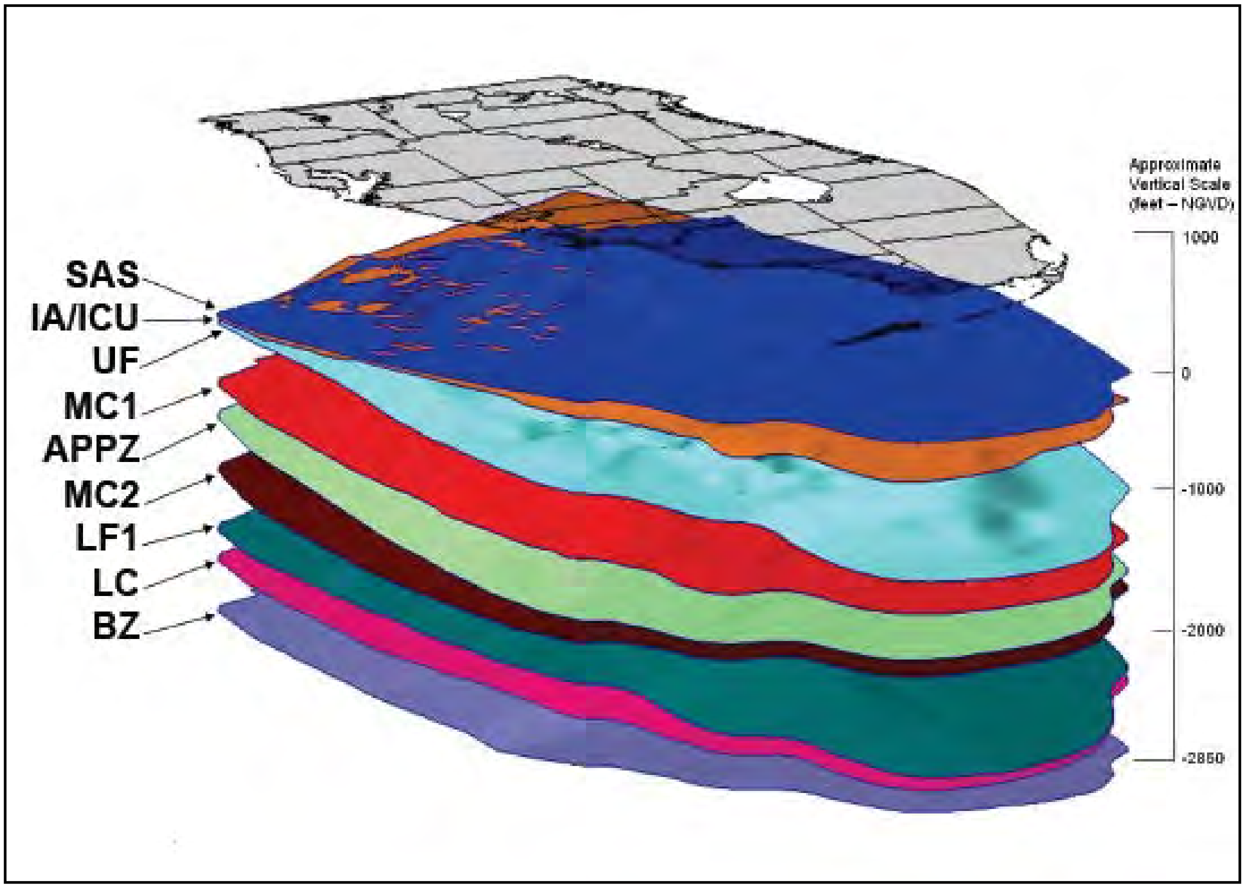
# CENTRAL AND SOUTHERN FLORIDA PROJECT

# COMPREHENSIVE EVERGLADES RESTORATION PLAN



## DRAFT TECHNICAL DATA REPORT

## AQUIFER STORAGE AND RECOVERY REGIONAL STUDY

October 2014

Cover photo:  Hydrostratigraphic layers defined in the Regional ASR groundwater flow model.  Figure from USACE (2011).

CENTRAL & SOUTH FLORIDA

COMPREHENSIVE EVERGLADES RESTORATION PLAN

DRAFT

# REGIONAL AQUIFER STORAGE AND RECOVERY
# TECHNICAL DATA REPORT

OCTOBER 2014

**This page intentionally left blank**

# Table of Contents

## List of Figures

## List of Tables

## Table of Appendices

## List of Acronyms

| | |
|---|---|
| ANOVA | Analysis of variance |
| APPA | Artesian pressure protection area |
| APPZ | Avon Park Permeable Zone |
| APT | Aquifer Performance Test |
| ASR | Aquifer Storage and Recovery |
| ASRRS | ASR Regional Study |
| ASTM | American Society for the Testing of Materials |
| AWS | Alternative water supply |
| BGD | billion gallons per day |
| BLS | below land surface |
| BZ | Boulder zone |
| C&SF | Central and South Florida Project |
| CEPP | Central Everglades Planning Project |
| CERP | Comprehensive Everglades Restoration Plan |
| CHD | Specified Head Package (in SEAWAT) |
| CMP | Common mid-point |
| CRASR | Caloosahatchee River ASR system |
| CROGEE | Committee for Restoration of the Greater Everglades Ecosystem |
| CT | Computed tomography |
| %CV | Percent coefficient of variation |
| DO | Dissolved oxygen |
| DOC | Dissolved organic carbon |
| E | Modulus of elasticity |
| EFDC | Environmental fluid dynamics code |
| EIS | Environmental impact statement |
| ELM | Everglades landscape model |
| ENP | Everglades National Park |
| EPA | Everglades protection area |
| ERA | Ecological Risk Assessment |
| ERDC | Engineer Research & Development Center |
| FAS | Floridan Aquifer System |
| FDEP | Florida Department of Environmental Protection |
| FEB | Flow equalization basin |
| FETAX | Frog embryo teratogenesis assay-*Xenopus* |
| FFWCC | Floridan Fish and Wildlife Conservation Commission |
| FGS | Florida Geological Survey |
| FIB | Fecal indicator bacteria |
| FS | Factor of safety |
| GIS | Geographic information system |
| HASR | Hillsboro ASR system |
| IAS | Intermediate Aquifer System |
| ICU | Intermediate Confining Unit |
| IMC | Interagency Modeling Center |
| KRASR | Kissimmee River ASR system |
| $K_x$, $K_y$ | Hydraulic conductivity in the x- and y-directions |
| LC | Lower confining unit |

| | |
|---|---|
| LEC | Lower east coast |
| LFA/LFA1 | Lower Floridan Aquifer (zone 1) |
| LOEM | Lake Okeechobee environmental model |
| LOOPS | Lake Okeechobee operations planning spreadsheet |
| MC1, MC2 | Middle Confining Unit 1 (upper); Middle Confining Unit 2 (lower) |
| MDWASD | Miami-Dade Water and Sewer Department |
| MFA | Middle Floridan Aquifer |
| MFL | Minimum flows and levels |
| MHASR | Moorehaven ASR system |
| MOC | Method of characteristics |
| MSS | Multi-spectral scanner |
| NAS | National Academy of Sciences |
| NELAP | National Environmental Laboratory Accreditation Program |
| NEEPP | Northern Everglades and Estuaries Protection Plan |
| NGVD | National Geodetic Vertical Datum |
| NPDES | National Pollutant Discharge Elimination System |
| NRC | National Research Council |
| NTU | Nephelometric Turbidity Units |
| ORP | Oxidation-reduction potential |
| OTU | Operational taxonomic units |
| PDT | Project delivery team |
| PMASR | Port Mayaca ASR system |
| PMP | Project management plan |
| PPDR | Pilot project design report |
| RASRSM | Regional ASR Study Model |
| RFGW | Regional Floridan ground water (network) |
| RFP | Request for proposal |
| ROMP | Regional observation monitoring program |
| SAS | Surficial Aquifer System |
| SAV | Submerged aquatic vegetation |
| SDWA | Safe Drinking Water Act |
| SJRWMD | St. Johns River Water Management District |
| SFWMD | South Florida Water Management District |
| SFWMM | South Florida Water Management Model |
| SFERWG | South Florida Ecosystem Restoration Working Group |
| SFNRC | South Florida Natural Resources Center |
| SOFIA | South Florida Information Access |
| SSM | Source and Sink Mixing package (in SEAWAT) |
| STA | Stormwater treatment area |
| SWFWMD | Southwest Florida Water Management District |
| SZMW | Storage zone monitor well |
| $T_x$, $T_y$ | Transmissivity in the x- and y-directions |
| TDS | Total dissolved solids |
| TH | Total head |
| TOC | Total organic carbon |
| TP | Total phosphorus |
| TVD | Total variation diminishing (method) |
| UFA | Upper Floridan Aquifer |

| | |
|---|---|
| UIC | Underground injection control |
| USACE | US Army Corps of Engineers |
| USDW | Underground source of drinking water |
| USEPA | US Environmental Protection Agency |
| USFWS | US Fish & Wildlife Service |
| USGS | US Geological Survey |
| UV | Ultraviolet |
| WCA | Water conservation area |
| WRDA | Water resources development act |
| WQCE | Water quality criterion exemption |

## List of Units

| | |
|---|---|
| ac-ft | acre-feet |
| cfs | cubic feet per second |
| CFU | colony forming unit |
| ft | feet, foot |
| $ft^2$/day | foot-squared per day |
| ha | hectares |
| hrs | hours |
| Hz | hertz |
| in | inch |
| $\log_{10}(CFU*mL^{-1})$ | $\log_{10}$(colony forming units per milliliter) |
| μg/L | micrograms per liter |
| μm | micrometer, micron |
| m | meter |
| md | millidarcy |
| mg/kg | milligram per kilogram (parts per million) |
| mg/L | milligram per liter |
| MGD | million gallons per day |
| MG | million gallons |
| mL | milliliter |
| MPa | megapascals |
| mTons/yr | million tons per year |
| NTU | Nephelometric turbidity units |
| PCU | platinum cobalt units |
| psi | pounds per square inch |

# Foreward

The U.S. Army Corp of Engineers and the South Florida Water Management District are pleased to present this Technical Data Report for the Aquifer Storage and Recovery Regional Study. To demonstrate what has been accomplished during the course of this project, this foreword provides a brief history of the Comprehensive Everglades Restoration Plan's (CERP) ASR Program.

In 1999, up to 333 Aquifer Storage and Recovery (ASR) wells were proposed by the CERP to recharge, store and recover water underground to ensure water for the Everglades and natural systems, improve conditions in Lake Okeechobee and minimize damaging releases of fresh water to coastal estuaries. Acknowledging this unprecedented scale of ASR technology proposed, the plan included pilot projects to address and reduce uncertainties about its use.

Concerns have been expressed about the use of ASR in the CERP: possible fracturing of rock formations and the movement of stored water within the aquifer; perceived growth management conflicts; preference for "natural" rather than "artificial or engineered" solutions; or possible increases in groundwater arsenic concentrations, for example.

Technical uncertainties about ASR have also been numerous and varied, especially due to limited understanding of regional-scale ASR implementation. These questions prompted the formation of a multiagency team of scientists, engineers and planners to develop plans for and conduct the CERP ASR Regional Study, in coordination with the ASR pilot projects. Designed to evaluate CERP ASR feasibility, the plans were approved in 2002–2003 and an intensive data collection effort began.

Today, despite tremendous challenges and constraints, many studies have been performed by our organizations and others and a great deal of knowledge has been gained about ASR for the CERP. Significant contributions to this work effort have been made by the United States Geological Survey, the Florida Geological Survey, the Florida Department of Environmental Protection and the United States Fish and Wildlife Service, to name a few. The best available data and state-of-the-art methods and models have been used throughout the study process. This report documents the results of over a decade of scientific and engineering investigations. Summaries of research and results are presented in this volume and the attached CD contains expanded documentation of each study. This publication continues our commitment to communicate with the public as work progresses toward restoration of the south Florida ecosystem.

# How To Read This Document

Certain practitioners will be more interested in some sections than others, so the following lists chapters of interest by sub-discipline. All readers should consult the **Executive Summary** and **Chapter 1**, Introduction and Authorization, to gain an understanding of the background of the CERP ASR technical program. **Chapter 2** contains descriptions of some "early evaluations" that were conducted when this project was first initiated, along with related CERP and non-CERP projects, and summaries of the CERP ASR pilot project results. For more information about the ASR pilot projects – specifically the Kissimmee River and Hillsboro ASR systems, the reader is also encouraged to review the Technical Data Report for them, published in 2013.

**Hydrogeologic Framework and Geotechnical Evaluations for ASR Operations – Chapter 3** describes the development of a conceptual hydrogeologic framework for the Floridan Aquifer System (FAS). Also included here are studies to define hydraulic characteristics of permeable zones in the FAS, and analyses of borehole geophysical and seismic reflection data to evaluate subsurface structural geology. **Chapter 4** summarizes geotechnical analyses to evaluate the potential for rock fracturing and subsidence during ASR operations.

**Native Surface and Groundwater Quality Evaluations for ASR Operations - Chapter 5** summarizes native surface and groundwater quality around Lake Okeechobee. Selected wet- and dry-season surface water quality characteristics are characterized in the context of operating the water treatment components of an ASR system. Native groundwater quality also is characterized with implications for percent recovery, potential for calcium carbonate dissolution, and arsenic mobilization. **Chapter 6** summarizes studies to characterize native subsurface microbial communities in the FAS, and implications for survival of fecal indicator bacteria such as coliforms.

**Regional Groundwater Flow Model and Simulations of Regional ASR Implementation. Chapter 7** presents the development of the groundwater model, which evaluates regional hydraulic effects of operation of the ASR wells envisioned by CERP, including an estimate of total number of ASR wells that could safely be implemented under the program. Familiarity with the hydrogeological framework in **Chapter 3** is helpful for full understanding of this model.

**Ecotoxicological Studies and Ecological Risk Assessment.** Chapter 8 presents the ecological evaluations that were undertaken to determine the effects of water recovered from the CERP ASR systems on the greater Everglades environment, including the findings of an ecological risk assessment.

**Addressing Concerns of Stakeholders, the National Research Council, and the ASR Issue Team.** Chapter 9 presents a synthesis of findings of the individual studies conducted during this project, and formats them as responses to the technical concerns that had been raised by the 1999 ASR Issue team and later recommendations that were made by CROGEE.

# Executive Summary

## Synopsis

This report summarizes a 12-year effort to assess the regional feasibility of constructing Aquifer Storage and Recovery (ASR) wells throughout south Florida as a component of the Comprehensive Everglades Restoration Plan (CERP). This project was conducted by a multi-agency, multi-disciplinary team of scientists and engineers who formulated and executed numerous investigations in response to critiques and recommendations by the National Research Council's Committee on Restoration of the Greater Everglades Ecosystem (CROGEE). In tandem with this project, the United States Army Corps of Engineers and South Florida Water Management District constructed and tested two ASR pilot facilities adjacent to Lake Okeechobee and the Hillsboro Canal, to determine site-specific aspects of ASR system permitting, design, operation, and testing. The results from the ASR pilot projects have been integrated into the regional synthesis of information contained herein.

Hydrogeologic evaluations were conducted in coordination with the United States Geological Survey and the Florida Geological Survey to fill data gap areas with new wells, aquifer tests, seismic surveys, and geophysical measurements. This work resulted in a new synthesis of the hydrostratigraphy and structure of the Floridan Aquifer System (FAS) throughout south Florida. Groundwater levels and quality within the FAS were also documented and mapped as a result of an extensive groundwater monitoring program. Rock cores and geotechnical analyses were integrated with this evaluation, to determine the safe operating pressures that would not result in fracturing or subsidence of strata near the ASR wells.

Geochemical evaluations took place during testing of the ASR pilot facilities, including construction of geochemical models based on actual recovered water quality. Concerns about the mobilization of metals resulting from leaching of the aquifer matrix prompted extensive bench-top evaluation of water-rock interactions by the Florida Geological Survey and extensive monitoring of surface and groundwater quality at the Kissimmee River ASR system during operational testing.

These data were then used to construct a three-dimensional, density-dependent groundwater flow model that was used to predict the number and approximate locations of ASR wells that might reasonably be operated without causing adverse impacts to existing users, the strata, and groundwater regime.

In addition to questions about the physical effects of ASR operation, a number of analyses were conducted to ascertain the ecological responses that might occur from water recovered from ASR systems. As part of this effort, a 3-year "pre-ASR" baseline environmental survey was performed, including source water quality, sedimentologic, vegetation, and fish and macroinvertebrate assessment was conducted at locations where ASR was envisioned, to establish existing environmental conditions, so that comparisons could be made whenever ASR operation might commence. Toxicity tests and bioaccumulation studies were performed on organisms placed within the stream of water recovered from the ASR systems.

