under an ASR operational strategy that builds and maintains a buffer zone within the aquifer (a target storage volume approach). For mercury methylation in the Everglades, the impacts are likely to decrease because groundwater contributions of sulfate would be reduced. Toxicity and bioconcentration of arsenic and trace metals would likely differ with a target storage volume 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. Planners could also consider ways to manage the risks of mercury methylation through sulfate concentration limits during ASR recovery.

Future ecotoxicological testing should be designed in light of the fact that water from ASR operations will primarily be recovered during dry, low-flow conditions. If toxicity or bioconcentration is determined, more work is needed to understand the underlying causes so that strategies can be developed to mitigate these effects, if feasible. Additionally, researchers should examine the availability of mixing zones under a range of hydrologic conditions at potential ASR sites to reduce near-field ecological effects. As additional toxicological uncertainties are evaluated, results should be incorporated into a modernized probabilistic regional assessment of relative risk of adverse effects to receptor populations. In addition, a formal sensitivity analysis will help guide the prioritization of what additional toxicological data should be generated to inform future assessments.

Understanding Phosphorus Reduction Potential

Removal of phosphorus represents a key unexplored benefit of ASR, and more research is needed to examine the long-term rates and extents of subsurface phosphorus removal under various aquifer conditions. Laboratory experiments could be developed to better understand these processes, with subsequent field testing to examine phosphorus removal at larger scales. If ASR proves to substantially remove phosphorus over long-term operations, additional work is warranted to examine whether ASR wells could also be sited south of Lake Okeechobee in addition to the originally planned sites north of Lake Okeechobee (see Figure 1-1). The benefits of near-term water storage and water quality improvements to the remnant Everglades ecosystem would need to be weighed against potential ecological risks at these sites.

Disinfection

Disinfection permitting requirements were not uniformly achieved during the pilot studies due to high organic matter in the recharge water. To meet regulatory requirements, additional work is needed to determine appropriate pretreatment strategies—ones that would not hinder subsurface arsenic attenuation processes, which are thought to be particularly dependent on organic carbon and iron in recharge water. Some have suggested that a regulatory exemption may be possible for ASR with respect to microbial contaminants in recharge water. Laboratory research on pathogen survival in groundwater has demonstrated inactivation in flow-through chambers at varying rates, but substantial additional research is needed on a wider suite of pathogens under groundwater conditions before such an exemption is considered. Also, this information needs to be coupled with an understanding of groundwater travel times and flow patterns and the locations of potential human exposure to determine the level of disinfection necessary to protect human health and meet regulatory requirements.

Cost and Performance of ASR Compared to Alternatives

The Regional Study examined an array of configurations to provide 1.7 billion gallons per day storage capacity for Everglades restoration, but the Technical Data Report lacks a comprehensive comparison of the costs and benefits of ASR technology with other storage alternatives. Regional modeling suggests that the number of 5-million-gallon-per-day wells feasible on existing state-owned land without exceeding well-pressure constraints is less than half of the number originally envisioned (131 versus 333 wells) and many of those have low assumed recoveries. The benefits provided by these wells are not clearly described in terms of flood prevention or water supplied during drought years, and the capacity for ASR to address the timing of storage and water supply demands remains poorly understood. Decision makers are unlikely to support continued research on ASR without clear documentation of the potential benefits of ASR relative to other possible alternatives. Thus, a comparative cost-benefit assessment for water storage alternatives is an important next step. Benefits should be assessed in terms of new water delivered to the Everglades, flood flow prevention, or water quality improvements, and opportunities to enhance these benefits through integrated operations of ASR wells with storage reservoirs should be examined. If a target storage volume approach is judged to be potentially beneficial, the analysis of costs and benefits should also consider the volume of water necessary to form and maintain the freshwater buffer zone. Cost and benefit analyses should also document performance uncertainties, which may help prioritize research needs to inform future decision making.