Data from the pilot projects, the groundwater model, baseline ecological studies, and geochemical analyses were then integrated into a comprehensive, regional environmental risk assessment (ERA). Evaluation of the potential for mercury methylation resulting from ASR was included in the ERA.

**Essential findings from this project are as follows:**

- Large capacity ASR systems can be built and operated in south Florida. However, variability in aquifer characteristics will result in varying well performances and makes it prudent to conduct an exploratory program before constructing surface facilities.
- To date, no "fatal flaws" have been uncovered that might hinder the implementation of CERP ASR, although the results of the groundwater modeling evaluation indicate that overall number of wells should be reduced from 333 wells to approximately 140 wells, completed in the upper and middle zones of the FAS.
- The potential for rock fracturing and land subsidence resulting from ASR is very low, provided that the wells are spaced at safe distances from each other and that pumping pressures are kept low.
- Despite generally favorable results from the ASR pilot projects, the surface water in south Florida presents some challenges to conventional disinfection technologies. Also, arsenic mobilization occurs during early cycle testing, but attenuates over time as the storage zone is conditioned.
- Water recovered from the ASR pilot projects did not result in any quantifiable acute or chronic toxicological effects on tested species, with the exception of a temporal inhibition of reproduction of a cladoceran, which should be verified by additional testing. Mussels and periphytometers deployed in the recovery stream at the Kissimmee River ASR did not exhibit significant negative bioaccumulation affects or shifts in community composition.
- The potential from mercury methylation from storage and recovery of water from within the FAS has been determined to be very low. However, groundwater from the FAS has sulfate concentrations that are higher than those in surface water, so recovery of ASR systems should be maintained so as not to result in deleterious concentrations of that constituent.
- Some reduction in phosphorus concentration was observed during ASR storage. This process is postulated to result from microbial uptake, aquifer matrix filtration, or mineral precipitation. The phenomenon should be considered when selecting ASR locations for maximum benefit.
- Implementation of CERP ASR should proceed in a phased approach, which includes expansion and continued testing of pilot facilities and construction of new ASR systems at environmental restoration features that could be optimized by underground water storage, treatment, and recovery.

## Narrative

Aquifer Storage and Recovery (ASR) is defined as the storage of excess water in an aquifer via a dual-purpose well for subsequent recovery when needed. ASR technology offers the potential to store and supply vast quantities of water without the need for large tracts of land, and as such it was included as a vital component of the Comprehensive Everglades Restoration Plan (CERP) being implemented by the

United States Army Corps of Engineers (USACE) and the South Florida Water Management District (SFWMD).

The Central & Southern Florida Project Comprehensive Review Study (Restudy; USACE and SFWMD, 1999) recommended the construction and operation of up to 333 ASR wells located in clusters throughout south Florida accounting for approximately 70 percent of the CERP system-wide water storage capacity. The unprecedented scale of ASR proposed in the Restudy led to public concerns about the application of ASR for Everglades restoration. The concerns included a range of issues including the potential for groundwater and surface water quality degradation associated with ASR operations, and subsequent effects on people and ecosystems; and the overall feasibility of regional scale ASR operations, including its impact on other users and the potential to induce structural damage to the aquifer. To address public concerns, identify uncertainties, and review the potential for regional-scale ASR implementation in Florida, the South Florida Ecosystem Restoration Working Group formed the ASR Issue Team in September 1998. The ASR Issue Team, as well as the National Research Council's Committee on Restoration of the Greater Everglades Ecosystem (CROGEE), developed a series of reports between 1999 and 2002 that provided recommended actions specific to ASR implementation in south Florida. The intent of these reports was to identify the additional information needed to reduce uncertainties surrounding implementation of ASR at a regional scale.

In response to the recommendations defined by the Working Group and the CROGEE, two related efforts were initiated: the ASR Regional Study, and the associated CERP ASR Pilot Projects at Kissimmee River and Hillsboro. The primary reference for results of the CERP ASR Pilot Projects is in a separate technical data report published previously (USACE and SFWMD, 2013). The following is a summation of knowledge gained since the Restudy on findings relevant to the feasibility of CERP ASR implementation. This work represents the efforts of a multiagency, multidisciplinary team of hydrogeologists, engineers, and environmental scientists who have developed plans, responded to reviews and critiques, formulated strategies, and conducted experiments to answer technical questions about the role of ASR in the CERP.

Results obtained from operations of the ASR pilot systems provided field data to augment scientific and engineering studies that have been conducted that helped determine:

- Optimal operations to maximize recharge, storage, and recovery;
- The effectiveness of water treatment technologies prior to recharge;
- Water-quality changes that take place during recharge, storage, and recovery;
- The potential for mercury methylation during ASR storage;
- The relationship between storage zone properties and recovery efficiency;
- The water-rock interactions and geochemical reactions within the aquifer;
- The impact of recovered water on test organisms through extended bioassay testing in laboratory and field settings; and
- The extent to which regulatory compliance during ASR cycle testing with regard to all relevant state and federal laws can be achieved without exemptions.

## Hydrogeologic Investigations

A collaborative effort was undertaken by the U.S. Geological Survey (USGS), Florida Geological Survey (FGS), USACE, and SFWMD to conduct a thorough review of available scientific literature on the hydrogeology of south Florida and compile the information into a working database. While building the database, numerous areas of missing information, or "data gaps" were identified. Extensive geological and geophysical investigations were then performed to fill in the missing information – including construction of seven new test wells and core borings throughout south Florida but focused on the pilot project sites. A regional, synoptic survey of ground water quality was completed to characterize the upper and middle portions of the Floridan Aquifer System (FAS) prior to ASR pilot system construction. Information collected at these sites has been used to establish baseline conditions prior to initiating pilot project cycle testing. The data collected has led to a more comprehensive understanding of water levels and water quality in the FAS, and has facilitated calibration of the regional groundwater flow and solute transport model.

A major contribution of the ASR Regional Study is the refined hydrogeologic framework for south Florida. A preliminary framework was published in 2008, which synthesized a significant amount of hydrologic, hydraulic, lithologic, and stratigraphic data to better define subsurface conditions in the FAS. One of the major findings of this report was the definition of the Avon Park Permeable Zone (APPZ), which is a regionally extensive permeable zone formerly known as part of the Middle Floridan Aquifer of southeastern Florida. An update to the preliminary hydrogeologic framework was published in 2014, which incorporated all data surrounding Lake Okeechobee obtained since 2008, along with seismic reflection survey interpretations beneath the Lake. The 2014 update identified geologic features that could affect ASR system placement and well construction. For example, the contact between the Ocala Limestone and overlying Hawthorn Group sediments was mapped throughout the study area, which defines the upper portion of a typical storage zone and overlying confining unit. Faults, fractures, and karst collapse structures also were identified in the upper portions of the FAS.

## Geophysical and Geotechnical Investigations

While drilling the test wells and exploratory wells at the proposed CERP ASR pilot project sites, extensive geophysical logging was completed to gather data on a range of hydrogeologic parameters including porosity, fracture potential, and the degree of confinement, all of which have aided in the understanding of patterns of flow and suitability at specific areas for ASR wells. Two reports were completed to evaluate pressure-induced fracturing: A desk-top analysis and a more detailed investigation based on geotechnical data from cores at proposed ASR system locations around Lake Okeechobee. These investigations concluded that there is a low risk for single-well ASR operations, or multi-well operations with adequate spacing, to induce fracturing of the aquifer matrix (Suwannee Limestone and Ocala Limestone) under normal operating conditions required by permit. The geotechnical analysis was conservative in that several failure mechanisms were investigated, with microfracturing of limestone being the most likely result. Induced microfracturing was evaluated with a factor of safety so that minimum pressure thresholds for the onset of microfracturing were defined.

Minimum pressures to induce microfracturing, with a 10 percent factor of safety, ranged between 85 psi and 149 psi for all proposed ASR systems. Propagation of shear fracture into the overlying Hawthorn Group confining unit also was determined to be unlikely. A more regional evaluation of fracturing potential was conducted as part of the regional groundwater flow model as discussed below.

To understand the location and direction of preferential flow in the FAS from a regional perspective, a lineament analysis was completed over the entire CERP ASR footprint. This analysis linked topographic features and known geologic formations to map linear trends in limestone formations, identify potential existing fractures, and from this extrapolate the degree and orientation of anisotropy, which is one factor controlling groundwater flow. The Restudy proposed several ASR well clusters along the perimeter of Lake Okeechobee; however, little was known of the hydrogeology beneath the lake. In 2007, a marine seismic reflection survey was conducted on Lake Okeechobee and found that the upper portion of the FAS is laterally continuous under the lake. This information led to the development of a new hydrogeologic framework for the FAS that was then integrated into a regional groundwater model. This information, combined with other regional geological, hydrogeological and geotechnical data, led to the development in 2008 of a new hydrogeologic framework for the FAS that was integrated into the regional groundwater flow model. Marine seismic reflection data beneath Lake Okeechobee were incorporated into an updated hydrogeologic framework published in 2014. The revised hydrogeologic framework confirmed layering of the regional groundwater flow model in the region beneath Lake Okeechobee.

## Geochemical Studies

In 2004, water chemistry data from 11 potable water ASR facilities in south Florida were compiled to characterize the changes in water quality that occur during ASR cycle testing. This report noted some initial water-quality changes that occurred during storage, including evolution of hydrogen sulfide and ammonia as a result of microbe-mediated reactions in the storage zone. Wells located in Lee and Hendry Counties, where the Upper Floridan Aquifer (UFA) is included within the Arcadia Formation, show naturally occurring gross alpha radioactivity and elevated activity of radium isotopes. ASR systems located in these regions could have recovered water that exceeds State and Federal criteria with regard to these radionuclides.

Mixing of recharged freshwater and native groundwater during cycle testing is an important control of geochemical reactions in the storage zone. Chloride is a conservative tracer of native groundwater, so changes in chloride concentrations can indicate how recharge water displaces and mixes with native groundwater during a cycle test. In 2004, chloride-based mixing models were developed using data obtained from municipal utility ASR systems. These early mixing models suggested that mixing trends are site-specific rather than uniform throughout the UFA. Mixing models also were developed during cycle testing at the KRASR system. Chloride-based breakthrough curves show that recharge water flows as a plug through preferential flow zones, rather than mixing to form a diffuse buffer zone.

A second report was released in 2008, which characterized major geochemical reactions that occur during the recharge, storage, and recovery phases of a cycle test. Recharging the UFA with oxygenated surface water initiates pyrite oxidation, which releases trace metals into the aquifer. The mobility of trace elements (for example, iron, arsenic, and molybdenum) is controlled by evolution of the redox environment in the aquifer as the cycle test proceeds, from oxygen-rich recharge conditions, to sulfide-rich (oxygen-poor) native conditions. A published report in 2012 confirms that geochemical conditions are favorable to limit arsenic mobility at the KRASR pilot system. Additional analysis presented in this report suggest that it is reasonable to extrapolate arsenic control reactions observed at KRASR to other ASR systems located in the interior of south Florida.

In order to quantify trace metal mobilization processes under controlled laboratory conditions, the FGS conducted water–rock interaction experiments under oxic and anoxic conditions, using limestone from many representative Florida limestone lithologies including those at proposed CERP ASR systems. These laboratory experiments simulated water-rock interactions during different phases of a cycle test. Oxic conditions would characterize recharge, while anoxic conditions would prevail during storage and recovery. Results indicated that trace elements such as iron, arsenic, and molybdenum are released when pyrite in the limestone is exposed to oxygenated water. As long as the water-rock environment remains oxic, arsenic can be captured by sorption on newly precipitated iron oxides. This reaction will limit arsenic mobility during the recharge phase.

Geochemical models were developed to interpret water-quality changes observed at CERP ASR systems particularly at KRASR. Models focused on evaluating two important geochemical processes: 1) mobilization and attenuation of arsenic; and 2) limestone dissolution. The KRASR water quality dataset enabled interpretation of arsenic geochemistry under oxic conditions of recharge, and anoxic conditions of storage and recovery. Arsenic attenuation can occur during recharge due to sorption on iron oxide surfaces in the aquifer. However, arsenic sorption is temporary due to instability of iron oxides under anoxic (specifically sulfate-reducing) conditions. Arsenic attenuation under anoxic (specifically sulfate-reducing) conditions during storage and recovery was demonstrated at KRASR. The geochemical model showed that arsenic co-precipitated with newly formed iron sulfide minerals in the aquifer, and arsenic concentrations were shown to decline below the 10 µg/L regulatory criterion. Geochemical reactions that attenuate arsenic under anoxic conditions are possible at other locations where surface water and groundwater quality characteristics are similar to that of KRASR.

Introduction of recharge water that is undersaturated with respect to calcium carbonate into the FAS will cause dissolution of limestone aquifer material. Calculation of calcium carbonate saturation indices in groundwater samples obtained throughout each KRASR cycle test show that dissolution occurs primarily during the recharge phase, and that stored water composition evolves toward calcium carbonate saturation. This process can be expected at other locations where surface water and groundwater quality characteristics are similar to that of KRASR.

## Microbiological Studies

Little is known about the survival of microorganisms that potentially could be introduced into the Floridan Aquifer during ASR operations. Bench-top and field studies were conducted to better quantify inactivation rates of representative bacteria and protozoans. Bench-top studies were conducted early in the ASR Regional Study to determine the effects of temperature and total dissolved solids concentrations on representative bacteria, phages, and protozoans. Higher temperatures (22°C and 30°C) decreased the survival of representative microbes (or, increased the inactivation rate). Total dissolved concentrations ranging between 200 mg/L and 10,000 mg/L had no effect on survival. A reduction of 99 percent (2-$\log_{10}$ inactivation) of fecal coliforms was predicted over periods of 2 to 6 weeks in groundwater, and 1 to 2 weeks in surface water.

Microbe survival was studied in the field using a novel flow-through mesocosm that was connected to wells open to the Upper Floridan Aquifer or the Avon Park Permeable Zone. The mesocosm was equipped with diffusion chambers inoculated with either *Escherichia coli* or *Pseudomonas aeruginosa*, two freshwater pathogens. The experimental design allowed contact between microorganisms and native groundwater under controlled conditions at the wellhead. Results of field experiments predicted faster inactivation rates for *E. coli* when compared to bench-top results, particularly during the early periods of exposure to groundwater.

Very little is known about the types of microorganisms, their abundance, and physiology that exist under native conditions of the FAS. Native bacterial communities extracted from the FAS were cultured in the laboratory and analyzed using DNA analysis (PhyloChip™) to characterize bacterial diversity in groundwaters of the Upper Floridan Aquifer and Avon Park Permeable Zone. This analysis revealed that native populations of bacteria and archaea are more diverse than expected.

## Groundwater Flow and Transport Modeling

Density-dependent groundwater flow and solute transport models can be used simulate the effects of density, pressure, flow, and solute transport on both local and regional scales. The ASR Regional Study groundwater model development was one of the key tools used for evaluation of ASR implementation. The groundwater model and simulations are major deliverables of this project. Primary goals of the groundwater flow modeling effort were:

- To evaluate the potential effects that regional-scale ASR implementation, as envisioned in the CERP, might have on the Floridan Aquifer System of south Florida
- To analyze the local- and regional-scale changes in groundwater levels and flow directions
- To determine the potential effects of aquifer pressure changes during recharge and recovery operations
- To predict regional water-quality changes within the Floridan aquifer system
- To propose locations and the number of ASR wells that optimize benefits and minimize or eliminate potential risks

Recharge and recovery scenarios over a long period of record were defined previously in the South Florida Water Management Model run known as D13R, and this simulation provided the timing and magnitude of recharge, storage, and recovery that was required in the CERP. The PDT and the model development team determined a series of performance indicators for the evaluation of each simulation.

Development of the groundwater flow model followed the adaptive management paradigm. The model was developed in phases, with most phases receiving external peer review by the Interagency Modeling Center (IMC). Those phases were: literature review of existing models; bench-scale analysis to compare different model codes for the effort; Phase I model development (coarse-grid); Phase II model development (fine grid) with calibration; and use of the Phase II model for D13R predictive simulations. As simulations were run, it became clear that the performance measures could not be met in many basins using the number of ASR wells proposed in CERP, open to the Upper Floridan Aquifer (UFA). Scenarios were then modified to reduce the number of ASR wells in the UFA, and assign them to other aquifers including the APPZ or the Boulder Zone.

The groundwater model was useful for testing scenarios that involved operation of ASR wells in the upper FAS and the APPZ, located deeper within the FAS. Multiple scenarios were tested, starting with the locations and number of ASR wells originally proposed by CERP. Eventually, the number of wells was reduced in order to minimize or eliminate detrimental effects to the aquifer, groundwater, or existing users. The final results show that it is unlikely that the aquifer will sustain the pumping requirements of 333 UFA ASR wells as defined in the CERP plan. The modeling process showed that pump pressure requirements and protection of the Artesian Pressure Protection Area (APPA) of Martin and St. Lucie Counties can be met with approximately 94 ASR wells in the UFA, 37 ASR wells in the APPZ and 101 wells in the BZ if the extraction at sites near the APPA is significantly reduced. (UFA and APPZ wells were assumed to have a 5 MGD capacity; BZ wells were assigned a 10 MGD capacity.) Simulated recovery efficiencies from these lower zones were reduced to 30 percent in most of the APPZ wells and 0 percent (i.e. recharge but no recovery) in the BZ wells.

## Ecotoxicology Analysis and Ecosystem Risk Assessment

A baseline environmental monitoring program and preliminary ecological tests have been performed to assess and predict the effects of the ASR Program on the south Florida ecosystem. Studies on the effects of chemicals on organisms and ecosystems, as well as potential for mercury contamination have been completed.

Extensive ecotoxicology investigations were conducted as a component of the cycle testing at the Lake Okeechobee ASR pilot project site. These investigations were intended to assess the potential of ASR recovered waters to reach acute and chronic toxicity levels and bioaccumulation of trace metals (e.g., arsenic, cadmium, selenium, and mercury) and radium in representative aquatic species native to surficial waters at and downstream of the ASR outflow locations. Toxicity bioassay series and acute static renewal definitive tests have been conducted at the Lake Okeechobee ASR Pilot Project with recovered cycle test waters.

Ecotoxicology studies have shown the recovered waters (i.e., surface water with varying mixtures of UFA water, representative of surface water stored via ASR wells) showed few toxic effects on organisms and had minimal impact on survival, reproduction, or embryo development in the representative fish, amphibian, and microorganisms tested. An exception was an inhibitory effect on the reproduction of the sensitive cladoceran *C. dubia*, which occurred occasionally in solutions where the proportion of recovered water was greater than 50 percent.

Results from these studies were integrated into a conceptual ecological model (CEM) with data obtained during pilot project cycle testing. The CEM provides insight into understanding the relationships between potential stressors and receptors on the environment resulting from CERP ASR. The model allowed an ecological risk assessment to be conducted that indicated significant environmental benefits and few if any risks that might occur from the proposed CERP ASR Program. Multiple scenarios were conducted during the model development that reflected the assumption that the overall number of ASR wells had to be reduced based on the groundwater model results.

## Mercury Methylation Studies

Mercury and methyl mercury investigations indicated that methyl mercury levels in the upper portions of the FAS are low and not likely to result in direct ecological contamination via recovered waters (31). Ambient (native) mercury and methyl mercury concentrations were characterized in 5 municipal wells open to the FAS. Total mercury concentrations were all less than 0.3 ng/L, and methyl mercury concentrations were all less than 0.1 ng/L.

The greatest concern is that the FAS redox environment will favor further mercury methylation reactions, and thus increase concentrations in stored and recovered water. Laboratory studies and cycle testing data indicate that mercury methylation does not proceed in the FAS. Laboratory incubation studies that react limestone aquifer matrix with surface water show rapid and substantial losses of total and methyl mercury. Cycle test data from the Kissimmee River ASR pilot site confirm that total and methyl mercury concentrations in recovered water are significantly lower those in surface water. Recovered water quality is in compliance with surface water and ground water regulatory criteria for mercury species.

## Conclusions

- Economically efficient, large capacity (i.e., 5 million gallons per day) ASR systems can be permitted, constructed and operated in geographically diverse areas throughout South Florida. Some variability in aquifer characteristics makes it prudent to conduct an exploratory program at any site where ASR is being considered.
- To date, no “fatal flaws” have been uncovered that might prevent the implementation of CERP ASR, although the overall number of ASR wells should be reduced, based upon groundwater modeling conducted as part of this study.
- The hydrogeologic characteristics of the Floridan Aquifer System (FAS) have proven to be generally advantageous, and suitable for implementation of ASR systems in areas of water availability important to Everglades Restoration to facilitate water storage.

- An extensive hydrogeologic, water quality, and ecological monitoring network has been established, to observe the "current state of the system" and reveal any changes that might take place as a result of future implementation of ASR.
- No hydraulic effects of the CERP ASR Pilot Projects were observed on the overlying Surficial Aquifer System (SAS) due in large part to the Hawthorn Group confining sediments that separate the SAS from the underlying upper portions of the Floridan Aquifer System targeted for ASR storage.
- Geotechnical analyses indicate that the potential for rock fracturing from ASR is very low, so long as operating pressures are maintained at levels required by permit, and wells are spaced at appropriate distances to minimize well-to-well interactions.
- Surface water from interior locations in south Florida is suitable for subsurface storage via ASR systems. However, the high organic content (indicated by high color) and presence of coliform bacteria in surface water requires treatment focused on filtration and disinfection technologies.
- Microbiological evaluations conducted in coordination with the SWFWMD and the USGS have defined rates at which various pathogens become "inactivated" under temperature conditions and total dissolved solids concentrations that are representative of the FAS. Generally, higher temperatures (22°C and 30°C) result in more rapid inactivation. TDS concentrations between 200 mg/L and 1,000 mg/L had no effect on inactivation rate. For fecal coliform, 99 percent (2-log) inactivation was predicted over 2 to 6 week periods. These studies provide a basis for evaluating the effectiveness of disinfection treatment prior to recharge into the FAS.
- Despite the generally favorable results of the CERP ASR Pilot Projects, arsenic mobilization and attenuation is still an issue that must be addressed regardless of location. This will require regulatory flexibility until the ASR storage zone is conditioned with successive cycles of operation -- and/or additional water quality treatment is conducted -- to achieve regulatory compliance with the drinking water standard.
- ASR systems should ideally be located adjacent to large, flowing water bodies to provide sufficient water availability for storage. These locations provide flexibility to comply with permit requirements for discharge of recovered water, by allowing for mixing zones in surface water bodies.
- The regulatory relief mechanisms associated with the (1) Underground Injection Control (UIC) Program (i.e., water quality criteria exemptions and Administrative Orders) and (2) National Pollutant Discharge Elimination System (NPDES) Program (i.e., mixing zones for select parameters) that were granted by FDEP were critical to the testing program, and would be anticipated to be critical for any future CERP ASR implementation.
- ASR systems located in the Lake Okeechobee area and completed in the upper portions of the FAS can achieve upwards of 100 percent recoverability of stored water due to the freshwater quality of the aquifer. Conversely, the brackish quality of the FAS in south Florida (e.g., Hillsboro site) will require successive cycles over a few years to achieve a target of 70 percent recoverability.

- The results of groundwater modeling have indicated that the overall number of ASR wells as originally envisioned by CERP should be reduced, to avoid deleterious effects to the aquifer, groundwater, and existing users.
- Multi-well ASR systems should be designed -- based in part on numerical modeling -- to ensure that appropriate, conservative, well spacing is implemented so that theoretical fracture pressures are not approached and subsurface storage is optimized.
- Water quality testing of recovered water from the CERP ASR Pilot Projects did not result in any unforeseen deleterious subsurface geochemical reactions that would cause adverse environmental effects on the receiving surface water body other than arsenic as previously anticipated and discussed.
- The potential for mercury methylation from storage and recovery of water from within the FAS has been determined to be very low. Water recovered from ASR systems may have concentrations of sulfate that could increase the load of this constituent in receiving water bodies. Mixing, dispersal, and dilution of this constituent within the system make predictions of this effect tenuous.
- Some reduction of phosphorous concentrations present in surface water is attenuated during ASR storage, and which is now better understood and postulated to be a result of microbial uptake, aquifer filtration, dilution and/or precipitation as calcium phosphate. This observation should be considered when selecting storage and treatment facilities to achieve CERP objectives.
- Based upon the successful results of the CERP ASR Pilot Projects and the regional evaluations conducted during this project, implementation of CERP ASR should proceed with a prudent, phased approach.
- A path forward is proposed that includes expansion of the existing pilot facilities and construction of additional ASR systems at locations originally envisioned in CERP. Evolution of restoration, storage, and treatment programs beyond what was defined in CERPP has resulted in new projects that could be optimized by ASR. As information is collected from future ASR facilities, new iterations of the groundwater and ecological models should be conducted, to guide additional phases of ASR implementation.

# 1 Introduction

To restore and preserve the Everglades and south Florida's natural environment, enhance water supplies, and maintain flood protection, the U.S. Army Corps of Engineers (USACE) in partnership with the South Florida Water Management District (SFWMD) developed a plan called the Comprehensive Everglades Restoration Plan (CERP). Successful implementation of the CERP requires finding ways to store water to improve quantity, quality, timing and distribution of flows to the Everglades system. Several possible technologies are being evaluated to accomplish this storage and distribution of water, of which aquifer storage and recovery (ASR) is one of the most challenging.

Although ASR technology has been used successfully in Florida since 1983, concerns have been expressed about the regional-scale use of ASR as envisioned in the CERP. These concerns were outlined in a 1999 report by the Aquifer Storage and Recovery Issue Team (ASR Issue Team) to the South Florida Ecosystem Restoration Working Group (SFERWG) and subsequent reports by the National Research Council Committee on the Restoration of the Greater Everglades Ecosystem (CROGEE). The CERP ASR pilot projects and ASR Regional Study were designed to address many of the technical, scientific, engineering and environmental questions that have been raised concerning the feasibility of regional-scale ASR implementation. This report documents the final products of the ASR Regional Study.

## 1.1 Aquifer Storage and Recovery Background

Used in the United States for more than 30 years, ASR refers to the process of recharge, storage, and recovery of water in an aquifer. Available surface water is collected during times when water is plentiful (typically during the wet season in south Florida), treated to meet Federal and state drinking water standards, and then pumped into an aquifer through a well. In south Florida, most ASR systems store treated water in permeable zones of the Floridan aquifer system. When recharged into the aquifer, the "stored" water displaces native aquifer water. **Figure 1-1** depicts this concept.

Stored underground, the fresh water is later "recovered" by pumping it out of the same well, and distributed for beneficial use (ecosystem restoration, municipal water supply, and other water needs in south Florida), typically during Florida's dry periods. This process of recharge, storage and recovery is called a cycle. Cycle tests serve as the primary means to analyze the performance of an ASR system at a given location.

The use of ASR is increasing nationally and worldwide as the need to utilize alternative water management options grows. Presently the largest ASR system in the world is located in Las Vegas, Nevada, utilizing a total of 99 active wells (Pyne, 2005). In south Florida, regional-scale implementation of ASR is envisioned as a significant component of the CERP.

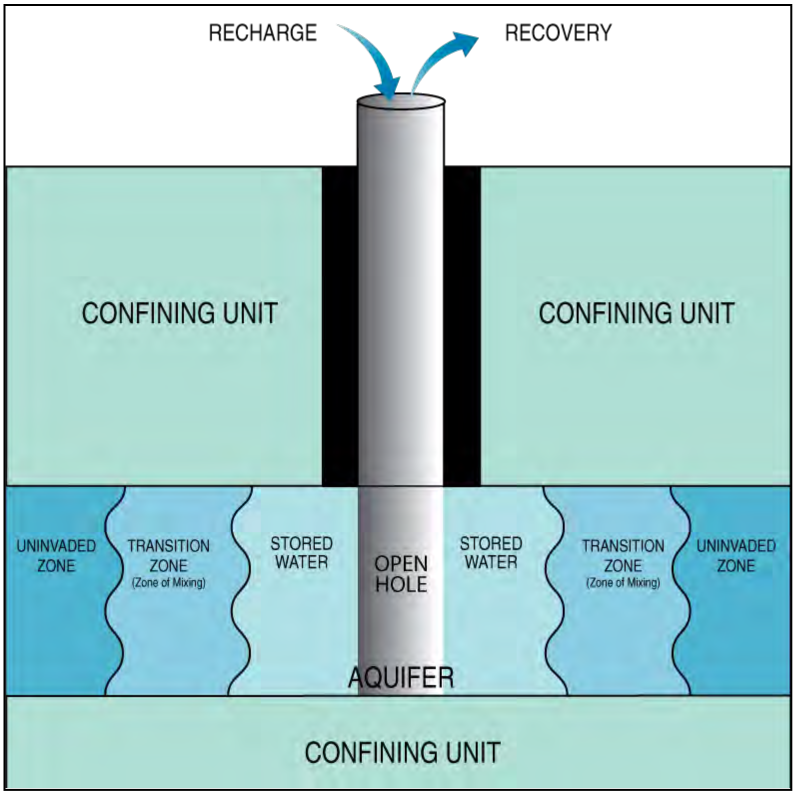


**Figure 1-1 -- Diagram showing an ASR well in a confined aquifer displacing native groundwater.** Figure modified from Reese (2002).

## 1.2 A Brief History of ASR in Florida

The first operational ASR well in Florida began storing drinking water in Manatee County in 1983. Since then, utilities throughout southeast and southwest Florida have installed ASR systems, often with the assistance of Alternative Water Supply (AWS) grants issued by the SFWMD and Southwest Florida Water Management Districts (SWFWMD). By 2010, there were approximately 10 permitted ASR wellfields in Florida and an additional 50 projects under development. To date, there are several large multi-well systems at Miami-Dade West and Southwest Wellfields, Marco Island, Tampa, and the City of Cocoa. Presently, the Peace River ASR system is the largest ASR wellfield in Florida, comprised of 21 ASR wells with a combined recovery capacity of 18 MGD (Pyne, 2005).

In 1997, a water sample collected by the Florida Geological Survey (FGS) during recovery from a new ASR well in Tampa contained arsenic results that exceeded the federal drinking water standard, which at that time was 50 micrograms per liter (μg/L). That set in motion an intensive effort to characterize arsenic concentrations at other ASR wellfields. In general, older ASR wellfields had acceptable arsenic concentrations while newer wellfields, particularly those still conducting cycle testing, did not. In 2005, the Florida drinking water standard for arsenic was lowered to 10 μg/L, which had the effect of re-classifying numerous ASR facilities as out of compliance with the standard. The Federal standard for arsenic was lowered to 10 μg/L in 2006. At the same time, regulators – the Florida Department of

Environmental Protection (FDEP) and the US Environmental Protection Agency (USEPA) - struggled to find a means to allow operators to safely continue operating their systems under the permitting criteria. As a result, the expansion of existing systems and the development of new ASR well systems was greatly curtailed.

During this period, a number of research projects were initiated to monitor and determine the occurrence, mobilization, and attenuation of arsenic in the subsurface. Alternative measures were also considered, such as pre-treatment technologies, development of initial "target storage volumes", and implementing institutional controls to prohibit nearby users from installing wells that might encounter groundwater with elevated arsenic concentrations. The efforts all presented technical and administrative options that were available to entities seeking to construct ASR systems.

As a result of the intensive research efforts to understand and control arsenic mobilization, the FDEP and USEPA now acknowledge multiple means to allow the continued safe use of ASR through a variety of technical and administrative processes. A recent letter from the USEPA to the FDEP, discussing this recent milestone, is contained in **Appendix A**.

## 1.3 ASR and the Comprehensive Everglades Restoration Plan

South Florida's existing water management system consists of an extensive network of canals, levees and water control structures, constructed as part of the Central and Southern Florida Flood Control Project (C&SF Project). Authorized by Congress in the late 1940s, the C&SF Project was constructed for many purposes: to provide flood control; to provide water supply for municipal, industrial and agricultural uses, as well as for Everglades National Park; to help prevent saltwater intrusion; and to help protect fish and wildlife resources.

Today, due to water management system limitations, discharges to the Everglades and estuaries are often too much or too little, and frequently occur at the wrong time of year. In addition, the C&SF Project sends billions of gallons per day of fresh water to tide that could otherwise be captured and stored for use when needed. The use of ASR technology to support CERP water management goals was first envisioned in 1996 as part of the consensus Conceptual Plan of the Governor's Commission for a Sustainable South Florida. The commission recommended in the plan, transmitted to then-governor Lawton Chiles, that "ASR technology should be investigated to determine its feasibility on a regional scale."

The C&SF Project Comprehensive Review Study ("Restudy"; USACE and SFWMD, 1999) presents a framework for Everglades restoration, preservation, and protection of the south Florida ecosystem while providing for other water-related needs of the region, such as municipal, industrial, and agricultural water supply and flood protection. The Restudy, now known as the CERP, is a cooperative effort containing 68 components, and including structural and operational changes to the existing C&SF Project. Implementation of the CERP is designed to improve the quality, quantity, timing and distribution of water flows, restore and enhance natural systems, and improve fish and wildlife habitats to promote recovery of native flora and fauna, including threatened and endangered species.