FUTURE IMPLEMENTATION

The high-priority uncertainties can be resolved through research at a range of scales, from laboratory experiments and computer modeling to continued cycle testing at existing sites with expanded ecotoxicological testing to phased expansion of ASR. Although current uncertainties are too great to justify near-term implementation of ASR at a large scale in the Everglades, opportunities exist to target future phased implementation of ASR in a way that addresses critical uncertainties and enhances future implementation. The National Research Council (NRC, 2007) advocated an "incremental adaptive restoration" (IAR) approach to expedite restoration in light of disagreements over scientific uncertainties that were holding back decisions on how to move forward. In contrast to pilot studies, which rarely provide restoration benefits, an IAR approach allows increments of proposed projects to move forward, providing tangible restoration benefits while resolving key uncertainties. Within an IAR strategy, decision-critical uncertainties that could be addressed by the project increment are clearly identified up front, so that subsequent implementation can be improved by knowledge gained. An IAR approach for ASR could involve one or more clusters of three to five ASR wells, perhaps including wells in both the Upper Floridan aquifer and the Avon Park permeable zone, to address critical uncertainties such as recovery efficiencies, performance, long-term water quality, and ecological effects. Given the existing uncertainties, these initial wells should be sited adjacent to large surface water mixing zones to reduce adverse ecological impacts. The downside of an IAR approach is that operations that aim to provide restoration benefits may come at the detriment of ideal experimental design, and, initially, resolving critical uncertainties may need to be the primary objective of near-term ASR testing. Additionally, several key uncertainties may be most cost-effectively addressed through continued cycle testing of existing wells. However, phased installation of ASR wells to resolve key uncertainties could provide earlier restoration benefits compared to continued operations of the single-well ASR pilots.

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Acronyms

APPZ	Avon Park permeable zone
ASR	aquifer storage and recovery
CERP	Comprehensive Everglades Restoration Plan
CFU	colony-forming unit
EPA	Environmental Protection Agency
FAS	Floridan aquifer system
FDEP	Florida Department of Environmental Protection
ft^2/d	square feet per day
GWUDI	groundwater under the direct influence of surface water
IAR	incremental adaptive restoration
ICU	intermediate confining unit
LF1	uppermost permeable zone of the Lower Floridan aquifer
LT2ESWTR	Long-Term-2-Enhanced Surface Water Treatment Rule
MCL	maximum contaminant limit
MGD	million gallons per day
NRC	National Research Council
PCU	platinum-cobalt color unit
ppb	parts per billion
psi	pounds per square inch
SFWMD	South Florida Water Management District
TDR	Technical Data Report
TDS	total dissolved solids
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
UV	ultraviolet

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Appendix A

Biographical Sketches of Committee Members and Staff

James Saiers, *Chair*, is a professor of hydrology, the Associate Dean of Academic Affairs, and professor of chemical engineering at the Yale School of Forestry and Environmental Studies. Dr. Saiers studies the circulation of water and the movement of waterborne chemicals in surface and subsurface environments. One element of his research centers on quantifying the effects that interactions between hydrologic and geochemical processes have on the migration of contaminants in groundwater. Another focus is on the dynamics of surface water and groundwater flow in wetlands and the response of fluid flow characteristics to changes in climate and water management practices. His work couples field observations and laboratory-scale experimentation with mathematical modeling. Dr. Saiers is a member of the National Research Council (NRC) Committee on Independent Scientific Review of Everglades Restoration Progress and was a member of the 2012 Hydraulic Fracturing Research Advisory Panel of the Environmental Protection Agency (EPA) Science Advisory Board. He earned his B.S. degree in geology from the Indiana University of Pennsylvania and his M.S. and Ph.D. degrees in environmental sciences from the University of Virginia.

Charles Harvey is a professor at Massachusetts Institute of Technology (MIT) and is an experienced scientist, mentor, and leader of multidisciplinary environmental science projects. He has worked extensively on issues of hydrology, biogeochemistry, and groundwater contamination. He is credited with making fundamental advances in understanding chemical transport and reaction in flowing groundwater. He has several built large-scale field programs to study (1) arsenic contamination in Bangladesh, (2) the ecology of peat swamp forests in Borneo, and (3) the interaction of fresh and saline groundwater beneath Cape Cod. He was awarded a National Science Foundation Career Award, the 2008 M. King Hubbert award for major scientific contributions to groundwater hydrology, the 2012 Prince Sultan Abdulaziz International Prize for Water, and the 2014 Geological Society of America Meinzer Award for seminal contributions to hydrogeology. Dr. Harvey is Co-Director of *Terrascope*, an undergraduate learning community at MIT built on a sequence of classes that investigate a different global environmental issue each year. He has taught workshops on hydrology and water contamination in Bangladesh, Denmark, Italy, and Singapore. He has advised the governments of Singapore, India, Kuwait, and Brunei on water resource management. Dr. Harvey holds a B.S. degree in mathematics from Oberlin College, and a Ph.D. degree from Stanford University.