Of the 68 original project components recommended in the CERP, seven components involved ASR systems. Combined, these components include as many as 333 wells with a total storage capacity of nearly 1.7 billion gallons per day. To address the uncertainties of ASR technology prior to regional implementation of these components, the CERP also recommended the construction of ASR pilot projects along the Caloosahatchee River, the Hillsboro Canal and adjacent to Lake Okeechobee. Two ASR pilot systems were constructed and tested. Results and conclusions are summarized in USACE and SFWMD (2013).

The CERP ASR components are envisioned to take surplus fresh surface water, treat it as required for permit compliance, and then store it in the Floridan aquifer system for subsequent recovery during dry periods. If implemented as part of CERP, ASR is anticipated to significantly increase freshwater storage capacity in the C&SF system. It is also expected to provide better management of Lake Okeechobee water levels over the long term (years), and in doing so, can minimize damaging high-volume freshwater releases to the St. Lucie and Caloosahatchee estuaries. During dry periods, water recovered from ASR wells would augment surface water supplies and maintain the water levels and/or flows within Lake Okeechobee, the St. Lucie and Caloosahatchee rivers and associated canals throughout south Florida. **Figure 1-2** shows the generalized locations of the CERP ASR wells as envisioned in the CERP (USACE and SFWMD, 1999).

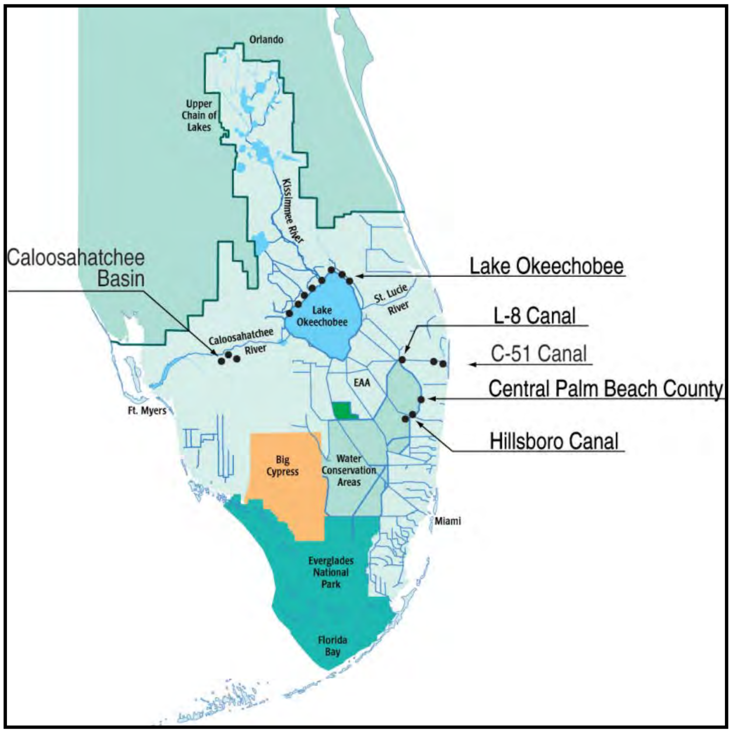


**Figure 1-2 -- Generalized CERP ASR Project Locations.**

The CERP also proposes to use ASR in longer-range water supply planning by storing water during wet years and delaying recovery until it is needed, potentially years later, and during multi-year droughts common in South Florida. Although ASR wells have been used in Florida for seasonal storage, the technology has never been implemented on such an unprecedented regional, multi-year scale.

## 1.4 Development of the CERP ASR Regional Study

Due to the limited understanding of effects from regional-scale ASR implementation, the South Florida Ecosystem Restoration Working Group formed the ASR Issue Team in September 1998 to conduct an independent scientific review of the conceptual CERP ASR system. The team's charter was to develop an action plan and identify projects needed to address the hydraulic, hydrogeologic and geochemical uncertainties associated with ASR. The final report from the ASR Issue Team was published by the SFERWG (ASR Issue Team, 1999) and recommended the study of seven issues as follows:

1. Characterization of the quality and variability of source waters that could be pumped into the ASR wells.
2. Characterization of regional hydrogeology of the Floridan aquifer system.
3. Analysis of critical pressure for rock fracturing.
4. Analysis of local and regional changes in groundwater flow patterns.
5. Analysis of water-quality changes during storage in the aquifer.
6. Potential effects of ASR on mercury bioaccumulation for ecosystem restoration projects.
7. Relationships among ASR storage interval properties, recovery rates and recharge volume.

The CERP ASR pilot projects and ASR Regional Study were conceived to address many of these uncertainties. The pilot projects provided the ASR Regional Study with platforms to conduct scientific and engineering studies as part of the adaptive assessment strategy. The seven issues identified by the ASR Issue Team were later augmented by other concerns raised by the National Research Council (NRC) Committee on the Restoration of the Greater Everglades Ecosystem's (CROGEE; NRC, 2001; 2002) and the public. In general, the CROGEE recommendations tracked those published in the ASR Issue Team report, with one exception. It was noted that the environmental and biological effects of 1.7 billion gallons per day of recovered water discharged back to the Everglades ecosystem was poorly understood. Therefore, the CROGEE recommended further studies to document or predict the effects of ASR-recovered water on the Greater Everglades ecosystem.

The goals of the ASR Regional Study, in coordination with the ASR pilot projects, were as follows:

- Answer the questions concerning the feasibility of regional-scale CERP ASR implementation.
- Reduce uncertainties related to regional-scale CERP ASR implementation by conducting scientific and engineering studies based on existing and newly acquired data.

- Develop a regional groundwater model of the FAS to identify an appropriate magnitude of ASR operations with minimal impact to the environment and existing users of the Floridan aquifer system.

The tasks required to perform the ASR Regional Study are described in the original CERP Aquifer Storage and Recovery Regional Study Project Management Plan (ASR Regional Study PMP; USACE and SFWMD, 2003). This study was developed by a multiagency team consisting of staff from the following entities: the SFWMD; the USACE; the FGS; the FDEP; the USEPA; the U.S. Geological Survey (USGS); the U.S. Fish and Wildlife Service (USFWS); the Florida Fish and Wildlife Conservation Commission (FFWCC); and local government agencies. The CROGEE conducted an independent technical review of the ASR Regional Study PMP to examine the adequacy of the proposed scientific methods to answer the issues raised by the ASR Issue Team and the original CROGEE review. Their findings were documented in National Research Council (2002).

## 1.5 Federal Authority and Authorization

The Water Resources Development Act of 2000 (WRDA 2000), Public Law 106-541, was enacted in December 2000. Title VI of WRDA 2000 approved the Comprehensive Everglades Restoration Plan and authorized an initial suite of projects plus design studies for many CERP components.

The Lake Okeechobee and Hillsboro ASR Pilot Projects were authorized by Congress in section 101(a)(16) of the WRDA 1999 (113 Stat. 276). Three ASR systems were planned under the Lake Okeechobee Pilot Project. These systems would be located around Lake Okeechobee, at the Kissimmee River (Okeechobee County), Port Mayaca (Martin County), and Moore Haven (Glades County). The Hillsboro ASR Pilot Project was the fourth system to be developed, and was authorized simultaneously with the Lake Okeechobee ASR Pilot Project. The WRDA 1999 authorization was modified in section 101 (b) (2) (B) (i) of the WRDA 2000 (114 Stat. 2681) to authorize a fifth ASR pilot system on the Caloosahatchee River (Hendry County). The Lake Okeechobee and Hillsboro ASR Pilot Projects authorization was modified further in section 6001 (a) of the WRDA 2007 (121 Stat. 1041) to increase the total cost of the project from $27,000,000 (WRDA 1999) to $42,500,000. Further definition of the ASR pilot projects was provided in section 6001 (b) (1) of the WRDA 2007, which stated "…that operation and maintenance costs of the Lake Okeechobee and Hillsboro ASR pilot projects shall remain a non-Federal responsibility". Subsequently, a Design Agreement was signed between the U.S. Army Corps of Engineers and the South Florida Water Management District to conduct these design studies including the PIR studies for the CERP ASR components.

The ASR Regional Study was not one of the original projects proposed in the CERP. Subsequent to the approval of the Regional ASR Study PMP in 2003, the project was funded as a separate feasibility-level study. The PMP described the various tasks to be conducted in support of the regional ASR evaluation, which would be conducted over a period of approximately nine years, at an estimated cost of $55,000,000.

## 1.6 State Authority

During the 1999 legislative session, Florida lawmakers created Section 373.1501 of the Florida Statues and amended Section 373.026 of the Florida Statutes. Section 373.1501 of the Florida Statues provides a legislative finding that the CERP is important for restoring the Everglades ecosystem and for sustaining the environment, economy, and social well-being of south Florida. Its purpose is to facilitate and support the CERP through an approval process concurrent with Federal government review and congressional authorization. Further, this section ensures that all project components are implemented through appropriate processes and are consistent with the balanced policies and purposes of Chapter 373 of the Florida Statutes, specifically Section 373.026. Section 373.026 (8)(b) directs the FDEP to collaborate with the SFWMD and to approve each project component, with or without amendments, within a specified period.

In the 2000 legislative session, the Florida Legislature created an act relating to Everglades restoration and funding, amending Section 215.22 of the Florida Statutes and creating Section 373.470 which is cited as the “Everglades Restoration Investment Act.” The purpose of this act is to establish a full and equal partnership between the state and the Federal governments for the implementation of the CERP. This act requires that a PIR be approved in accordance with Section 373.026 of the Florida Statutes before the SFWMD and the USACE execute a Project Cooperation Agreement.

# 2 Initial Studies and Related Projects

The ASR Regional Study team has addressed uncertainties associated with regional-scale CERP implementation involving a pilot-scale data collection effort at two ASR systems, which were then applied to various models to evaluate effects of ASR implementation on a regional (full) scale. Cycle testing at ASR pilot systems reduced uncertainties related to ASR system design, operation, permitting and regulatory compliance, and cost. For expanded discussion of the pilot projects, refer to the CERP ASR Pilot Project Technical Data Report (USACE and SFWMD, 2013). However, for convenience, a summary of the ASR pilot projects is provided below.

In addition to the development of the pilot ASR systems, other studies were initiated between 2003 and 2007 to address those issues which had the potential to impede ASR implementation. Other early studies provided baseline hydrological and ecological characteristics, for comparison of conditions after the completion of cycle testing. Finally, other projects have been undertaken as part of CERP and by other state-led initiatives that anticipate the use of ASR technology. Brief descriptions of those programs, projects and features are included herein.

## 2.1 ASR and Hydrogeology Literature Review

A reference database was compiled to include all references (published and unpublished), geophysical logs, lithologic descriptions, aquifer hydraulic properties, and other relevant hydrogeologic data available from various agencies dealing with the Floridan Aquifer System (FAS) in peninsular Florida from Lake County south to Key West up to 2006. The product was an annotated bibliography with abstracts, and a table of data associated with the abstract, along with information on available format and location. A reference list of more than 1,600 key documents related to ASR technology and the hydrogeology was compiled by the USACE and its contractors. Hydrogeologic and hydrologic characteristics and data were incorporated into early development of the ASR Regional groundwater flow model, and the initial hydrogeologic framework of Reese and Richardson (2008). All site-specific data (well construction reports, aquifer performance test data for example) were archived in the SFWMD DBHYDRO database. The literature review subsequently was incorporated into a larger CERP reference database available internally on the Cerpzone website.

## 2.2 Exploratory Wells and Initial Water Quality Characterization Studies

Exploratory well construction was completed at each proposed ASR pilot system location. The purpose was to confirm at each site that the FAS was productive and hydraulically capable of storing up to 5 MGD as envisioned in the CERP. The exploratory wells provided information about the hydrogeology of each site, and enabled the collection of water samples and geophysical data to determine aquifer characteristics. Results were summarized in the following reports: Hillsboro ASR (HASR), Bennett et al. (2001); Kissimmee River ASR (KRASR), CH2M Hill (2004); Port Mayaca ASR (PMASR), Bennett et al. (2004); Caloosahatchee River ASR (CRASR), Water Resource Solutions Inc. (2005); and Moorehaven ASR (MHASR), Bennett and Rectenwald (2002).

Additional characterization of baseline FAS groundwater quality was completed so that water-quality changes during ASR cycle testing could be identified or simulated (Tetra Tech, 2005a). Major and trace inorganic constituents and stable isotopes were analyzed in samples from 20 wells open to the Upper Floridan Aquifer (UFA) and Avon Park Permeable Zone (APPZ; **Figure 3-1**), supplementing data obtained from 5 proposed ASR pilot sites. Organic compounds (volatile and semi-volatile organics, pesticides, herbicides) were analyzed in 4 quarterly groundwater samples from each proposed ASR system (Tetra Tech, 2005a). Native FAS groundwater quality at the CERP ASR systems is summarized in USACE and SFWMD (2013). Native FAS groundwater quality throughout south Florida is summarized in **Chapter 5.**

Concurrent with the exploratory well program, other data collection efforts were initiated to support ASR operations. A study to characterize spatial and seasonal surface water quality variability was completed (PBS&J, 2003; Tetra Tech, 2005b). This information supported the design of the surface treatment systems, specifically for filtration and disinfection processes. Concurrently, a series of treatment technology studies were undertaken to evaluate different filtration systems that could remove turbidity, solids, and biological constituents from the source water, prior to being pumped into the ASR wells (Carollo Engineers, 2003). Disinfection studies also were undertaken to determine the most cost effective technology to meet regulatory criteria applicable to ASR systems. Among the disinfection technologies evaluated were ozonation, bank filtration, ultraviolet radiation, and mechanical separation (HSA Engineers and Scientists, 2003; PBS&J, 2004). A water treatment and pumping process was then designed to meet regulatory permitting criteria at each pilot ASR system.

## 2.3 Early Evaluation of Mercury Methylation Potential in the FAS

The mobilization, transport, and fate of mercury, and potential for increased mercury methylation were concerns identified by both the ASR Issue Team (1999) and the NRC (2002). A guiding hypothesis is that storage of surface water having measurable mercury in a sulfate-reducing aquifer would increase the mercury methylation rate. Consequently, recovery would distribute water with more methyl mercury into the surface water environments.

The potential for ASR cycle testing to increase mercury and methyl mercury was evaluated in a combined field and laboratory study completed by Krabbenhoft et al. (2007). Native FAS groundwater showed negligible concentrations of mercury and methyl mercury (mean values are 0.41 ng/L and 0.07 ng/L, respectively). Laboratory incubation of organic carbon- and sulfate-rich surface water and limestone did not show any increase in mercury and methyl mercury under sulfate-reducing conditions. Loss of mercury during incubation experiments may result from sorption to aquifer material. Additional discussion of mercury methylation potential is found in **Section 8.4.**

## 2.3 Early Ecological Characterization Projects

Many of the uncertainties identified by the NRC (2002) focused on identification of ecological and ecotoxicological effects of recovered water on freshwater communities and ecosystems. Baseline studies were initiated to characterize freshwater habitats and communities for later comparison of conditions at the completion of cycle testing. A large dataset consisting of mercury analyses in fish tissues also was compiled.

Baseline conditions of ecological communities at the five proposed ASR pilot systems (KRASR, HASR, PMASR, MHASR, and CRASR) were summarized in Tetra Tech (2007). This study characterized surface water and sediment quality characteristics, and macroinvertebrate and fish community composition. The study completed habitat assessments using the FDEP stream conditions index and the Vegetative Index of Wetland Conditions protocols. Fish tissue also was analyzed for mercury.