William A. Hopkins is a professor in the Department of Fish and Wildlife Conservation at Virginia Tech and the Program Director of the Interfaces of Global Change interdisciplinary graduate education program. His research program focuses on physiological ecology and wildlife ecotoxicology, addressing pressing questions in both basic and applied science. Current work in Dr. Hopkins' laboratory examines the bioenergetics of various processes including digesting various prey types, development under variable incubation conditions, mounting an immune response, and enduring parasitic infections. He is also interested in maternal effects and how maternal behavioral decisions may influence a mother's fitness and the fitness of her offspring. Dr. Hopkins' previous research experience at the Savannah River Ecology Laboratory, Mercer University's Medical School, Auburn University, and the University of South Carolina includes quantification of diverse physiological responses of invertebrates and vertebrates to natural and anthropogenic stressors. Hopkins serves as a toxicologist on the Scientific Advisory Board for the International Center for Birds of Prey, and served as a member of the National Research Council Committee on Mine Placement of Coal Combustion Wastes. Dr. Hopkins received his B.S. degree in biology from Mercer University, an M.S. degree in zoology from Auburn University, and a Ph. D. degree in ecology, evolution, and organismal biology from the University of South Carolina.

Kenneth W. Potter is a professor in the Department of Civil and Environmental Engineering at the University of Wisconsin. Dr. Potter's areas of research include estimation of hydrologic risk, especially flood risk; adaptation of hydrologic design to climate change; assessment and mitigation of human impacts on aquatic systems; and restoration of aquatic systems. Dr. Potter is a fellow of the American Association for the Advancement of Science, a fellow of the American Geophysical Union, and a Woodrow Wilson fellow. He has extensive NRC committee experience. He is a former member of the Water Science and Technology Board, chaired the NRC Committee on American River Flood Frequencies and the NRC Committee on Integrated Observations for Hydrologic and Related Sciences, and he served on the Committee on Restoration of the Greater Everglades Ecosystem. Dr. Potter received his B.S. degree in geology from Louisiana State University and his Ph.D. degree in geography and environmental engineering from Johns Hopkins University.

René Marie Price is an associate professor in the Department of Earth and Environment and the Southeast Environmental Research Center at Florida International University and is currently a Florida Professional Geologist. Dr. Price is a chemical hydrogeologist, who uses geochemical constituents to trace water flow throughout the hydrologic cycle. Her research interests include groundwater and surface water interactions, ecohydrology, karst hydrogeology, seawater intrusion, and sea level rise. She has conducted hydrologic research extensively in South Florida and the Everglades, and internationally in Spain, India, Mexico, and Australia. She also has served as science advisor on several Everglades Restoration science advisory boards. Dr. Price holds a B.S. degree in geology from Rensselaer Polytechnic Institute, an M.S. degree in environmental sciences from the University of Virginia, and a Ph.D. degree in marine geology and geophysics from the University of Miami.

R. David G. Pyne is President of ASR Systems, LLC. He has more than 40 years of water supply engineering and water resources management experience, including investigations, design, and construction of more than 40 wellfields. He is recognized as the pioneer and leader of aquifer storage recovery (ASR), having developed this technology in Florida, elsewhere in the United States, and overseas since 1978. In Florida this has included the first operational ASR wellfield in Manatee County which became operational in 1983, and many of the operational ASR wellfields completed since then. He has led research projects for the Southwest Florida Water Management District and the South Florida Water Management District addressing the fate of microbiota during storage in ASR wells, and operational measures to control arsenic mobilization and attenuation during ASR storage. He has actively participated in the development of legislation, regulations, and policies governing ASR in Florida and nationwide. Mr. Pyne successfully established ASR Systems LLC during 2001 to provide water resources and ASR consulting services. Prior to that, he worked with CH2M HILL for 30 years, directing the firm's ASR program. He has provided ASR consultant assistance to the World Bank, International Atomic Energy Agency, UNESCO, and USAID. His technical expertise encompasses groundwater hydrology, surface water hydrology, water quality, water supply and wastewater systems planning, stormwater management, environmental studies, deep injection wells, bank filtration, and aquifer recharge. Mr. Pyne holds a B.S. degree in civil engineering from Duke University and an M.S.E. degree in environmental engineering sciences from the University of Florida.