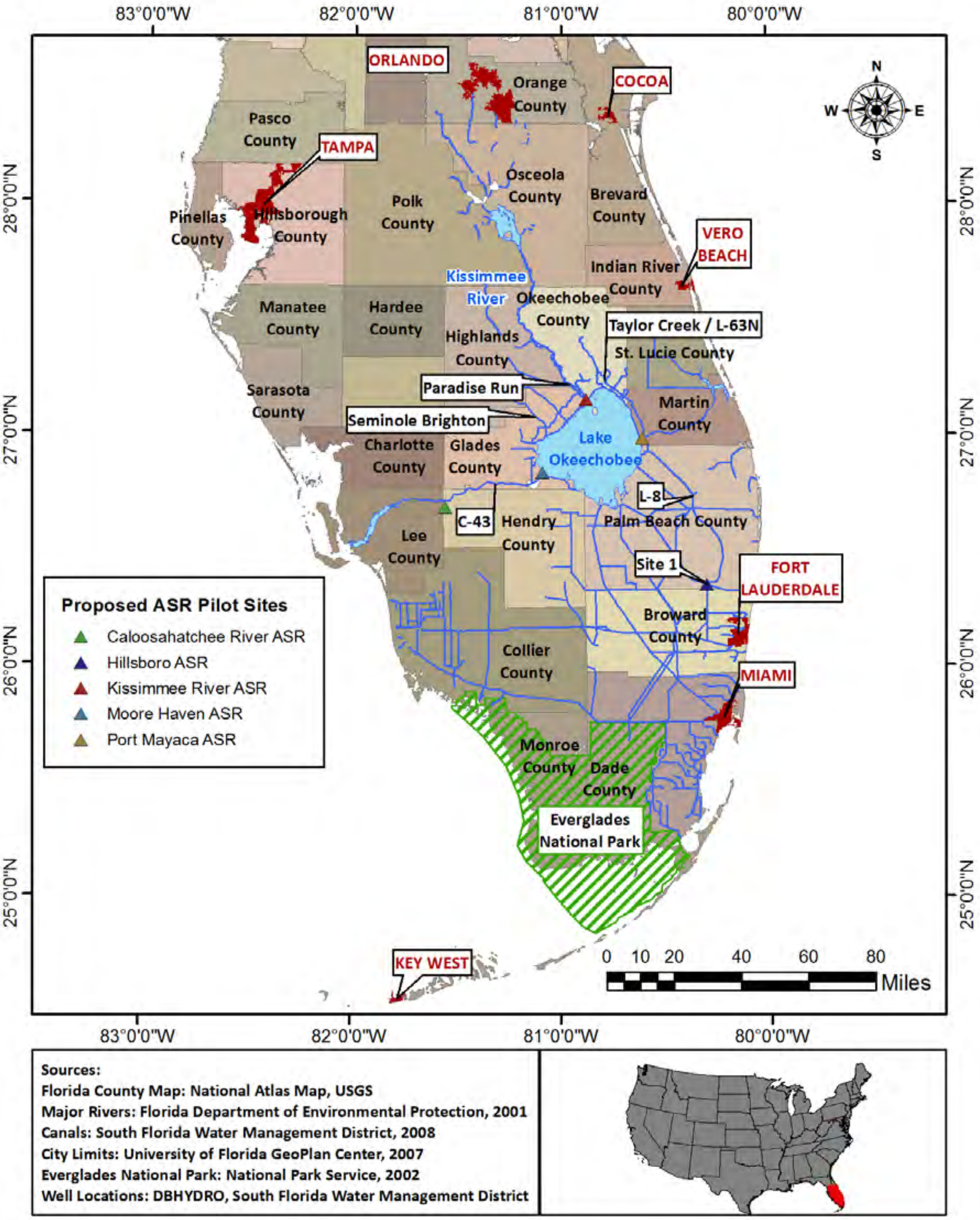
Baseline sediment quality results suggest that mercury and zinc frequently were detected at high concentrations. Habitat assessment indices showed that KRASR and CRASR baseline stream conditions were characterized as “most disturbed”, and PMASR and HASR were “somewhat disturbed”. The stream condition index (developed using macroinvertebrate species occurrence and abundance) varied seasonally and with location, with no statistically significant trends shown during four quarterly samples at each proposed ASR system. The fish community assessment results indicated that fish communities differ among all proposed ASR system locations. Native and total fish diversity was lowest at CRASR, and greatest at KRASR and MHASR. Mercury (primarily as methyl mercury) was detected in all fish tissue samples (n=262), at concentrations ranging between 0.412 mg/kg and 0.85 mg/kg.

## 2.4 The CERP ASR Pilot Projects

Three ASR pilot projects were authorized for the CERP ASR Program: Lake Okeechobee, HCASR, and CRASR. The scope of ASR envisioned around Lake Okeechobee was extensive because this project included construction of three separate ASR systems (PMASR, KRASR, and MHASR), bringing the total to five pilot projects. **Figure 2-1** shows the locations of the proposed pilot projects. KRASR and HASR systems are the only CERP ASR pilot systems constructed to date.

Sites for the ASR pilot projects were chosen based on location, land ownership, proximity to available surface water, and the lack of sensitive species or natural resources likely to be affected by pilot project operations. A siting analysis (Brown et al., 2005) was conducted for all well sites based on such factors as availability of surface water, property constraints, impacts to people, wetlands and threatened and endangered species, cultural resources, and aesthetics. A graphic showing site suitability for ASR systems show that areas having high “siting scores” lie north and west of Lake Okeechobee **(Figure 2-2**). Recommended sites were all similar in that they were publicly owned properties and had been previously developed or disturbed, thus minimizing the environmental impact of pilot project construction. The ASR well siting index was helpful for prioritizing locations under consideration for future construction of ASR systems, and to highlight areas that should undergo more rigorous evaluation during subsequent hydrogeologic investigations.

The ASR Pilot Projects were designed, constructed, and operated simultaneous with execution of the ASR Regional Study. Data obtained from operations of the ASR pilot systems have been incorporated into hydraulic, hydrogeological, and ecological aspects of the ASR Regional Study, and serve to validate some model simulations.



**Proposed ASR Pilot Sites**

- ▲ Caloosahatchee River ASR
- ▲ Hillsboro ASR
- ▲ Kissimmee River ASR
- ▲ Moore Haven ASR
- ▲ Port Mayaca ASR

**Sources:**
**Florida County Map: National Atlas Map, USGS**
**Major Rivers: Florida Department of Environmental Protection, 2001**
**Canals: South Florida Water Management District, 2008**
**City Limits: University of Florida GeoPlan Center, 2007**
**Everglades National Park: National Park Service, 2002**
**Well Locations: DBHYDRO, South Florida Water Management District**

**Figure 2-1 -- Map showing locations of proposed CERP and non-CERP ASR systems.**

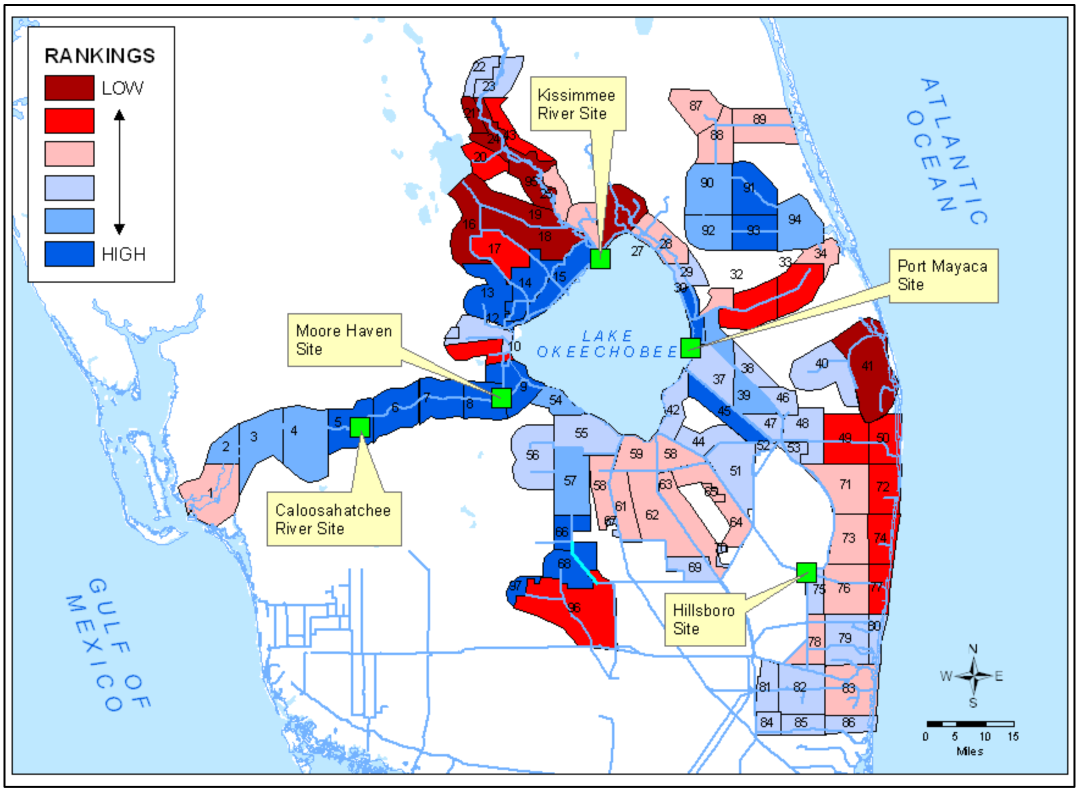


**Figure 2-2 -- Results of the ASR well siting study.**
Figure from Brown et al. (2005). Numbers within polygons are for index only, not ranking.

### 2.4.1 Kissimmee River ASR Pilot Project

The Kissimmee River ASR (KRASR) Pilot Project is located on the eastern bank of the C-38 Canal (Kissimmee River), 5 miles west of the City of Okeechobee (**Figure 2-1, Figure 2-3**). This facility is designed as a single-well ASR system having a production capacity of 5 MGD. Surface water is drawn from the Kissimmee River, and then treated with a pressure media filter (sometimes referred to as a sand filter) coupled with ultraviolet disinfection to meet primary drinking water standards prior to recharge into the upper Floridan Aquifer (UFA). The filter media is a combination of gravel, sand and anthracite. Treated surface water is stored at depths between 572 and 880 feet below land surface (bls). A cycle testing strategy involving short and long recharge, storage, and recovery periods was developed and implemented at KRASR. When stored water is recovered and retreated, it is discharged through a constructed cascade to aerate the water to make it compatible with surface water before it enters the river.

Exploratory well construction at the KRASR system was initiated in 2003 and completed in 2004 by the SFWMD (CH2M Hill, 2004). The KRASR system incorporated several monitor wells that had been constructed previously by the SFWMD for the Regional Floridan Aquifer Groundwater (RFGW) monitoring program, for cost savings. These wells were supplemented by three storage zone monitor wells constructed by the USACE. A single-zone storage zone monitor well (SZMW) located 350-ft from the ASR well (MW-10) was completed in 2007 (Golder Associates, Inc., 2007). A dual-zone SZMW (OKF-100 U and L; Goldler Associates, Inc. 2006) serves as a distal monitor well open to the UFA and APPZ located approximately 1,100 ft from the ASR well. Well OKH-100 monitors water levels in the overlying Hawthorn Group confining unit. Well OKS-100 monitors water levels in the surficial aquifer. Conceptualization and design of the surface facility began in 2003, culminating in a design documentation report (USACE and SFMWD, 2004). Plans and specifications were completed for the surface facility, and a request for proposals (RFP) for construction of the surface facility was issued during January 2006. The surface facility was constructed and accepted after performance testing was completed during December 2007. During performance testing, it became clear that the original two-unit ultraviolet (UV) disinfection system was insufficient for coliform inactivation. After consultation with the FDEP, the construction contract was modified to add a third UV unit and by-pass piping so that the UV system could be tested without recharging the Floridan Aquifer. ASR system modifications and additional operational tests were completed, and a revised ASR system performance submittal was accepted in December 2008. Cycle testing was initiated in January 2009. The ASR wellfield was subsequently expanded with the addition of two distal SZMWs between cycle test 2 and 3, to evaluate effects in the aquifer at distances up to 4,200-ft away from the ASR well. The fourth and final cycle test was completed in July 2013.

The KRASR system surface facility construction was completed in late 2007, at a cost of $6,138,253 (contract 1 award plus modifications). Four storage zone monitor wells plus a surficial aquifer well were constructed at a cost of $1,741,171. Post-construction system upgrades and testing of the UV disinfection system were required to ensure continuous operation and regulatory compliance. This delayed the initiation of operational cycle testing until January 2009. Four operational cycle tests were completed at the KRASR system in July 2013. For each successive cycle test, the volume of surface water recharge and the duration of storage in the aquifer increased. Cycle test 4 was one of the largest single-well recharge events conducted to date in Florida, and most closely resembles the typical operation envisioned in the CERP for Lake Okeechobee. Percent recovery of recharged water from the UFA was approximately 100 percent by volume for each cycle test, which exceeds the maximum percent recovery estimated for the CERP. High percent recoveries are expected at KRASR because the native groundwater is relatively fresh.

### 2.4.2 Hillsboro ASR Pilot Project

The Hillsboro ASR (HASR) Pilot Project is located west of Boca Raton (southwestern Palm Beach County) adjacent to the Loxahatchee National Wildlife Refuge and the Hillsboro Canal (**Figure 2-1, Figure 2-3**). This facility was designed as a single ASR well system having a production capacity of 5 MGD. The ASR system withdraws surface water from the Hillsboro Canal through an intake-discharge structure. Similar to the KRASR system, surface water is treated to meet primary drinking water standards via screen filtration with UV disinfection prior to recharge. Treated surface water is stored at depths between 1,015 and 1,225 feet bls. A cycle-testing strategy involving shorter recharge, storage, and recovery durations was evaluated at the HASR pilot system. This project is in close proximity to the proposed

CERP Site 1 Impoundment at Fran Reich Preserve, and was originally envisioned as the first of up to 30 ASR wells that could be integrated into that CERP feature.

Exploratory well construction at the HASR system was initiated in 1999 and completed in 2001 by the SFWMD. Additional monitor wells were constructed at the site during subsequent years. Conceptualization and design of the surface facility began in 2004, culminating in a design memorandum (PBS&J, 2005). Plans and specifications were completed shortly thereafter, and a construction contract was awarded by the SFWMD during December 2005. Construction of all wells and the surface facility was completed by November 2008 at a cost of $2,277,598.30 (construction award plus modifications). There were several factors that delayed initiation of cycle testing at the HASR system. Recharge was not permitted due to low water levels in the Hillsboro Canal during late 2008 and 2009. The position of the vertical turbine pump in the ASR well was adjusted for better operation. These issues were resolved and cycle testing was initiated in January 2010. The third and final cycle test was completed by June 2012.

**Figure 2-3 -- Photographs showing the Kissimmee River ASR system (left) and the Hillsboro ASR system (right).**

Three cycle tests at HASR were designed to test the feasibility of wet-season recharge and dry-season recovery during an annual cycle test. Percent recovery improved from 21 percent during cycle test 2, to 41 percent by volume during cycle test 3. Lower percent recovery is expected at HASR (compared to KRASR) due to mixing with native brackish groundwater during each cycle test.

### 2.4.3 Port Mayaca ASR Pilot Project

The Port Mayaca ASR (PMASR) Pilot Project was designed, and an exploratory well (EXPM-1) was constructed in 2004 by the SFWMD. Well MF-37 was converted to a dual-zone (UFA and APPZ) monitor well by the USACE in 2007 (Mactec Engineering and Consulting, 2007). The UFA occurs at depths between 800 and 900 ft bls, which is favorable for ASR implementation. This pilot project is of particular interest to the CERP ASR program because the design called for a multi-ASR well facility, to determine the hydraulic interactions among a cluster of ASR wells. **Figure 2-4** presents a conceptual design of the multi-well system.

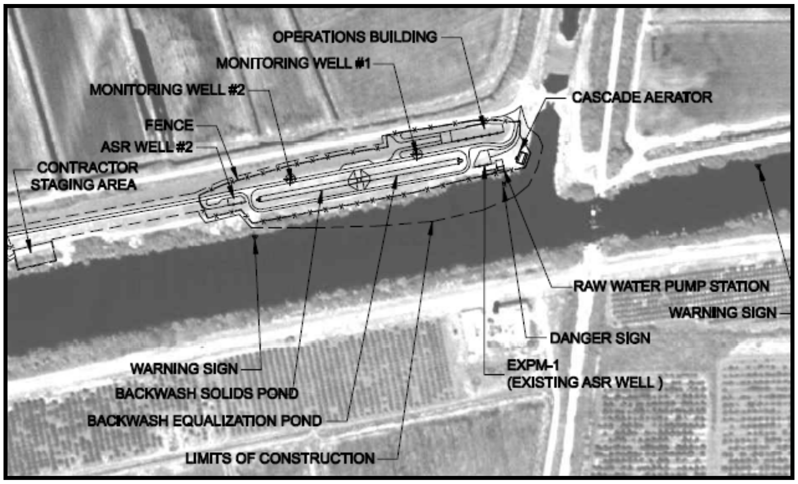


**Figure 2-4 -- Aerial photograph showing plan view of the proposed Port Mayaca ASR system.**

### 2.4.4 Conclusions and Recommendations from the CERP ASR Pilot Projects

The following conclusions were drawn from cycle testing at KRASR and HASR systems. Data and interpretations from cycle testing at the individual systems are documented in the CERP ASR Pilot Project Technical Data Report (USACE and SFWMD, 2013).