Larry Robinson is a Distinguished Professor in the School of the Environment at Florida A&M University (FAMU). Previously he served as the Interim President at FAMU from July 2012 to April 2014. His research interests include environmental chemistry and the application of nuclear methods to detect trace elements in environmental matrices and environmental policy and management. In May 2010, Robinson took a leave of absence from FAMU to serve as Assistant Secretary of Commerce for Conservation and Management at the National Oceanic and Atmospheric Administration (NOAA). While there, he supported and managed NOAA's coastal and marine programs, including marine sanctuaries for preserving areas of special national significance, including fisheries management and preparation of nautical charts. He also supported NOAA's participation in addressing the BP oil spill crisis and served on the Ocean Policy Task Force. He returned to the university as a special assistant to the FAMU president in November 2011 and was selected as Provost and Vice President for Academic Affairs in March 2012. From 2001 to 2010, he served as Director of NOAA's Environmental Cooperative Science Center housed at FAMU. Dr. Robinson was on the NRC Committee on Mine Placement of Coal Combustion Wastes and the Committee on Restoration of the Greater Everglades Ecosystem. He earned a B.S. in chemistry from Memphis State University and a Ph.D. in nuclear chemistry from Washington University in St. Louis, Missouri.

Elizabeth J. Screaton is a professor of hydrogeology at the University of Florida, Gainesville. Dr. Screaton studies groundwater flow in geological process, the exchange of surface and groundwater in karst aquifer systems, and the interactions between water flow and deformation in subduction-zone sediments. Her work in subduction-zone research combines field work, laboratory work, and numerical modeling to investigate the interrelationship of fluid flow and deformation. Dr. Screaton earned her B.A. degree in geology from Carleton College, M.S. degree in Earth sciences from the University of California, Santa Cruz, and a Ph.D. degree in Earth sciences from Lehigh University.

Rhodes Trussell, NAE, is the founder of Trussell Technologies, Inc. Previously he was the lead drinking water technologist at Montgomery Watson Harza, Inc. He is recognized worldwide as an authority in methods and criteria for water quality and the development of advanced processes for treating water or wastewater to achieve the highest standards. He has worked on the process design for dozens of treatment plants, ranging from less than 1 to more than 900 million gallons per day in capacity and has experience with virtually every physiochemical process and most biological processes as well. He has a special interest in emerging water quality problems and water reuse. Dr. Trussell is a member of the National Academy of Engineering and has served for more than 10 years on the U.S. Environmental Protection Agency's (EPA's) Science Advisory Board. He also served as chair of the Water Science and Technology Board, has been a member of numerous NRC committees, including the Committee on Indicators for Waterborne Pathogens, and chaired the NRC committee on water reuse. Dr. Trussell holds B.S., M.S., and Ph.D. degrees in environmental engineering from the University of California, Berkeley.

STAFF

Stephanie E. Johnson, study director, is a senior program officer with the Water Science and Technology Board. Since joining the National Research Council in 2002, she has worked on a wide range of water-related studies, on topics such as desalination, wastewater reuse, contaminant source remediation, coal and uranium mining, coastal risk reduction, and ecosystem restoration. She has served as study director for over fifteen committees, including the Panel to Review the Critical Ecosystem Studies Initiative and all five Committees on Independent Scientific Review of Everglades Restoration Progress. Dr. Johnson received her B.A. from Vanderbilt University in chemistry and geology, and her M.S. and Ph.D. in environmental sciences from the University of Virginia.

Brendan McGovern is a senior program assistant with the Water Science and Technology Board (WSTB). Since joining the NRC in 2014, he has contributed to the production of Reducing Coastal Risk on the East and Gulf Coasts and Progress Toward Restoring the Everglades: The Fifth Biennial Review. Prior to joining the WSTB, Brendan worked with the American Association for the Advancement of Science and the Henry L. Stimson Center. Mr. McGovern received his B.A. degrees in political science and history from the University of California, Davis.