- Five MGD ASR systems can be permitted, designed, constructed and operated in geographically diverse areas in South Florida.
- The hydrogeologic characteristics of the upper portions of the FAS are laterally continuous, and suitable for implementation of ASR systems in areas of water availability important to Everglades Restoration. Some variability in aquifer characteristics make it prudent to conduct an exploratory program at the location where ASR is being considered.
- No effects of the ASR pilot projects were observed on the overlying Surficial Aquifer System (SAS). The thickness of the Hawthorn Group sediments ranges between 400-ft and 700-ft at the pilot sites, providing effective hydraulic separation between the SAS and storage zone in the FAS.
- Surface water in South Florida generally is suitable for subsurface storage via ASR systems. The high organic content (i.e., color) and presence of coliform bacteria in surface water requires treatment focused on filtration and disinfection technologies.
- Despite a clear understanding of potential challenges beforehand, and several efforts including literature searches and pre-pilot-project bench and field-scale testing, the functionality of the ASR Pilot Project water quality treatment systems was continuously challenged given the surface water quality and variability. Further research and testing of filtration and disinfection systems beyond those tested in the CERP ASR Pilot Projects would be beneficial to avoid or minimize some of the operational challenges experienced.
- Published research from cycle testing at KRASR indicates that arsenic is released but is subsequently precipitated in the aquifer during a single cycle test, such that nearly all recovered water in successive cycle tests is in regulatory compliance with the Safe Drinking Water Act.

- Despite the generally favorable results of the ASR pilot projects, arsenic mobilization and attenuation is still an issue that must be addressed regardless of location. This will require regulatory flexibility until the ASR storage zone is conditioned with successive cycles of operation -- and/or additional water quality treatment is conducted -- to achieve regulatory compliance with the 10 μg/L arsenic drinking water standard.
- As stated in the Pilot Project Design Report – and as experienced at the ASR Pilot Projects – ASR systems should ideally be located adjacent to large, flowing water bodies to provide sufficient water availability for storage and provide flexibility to comply with National Pollution Discharge Elimination System (NPDES) permit requirements by allowing for mixing zones in surface water bodies for water quality parameters as appropriate.
- The regulatory relief mechanisms associated with the (1) Underground Injection Control (UIC) Program (i.e., water quality criteria exemptions for secondary standards; administrative orders for arsenic and total coliform); and (2) National Pollutant Discharge Elimination System (NPDES) Program (i.e., mixing zones for select parameters) that were granted by FDEP were critical to the testing program. Most of these requirements would be anticipated to be critical for any future CERP ASR implementation.
- ASR systems located in the Lake Okeechobee area and completed in the upper portions of the Floridan Aquifer can achieve upwards of 100 percent recovery of stored water due to the freshwater quality of the aquifer. Conversely, the brackish quality of the Floridan aquifer in South Florida (e.g., HASR) will require successive cycles over a few years to achieve a target of 70 percent recovery.
- Given the exploratory nature of the CERP ASR pilot projects, operational and monitoring costs were expected to be greater than those for municipal ASR systems and that assumption proved to be correct. Some cost savings can be realized (compared to cycle testing costs at CERP ASR systems) by reducing groundwater quality monitoring frequency or number of analytes, especially if newer systems are located in the vicinity of the CERP ASR systems.
- Water quality testing of recovered water from the ASR Pilot Projects did not result in any unforeseen subsurface geochemical reactions that would cause adverse environmental effects on the receiving surface water body other than arsenic as previously anticipated and discussed.
- Some reduction of source water phosphorus concentrations occurs during ASR storage, and this is postulated to result from microbial uptake, aquifer filtration, dilution and/or precipitation as calcium phosphate. This observation should be considered when selecting storage and treatment facilities to achieve CERP objectives.
- Wellhead operating pressures observed during the recharge phase at both CERP ASR systems were monitored as required by permit. As expected, wellhead pressures did not approach the calculated thresholds to initiate fracturing of the overlying Hawthorn Group confining sediments. It is unlikely that hydraulic fracturing and subsequent upward movement of stored water into the overlying Surficial Aquifer System will occur during ASR cycle testing.
- Some degree of periodic well maintenance, in the form of wellbore cleaning or acidization should be anticipated at operational systems, as a long-term procedure to keep ASR wells hydraulically efficient.

- Multi-well ASR systems should be designed -- based in part on numerical modeling -- to ensure that appropriate, conservative well spacing is implemented so that theoretical fracture pressures are not approached and subsurface storage is optimized.

## 2.5 Other Related Projects

ASR is a water resource management technology that can be integrated into other projects within and beyond the CERP. Several of these projects were executed by the SFWMD as non-CERP projects. Project locations are shown on **Figure 2-1**.

### 2.5.1 CERP Site 1 Impoundment at Fran Reich Preserve

The proposed Site 1 Impoundment is an above-ground storage reservoir located on a 1,660 acre footprint that is bounded on the south by the Hillsboro Canal, on the north and west by the L-40 canal, and on the east by a header canal, as shown on **Figure 2-5**. This project is divided into two phases: Phase I will reinforce the L-40 levee that separates the Loxahatchee National Wildlife Reserve from the impoundment; Phase II will complete the impoundment levee reinforcement, add two pump stations, and incorporate the HASR system into impoundment operations. When completed, this project could integrate up to 30 ASR wells within its operation. This combined facility would be one of the few conjunctive ASR-reservoir operations in Florida.

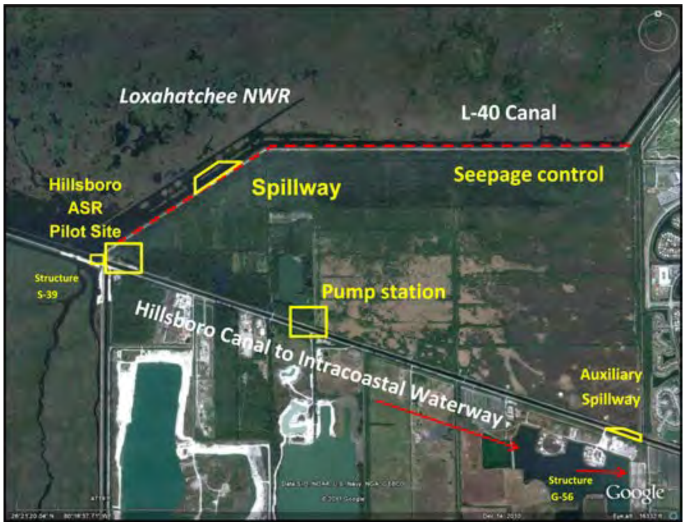


**Figure 2-5 -- Aerial photo showing the Hillsboro ASR pilot system and other water management structures associated with the proposed Site 1 Impoundment project.**

### 2.5.2 CERP C-43 Reservoir

The Caloosahatchee River (C-43) West Basin Storage Reservoir (WBSR) Project was initiated under the Water Resources Development Act (WRDA) of 2000. The project includes an above-ground reservoir having a total storage capacity of approximately 170,000 acre-feet, and also will integrate up to 44 ASR wells. The reservoir will be located in the C-43 Basin, which spans Hendry, Glades, Charlotte, Collier, and Lee Counties **(Figure 2-1)**. This project is designed to capture C-43 Basin runoff and releases from Lake Okeechobee. The SFWMD acquired the project land and completed the construction and testing of test cells to evaluate seepage barriers and levee construction design. This information was applied to the detailed design of the reservoir, which was completed in January 2008. Later in 2008, a corporate decision was made to suspend development of this project. In August 2014, initial stages of the C-43 WBSR were re-initiated. Currently, all necessary permits have been obtained. Revisions to project design of the reservoir and pump station were initiated by the SFWMD in August 2014.

### 2.5.3 CERP L-8 Reservoir

The CERP Loxahatchee River Watershed Restoration Project (formerly known as the Northern Palm Beach County Project) may integrate up to 10 ASR wells associated with the L-8 reservoir feature (**Figure 2-1**). The L-8 site originally was acquired to provide an element of the minimum flows and levels (MFL) recovery strategy for the Loxahatchee River. Recently, the Restoration Strategies Regional Water Quality Plan incorporated the L-8 reservoir as one of its features. It is now under construction for use as a flow equalization basin for the eastern flow-way, and will provide storage to allow for the delivery of consistent flows that are needed to optimize performance of stormwater treatment areas. The target date for the completion of this feature is 2016.

### 2.5.4 Northern Everglades and Estuaries Protection Plan

Underscoring the State's commitment to restoring the Greater Everglades ecosystem, the Florida Legislature in 2007 expanded the Lake Okeechobee Protection Act to strengthen protection for the Northern Everglades by restoring and preserving Lake Okeechobee and the Caloosahatchee and St. Lucie rivers and estuaries **(Figure 2-6)**. Implementation of the Northern Everglades and Estuaries Protection Plan (NEEPP) will improve the quality, quantity, timing and distribution of water to the natural system and re-establish salinity regimes suitable for maintaining healthy, naturally diverse and well-balanced estuarine ecosystems. The health of the Northern Everglades will be enhanced by improving land management to reduce nutrient run-off, by constructing treatment wetlands to improve water quality and by completing water storage projects to better connect, manage and distribute water to the natural system. Those responsible for this plan are considering the use of ASR to optimize storage capacity, treatment and the timing, location, and distribution of flows. Additionally, three ASR projects were initiated by the SFWMD as distinct projects within the NEEPP, including the Seminole Brighton Reservation, the L-63N Canal (Taylor Creek) and Paradise Run. The Northern Everglades & Estuaries Protection Program includes the following concepts:

- Recognizes that the Lake Okeechobee, Caloosahatchee and St. Lucie watersheds are critical water resources of the State.
- Builds upon and consolidates numerous restoration activities into a comprehensive approach.
- Expands the use of the Save Our Everglades Trust Fund to include Northern Everglades restoration and extends it through 2020.

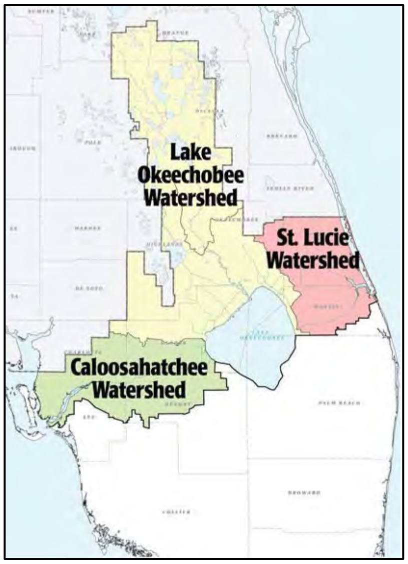


**Figure 2-6 -- The project area of the NEEPP.**

### 2.5.5 Seminole-Brighton ASR Project

The Seminole-Brighton project site is located on the north bank of the C-41 Canal in Glades County (**Figure 2-1**), on agricultural lands of the Brighton Reservation of the Seminole Tribe. Exploratory well construction was completed on behalf of the Seminole Tribe to evaluate ASR feasibility and hydrologic characteristics of potential storage zones in the UFA and APPZ (Missimer Groundwater Science, 2007). Aquifer performance testing results indicated that the hydrologic characteristics of the UFA and APPZ were suitable for ASR. Subsequently, alternatives for the design of the surface facility were developed for pre-treatment and disinfection of source water prior to recharge.

### 2.5.6 L-63N (Taylor Creek) ASR System Reactivation

The L-63N ASR system was one of the first ASR systems developed in the region, with construction of an exploratory well and a dual-zone monitor well completed in 1989 adjacent to Taylor Creek in Okeechobee County (**Figure 2-1**). This ASR system was envisioned as a large-capacity (10 MGD) system with a large storage interval (1,275 ft to 1,700 ft bls) in the APPZ. Four cycle tests were conducted in 1989 and 1991 (Reese and Alvarez-Zarikian, 2007). Recharge volumes ranged between 181 and 355 million gallons (MG), but percent recoveries were low (2.7 to 7.2 percent by volume). Low recovery performance probably occurred because the durations of the recharge phase were of short (20 to 65 days), and storage occurred in a highly transmissive aquifer (APPZ). Longer recharge phases and larger recharge volumes could result in improved percent recovery at this ASR system. Presently, the design for reactivation of the system does not include a disinfection system, and a petition by the SFWMD for an aquifer exemption currently is pending with the USEPA.

### 2.5.7 Paradise Run ASR System

The Paradise Run project site is located seven miles north of KRASR, on the west bank of the Kissimmee River south of its confluence with C-41A and spillway and lock structure S-65E in Glades County (**Figure 2-1**, **Figure 2-7**). The project site is within a former alluvial plain wetland and meander belt of the Kissimmee River. An exploratory borehole was tested, and monitor well (HIF-42) construction was completed in 2008 (CH2M Hill, 2008). A conceptual ASR system design for a 10-well ASR system that would recharge and recover water from the UFA and APPZ (CH2M Hill, 2008).

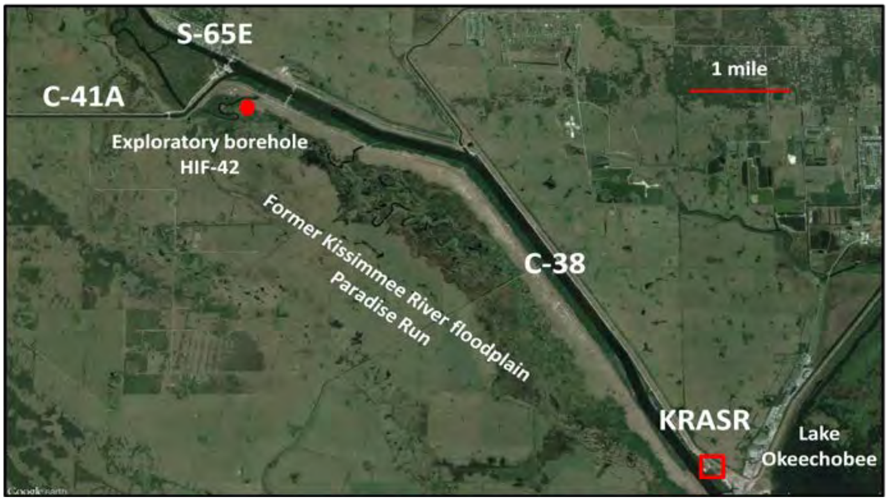


**Figure 2-7 -- Image showing proposed location for the Paradise Run ASR system.**

This project defined the thickness and hydrologic characteristics of potential storage zones in the UFA and the APPZ. The ASR system would use surface water from the Kissimmee River to recharge the aquifers through well pairs open to the UFA and APPZ. The conceptual design of this ASR system incorporates several novel features such as passive (artesian) recovery to reduce energy consumption, and use of wetlands for rehydration and ecosystem restoration.

### 2.5.8 Central Everglades Planning Project

In October 2011, the intergovernmental South Florida Ecosystem Restoration Task Force endorsed a state-federal initiative to speed up planning for key Everglades restoration projects. The Central Everglades Planning Project (CEPP) defines a suite of restoration projects in the central Everglades. When completed, approximately 210,000 acre-feet (ac-ft) of water will be captured annually and directed south to provide ecological benefits. CEPP components are integrated, and include: Everglades Agricultural Storage Reservoirs, Water Conservation Area 3 (WCA-3) Decompartmentalization and Sheetflow Enhancement, S-356 Pump Station Modifications, L-31 Levee Seepage Management, Flow to Northwest and Central WCA-3A, and Everglades Rain-Driven Operations. Several of the features within this plan may utilize ASR to optimize storage capacity, treatment and the timing, location, and distribution of flows, although integration of ASR into any specific component within the plan is conceptual at this time.

# 3 Hydrogeologic and Geophysical Investigations

Expansion of ASR technology to a regional scale requires a detailed understanding of the hydrogeologic setting and hydraulic characteristics of major aquifers and permeable zones of the Floridan Aquifer System. These data define a conceptual hydrogeologic framework, which is the basis for the Regional Groundwater Flow and Solute Transport model described in **Chapter 7.**

The hydrogeologic framework for the FAS developed in two phases: a preliminary framework (Reese and Richardson, 2008), and a final hydrogeologic framework (Reese, 2014). These works build on earlier hydrogeologic investigations published by the USGS for Martin and St. Lucie Counties (Reese, 2004), Palm Beach County (Reese and Memberg, 2000), Broward County (Cunningham, 2013; Reese and Cunningham, 2014), and southwest Florida (Reese, 2000).

## 3.1 Preliminary Hydrogeologic Framework

A comprehensive understanding of the hydrogeologic framework of the Floridan Aquifer System (FAS), and how that framework influences the movement of water within the FAS, is the foundation for addressing questions about regional ASR implementation on the scale envisioned for Everglades restoration. **Figure 3-1** presents a conceptual geologic column of south Florida's hydrogeologic and lithostratigraphic units as it appeared in the preliminary hydrogeologic framework.

Few studies have mapped the entire FAS in Florida. When the ASR Regional Study was initiated, the principal reference (Miller, 1986) was becoming quite dated. Since Miller (1986), numerous deep wells had been drilled for hydrogeologic testing (e.g. FAS test well programs at SFWMD, SWFWMD, and St. Johns River Water Management District (SJRWMD)). Hydrogeologic exploration projects also were developed to evaluate deep well injection into the Boulder Zone, and Lower Floridan Aquifer as a water supply source. It was recognized that these, and other new data sources, might significantly alter the conceptualization of the FAS envisioned by Miller (1986). The scope of the preliminary hydrogeologic framewor, as originally defined, was to synthesize previous major regional works on the FAS into a single comprehensive view of the hydrostratigraphy and hydraulic properties of the FAS from Orlando to Key West.

A detailed review of eight significant regional publications about the FAS was conducted. Combined, these reports encompassed the entire study area and presented a fairly comprehensive (though disconnected) picture about the state of hydrogeologic knowledge of the FAS. In addition to the literature review, newly compiled hydrogeologic data from approximately 400 deep wells were incorporated into the preliminary hydrogeologic framework. These data included lithologic descriptions, geophysical logs, interpreted elevations for hydrostratigraphic formations, aquifer pumping tests, and water-quality analyses. All data for the project are located in the SFWMD environmental database, DBHYDRO.

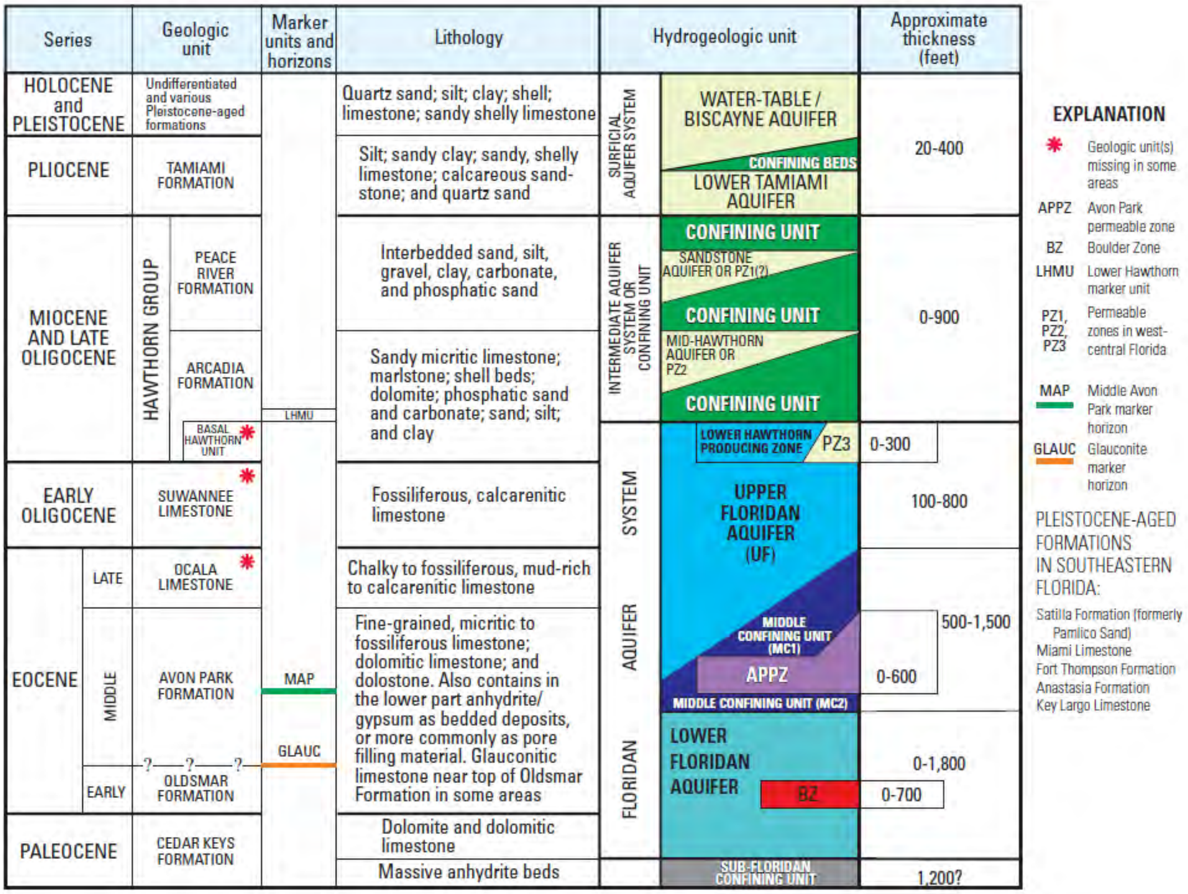


**Figure 3-1 -- Chart showing correlation of hydrogeologic units as defined for the ASR Regional Study, with stratigraphic units and their lithologies. Figure from the preliminary hydrogeologic framework (Reese and Richardson, 2008; Figure 8).**

Geologic cross-sections across the study area were then used to identify and resolve discrepancies in the literature (**Figure 3-2**). The team generated maps of bounding surfaces and hydraulic properties for the major hydrogeologic units of the FAS. This effort was labeled preliminary because it utilized only data that was obtained during the literature search and database compilation tasks. The preliminary framework results were subjected to independent expert review, and then utilized as the conceptual hydrogeologic model for the ASR Regional Study groundwater flow and solute transport model. Key findings from this task were published in Reese and Richardson (2008). In addition to the map products, key findings include:

- Identification and resolution of differences in hydrogeologic nomenclature and interpretation across the study area.
- Introduction and delineation of a major, regionally correlative productive zone referred to as the Avon Park Permeable Zone (APPZ). This zone formerly was a poorly defined permeable zone in the Middle Floridan Aquifer (MFA).

- Development of a correlative or approximate time-stratigraphic framework to identify and define aquifers, producing zones, and confining units within the FAS and to determine their structural relations.

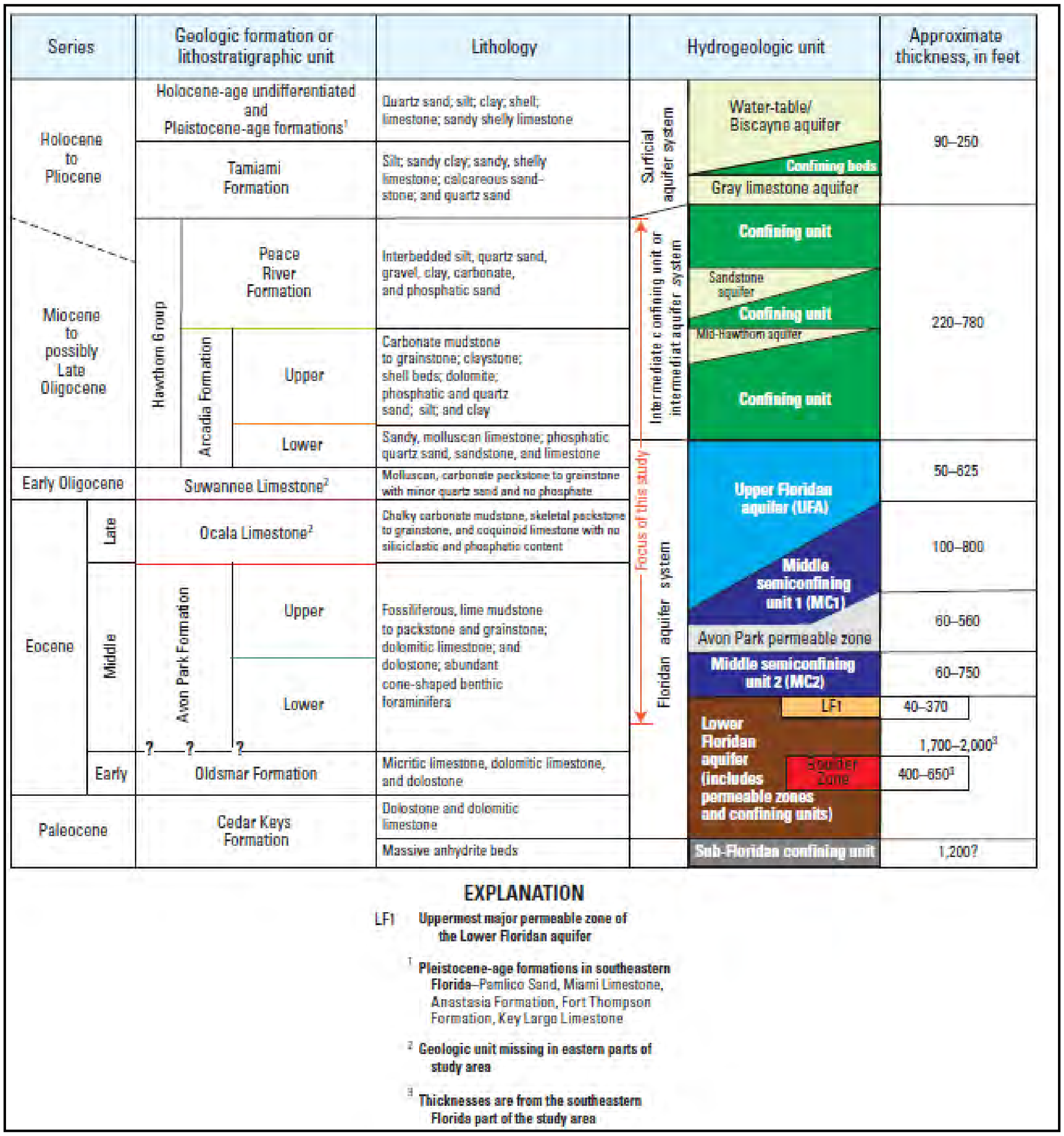
The preliminary framework also identified data gaps and areas requiring additional analysis. In general, the amount of data available from wells decreased with depth because fewer wells are drilled to the depths (about 3,000 ft deep) fully penetrating the FAS. Additional hydrostratigraphic data were needed in several areas, including central Palm Beach County and the Lower Kissimmee Basin. Additional information about the hydraulic properties of the FAS along an area thought to be a hydrologic "divide" in the center part of the state was also identified. These areas of missing information were guided subsequent data collection efforts and construction of new test wells.

## 3.2 Final Hydrogeologic Framework

Additional hydrogeologic, lithologic, and geophysical data were obtained by the USGS, USACE, SFWMD, and water utilities since publication of the preliminary hydrogeologic framework (Reese and Richardson, 2008). Much of the data are summarized in well construction reports and other technical publications detailed in the following sub-sections. Reese (2014) interpreted these data in a regional context, and refined the existing FAS hydrogeologic framework **(Figure 3-3).**

New hydrogeologic cross-sections show the distribution of three major continuous permeable zones within the FAS: the UFA, the APPZ, and an uppermost major permeable zone in the Lower Floridan Aquifer (LFA). These permeable zones were recognized and defined in Reese and Richardson (2008), but a much greater resolution of these features is provided for the Lake Okeechobee region by Reese (2014).

The UFA commonly serves as the storage zone at many ASR systems in south Florida. Reese (2014) reports the lateral extent and hydraulic characteristics of the UFA in the Lake Okeechobee region. The UFA is thinnest in the northwestern portion of Lake Okeechobee, and thickest around the lake's southern end. The upper boundary of the UFA commonly coincides with the erosional contact of the Ocala Limestone. A preferential flow zone was identified at this hydrostratigraphic horizon (Reese and Alvarez-Zarikian, 2007), and was estimated to represent 60 percent of total flow in the ASR well at KRASR (Mirecki et al., 2012). This preferential flow zone is a regional feature observed in wells open to the UFA near Lake Okeechobee. The upper surface of the Ocala Limestone and overlying Arcadia Formation also show pronounced depressions, having relief of up to 300 ft along the northeastern and southwestern sides of Lake Okeechobee. These structures, now mapped, could be the result of karst collapse structures that were identified elsewhere in seismic reflection studies (Cunningham, 2013).



**EXPLANATION**

LF1 **Uppermost major permeable zone of the Lower Floridan aquifer**

[1] **Pleistocene-age formations in southeastern Florida**–Pamlico Sand, Miami Limestone, Anastasia Formation, Fort Thompson Formation, Key Largo Limestone

[2] **Geologic unit missing in eastern parts of study area**

[3] **Thicknesses are from the southeastern Florida part of the study area**

**Figure 3-2 -- Chart showing correlation of hydrogeologic units as defined for the ASR Regional Study, with stratigraphic units and their lithologies.** Figure from the final hydrogeologic framework of Reese (2014).

In addition to the map products, key findings from the final framework include:

- The lateral extent of the APPZ is further defined. Hydraulic connectivity within the APPZ in wells along the Atlantic coast of Martin and Palm Beach Counties is uncertain.
- The lateral extent of the upper permeable zone of the LFA is further defined. Hydraulic connectivity in wells west of Lake Okeechobee (Labelle and Glades County) is uncertain.

## 3.3 Floridan Aquifer Monitoring Network Expansion

Previous investigations of the FAS in south Florida identified the lack of sufficient water-level data to develop a comprehensive groundwater model. Water-level data are needed to define existing conditions, and to calibrate the groundwater model for the prediction of future groundwater levels. The geographic distribution of the available water-level data was focused primarily along the coasts, whereas few data were available in the interior of the state. A critical need for sites showing the vertical distribution of water levels within the FAS also was identified. The ASR Regional Study allowed for the installation and maintenance of continuous water-level recorders at several FAS wells in key locations to improve the quality and quantity of data available for groundwater modeling **(Figure 3-4)**.

The current extent of the FAS recorder network is shown in **Figure 3-5**. Thirty sites were added to the network since project initiation, with many of the sites monitoring multiple depth intervals within the FAS. The current network consists of 70 sites monitoring 95 discrete zones within the FAS. Each monitored interval was surveyed and instrumented with automatic recorders, pressure transducers, and telemetry equipment to transmit the recorded pressure data to the SFWMD. These data are reviewed by SFWMD staff, converted to water-level data and uploaded to the DBHYDRO database. All sites are visited quarterly for maintenance service and an instrumentation calibration check.

**Figure 3-3 -- A continuous groundwater monitoring station at an FAS well.**

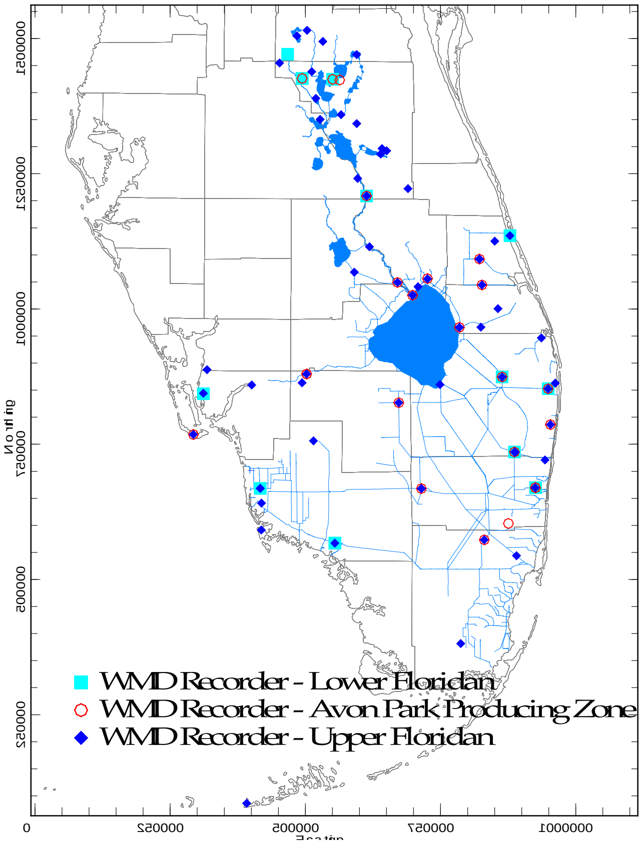


**Figure 3-4 -- Current FAS water-level recorder network.**

## 3.4 Well Construction for Hydrologic and Geophysical Testing

Construction of four individual wells was specified within the hydrogeologic field data collection program for the ASR Regional Study, which supplemented an existing hydrogeologic data collection program at SFWMD. By 2011, five additional FAS wells or well clusters were constructed by the SFWMD to augment their existing Regional Floridan Aquifer Monitoring program. Well construction and aquifer performance testing (APT) results are cited as references in **Table 3-1**, and are available for download in the SFWMD DBHYDRO database. These wells were constructed at Allapattah (Sunderland, 2008), Alligator Alley, L-8 (Anderson, 2008), S-65A (AECOM Water, 2008), S-65C (Sunderland et al., 2011), and northwest Lake Okeechobee (CH2M Hill, 2008). The initial field data collection plan conformed closely to the vision outlined in the PMP. As project goals, schedule, and funding evolved over time, the plan was adapted to adjust to these constraints. Proposed locations for field data collection tasks are shown in **Figure 3-6.**

**Table 3-1 -- Field Data Collection Tasks Completed for the ASR Regional Study.**

| Legend | Field Task | Hydrogeologic Report Reference |
|---|---|---|
| TWP | Task 1: Test Well Pairs | CH2M Hill, 2007a, b; CH2M Hill, 2008; Anderson, 2008; Sunderland, 2008; AECOM Water, 2008; Sunderland et al., 2011 |
| PM | Task 2: ASR Pilot Site Monitor Wells | Bennett et al., 2001; Bennett and Rectenwald, 2002; Golder Associates, Inc., 2006, 2007; Mactec, 2007; Water Resource Solutions, Inc., 2004, 2005; Entrix, 2010 a, b |
| CC | Task 3: Continuous Cores | CCBRY-1 at CRASR; in Arthur et al., 2007. |
| SPS | Task 4: Single Wells near Pumping Stresses | Sunderland et al., 2011 |
| SR | Task 5: Seismic Reflection Survey | Lake Okeechobee - CH2M Hill, 2006; Townsend Canal - Walker Marine Geo-physical Co. LLC, 2004 |
| All | Task 6: Supplementing the SFWMD Water-level Monitoring Network | Same as Task 1 |
| All | Task 7: Water-Quality Monitoring Network | Same as Task 1 |
| TT | Task 8: Tracer Tests | Not conducted |
| APT | Task 9: Aquifer Performance Testing at Existing Wells | Same as Task 6 plus Clewiston FAS well |
| TOM | Task 10: Tomography | Port Mayaca ASR |
| | Task 11: Post cycle test logging / in-situ dissolution | Not conducted |

Note: Field task locations are identified by "legend" acronyms on **Figure 3-6**.

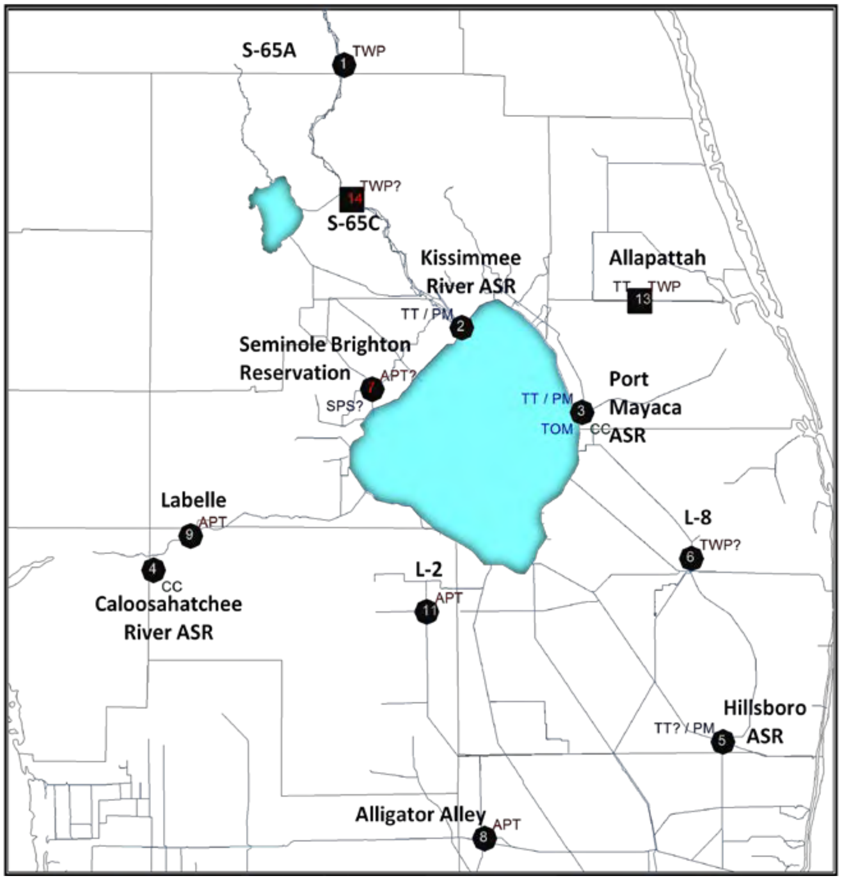


**Figure 3-5 -- Map showing locations of wells for hydrologic and geophysical data collection.** Acronyms defined in Table 3-1.

Test and monitor well locations were chosen based on proximity to source waters for ASR, availability of existing wells, and other hydrogeologic factors. Two existing wells, at L-2 and LaBelle, were rehabilitated and retrofitted to accommodate further exploration of the FAS (CH2M Hill, 2007a,b). Additional wells and testing supplemented the development of the four CERP ASR Pilot Project sites (CRASR, HASR, KRASR, and PMASR). These well tasks included conversions of single-zone to dual zone wells at KRASR (Golder Associates, Inc., 2006), PMASR (Mactec, 2007), and CRASR (Water Resource Solutions, Inc., 2004, 2005) plus construction of additional storage zone monitor wells at KRASR (Golder Associates, Inc. 2007; Entrix, 2010 a,b). New wells were constructed at Allapattah (Sunderland, 2008), Alligator Alley, L-8 (Anderson, 2008), S-65A (AECOM Water, 2008), S-65C (Sunderland et al., 2011), and northwest Lake Okeechobee (CH2M Hill, 2008). Wells at these sites were designed to provide hydrogeologic information and serve as long-term monitoring sites in the FAS and confining units.

The test wells were designed to characterize distinct zones of the FAS to be monitored during the ASR Regional Study. The storage zone typically targeted for use is the UFA, but the APPZ and the Lower Floridan aquifers also were considered. A variety of hydrogeologic data were collected at the test well sites, including water quality, rock cuttings and cores, APT data, and borehole geophysical logs to provide information about the lithology and the physical properties of the water, rock, and borehole.

## 3.5 Estimation of Hydraulic Parameters in the FAS

A major objective of the hydrologic portion of the ASR Regional Study was to synthesize all existing hydraulic data for the FAS, for regional characterization of potential storage zones, and also to support groundwater flow model development. The preliminary hydrogeologic framework defined boundary conditions for layers representing aquifers and confining units. Estimates of aquifer transmissivity and storage parameters were compiled from APTs, packer tests, core permeability measurements, and other hydrologic tests conducted in the FAS of south Florida. Test data were evaluated in context of the lithologic units penetrated, and the degree of penetration of the aquifer, then reviewed for technical soundness. After this quality assurance process was completed, hydraulic data were entered into the SFWMD DBHYDRO database, and incorporated into the ASR Regional groundwater flow model.

The majority of aquifer testing conducted previously in the FAS was performed either to assess the potential for water supply, or to assess confinement for deep well (Boulder Zone) injection facilities. Water supply applications often produce tests that encompass multiple hydrostratigraphic units. Tests that encompassed more than one production interval, or production interval and confining unit, were identified and coded. **Table 3-2** summarizes the results of the test classifications.

**Table 3-2 -- Classification of Hydraulic Test Data.** Table shows number of tests that describe hydraulic characteristics of each aquifer and/or confining unit.

| Code | Hydrostratigraphic Unit | APT / Packer | Core |
|---|---|---|---|
| IC/IA | Intermediate Confining Unit/<br>Intermediate Aquifer | 32 | 5 |
| UF | Upper Floridan | 113 | 36 |
| UFP | Upper Floridan, partial (P) | 165 | |
| MC1 | Middle Confining Unit 1 | 9 | 45 |
| MC1P | Middle Confining Unit 1 partial | 27 | |
| UFMFP | Upper Floridan /<br>Middle Floridan partial | 52 | |
| UFMF | Upper Floridan/Middle Floridan | 9 | |
| MF | Middle Floridan | 26 | 8 |
| MFP | Middle Floridan partial | 39 | |
| MC2 | Middle Confining Unit 2 | 0 | 62 |
| MC2P | Middle Confining Unit 2 partial | 76 | |
| LF1 | Lower Floridan Unit 1 | 29 | 22 |
| LF1P | Lower Floridan Unit 1 partial | 9 | |
| LC | Lower Confining Unit | 0 | 151 |
| LCP | Lower Confining Unit partial | 25 | |

Notes: P indicates partial penetration of that unit or aquifer

## 3.6 Supplementary Analyses of Field Data

Additional geotechnical and geophysical analyses were performed at individual wells to better characterize the FAS. These studies were completed by the SFWMD using CERP and other non-CERP funds.

### 3.6.1 Sequence Stratigraphic Analysis: ROMP 29A Corehole

Sequence stratigraphy is a specialized branch of geology that links sediment deposition to changes in sea level. The basic idea is to map rock layers based on identification of transgressive (sea level rising) and regressive (sea level falling) sequences. This approach was developed to predict subsurface patterns in rock material and permeability. A sequence stratigraphic approach to understanding the subsurface geology in the FAS was evaluated to identify relationships between sequences and the flow characteristics of the aquifer. This understanding was sought to better predict aquifer characteristics in the areas between test wells, which would help determine the regional extent of water-bearing layers feasible for ASR.

A study was initiated with the USGS to describe and interpret the lithology in a single continuous corehole in the context of sequence stratigraphy, and evaluate the utility of this information for delineation of candidate flow zones and confining units for CERP ASR (Ward et al., 2003). The Regional Observation Monitoring Program (ROMP) 29A test well, located in Highlands County **(Figure 2-1)**, was used for this evaluation. Well 29A penetrated the Avon Park Formation, Ocala Limestone, Suwannee Limestone and Hawthorn Group, representing rocks of Middle Eocene to Miocene age (40–10 million years before present) to a depth of 1,244 feet bls.

The report provides a detailed description of the Avon Park Formation of Middle Eocene age, Ocala Limestone of Late Eocene age, and Suwannee Limestone of Late Eocene and Oligocene ages. Particular attention was given to the stratigraphic distribution and thickness of porous and permeable zones and their relation to a sequence-stratigraphic framework established from this core. Lithologic descriptions are based on examination of 834-ft of slabbed core and 59 petrographic thin sections, and include petrologic and microfaunal analyses to determine the mineralogy, geologic age, and paleoenvironments of deposition. Percent vuggy porosity was estimated by a new method for the quantification of vuggy porosity using digital borehole images (Cunningham et al., 2004).

Geophysical log and APT data collected in Highlands County and elsewhere were compared to assess relationships among geology, hydrogeology, and transmissivity. Within this interval, the USGS was able to identify numerous sequences of rock, relating lithology to various stages of a rising and falling sea, as shown in **Figure 3-7**. The USGS then related lithologies to hydrologic characteristics, such as:

- Distribution of flow in the well from geophysical logs
- A quantification of the primary source of porosity
- Transmissivity from aquifer performance tests in the region

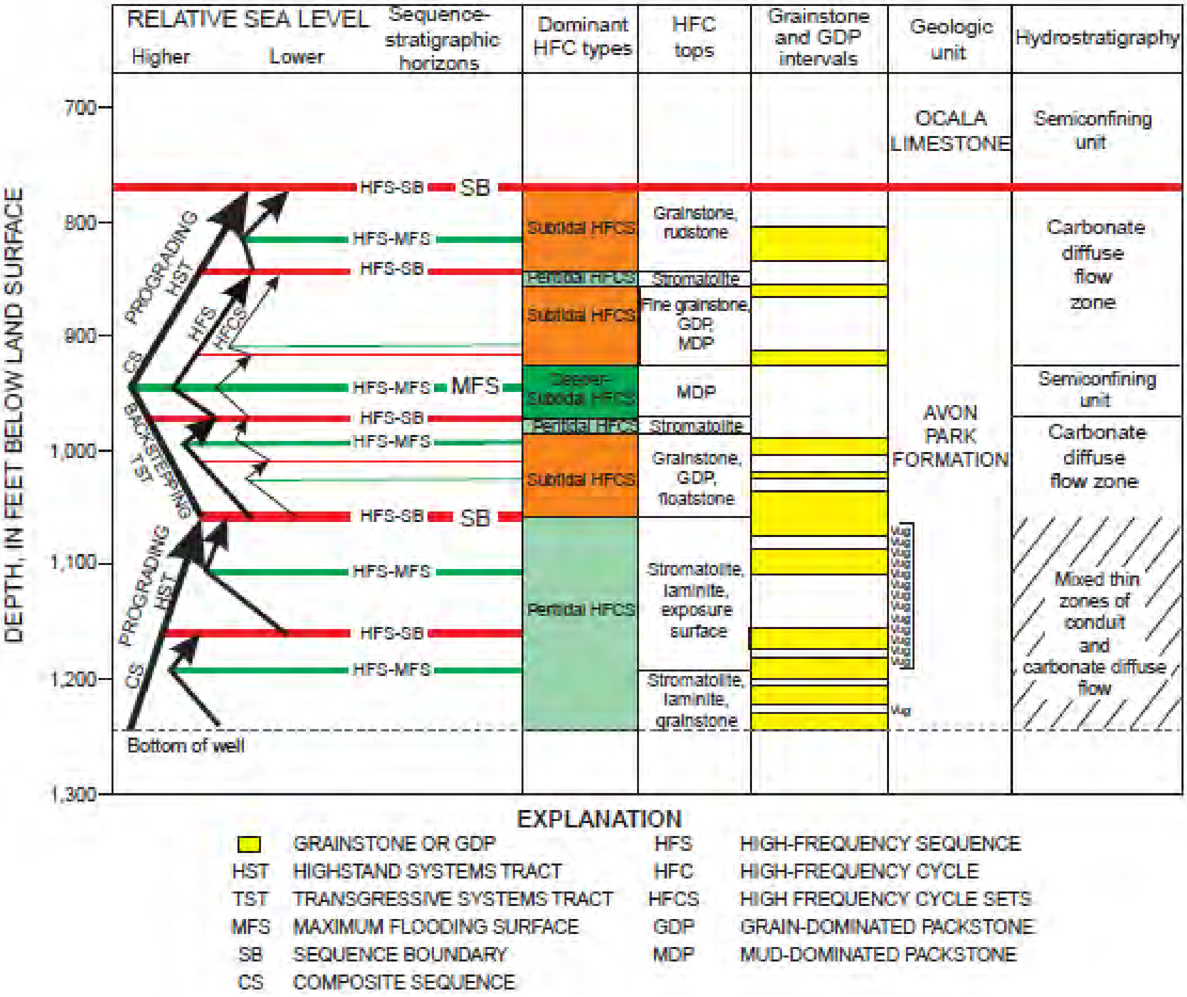


**Figure 3-6 -- Summary of sequence stratigraphic horizons from the ROMP 29A core.** Figure from Cunningham et al. (2004).

Results of these analyses indicated a correlation between zones of diffuse flow (most suitable for ASR) and certain portions of the cyclostratigraphic sequence. This study indicated that use of a sequence stratigraphic approach could reduce the risk of miscorrelation of groundwater flow zones and confining units and should be considered during future ASR-related investigations, should additional continuous core data become available.

### 3.6.2 Lineament Analysis

The concept of surficial topographic, geologic, or biologic elements reflecting the bedrock or geomorphic characteristics of an area has been recognized by geologists for over one hundred years. However, the practice of mapping lineaments and fractures received little attention until after World War II. Using aerial photography, geologists in the oil industry incorporated lineament and fracture trace analysis in their research to identify joint and fracture patterns, faults, and other geologic and geomorphic features. The purpose of the lineament analysis for this project was to identify subsurface features that could be observed on the land surface in order to develop relationships between geologic structures and areas of enhanced groundwater flow within the FAS.

Because of south Florida's low topographic relief, the surface features that identify lineaments are lakes, sinkholes and solution depressions, stream alignments and river patterns, and variations in soil and vegetation patterns. This investigation (USACE, 2004) involved lineament identification on Landsat digital photographs and comparison of those lineaments with known geologic features. **Figure 3-8** shows the lineaments identified in south Florida. The red lines in the figure have been documented in previous lineament studies, whereas the black lines are more conjectural and have yet to be confirmed through field observation. Azimuths and lengths of each lineament were measured and rose diagrams and histograms were created. Digital orthophoto quadrangle aerial photos also were viewed as part of the analysis for the CERP ASR pilot projects. The size of the study area limited the field proofing of potential lineaments.

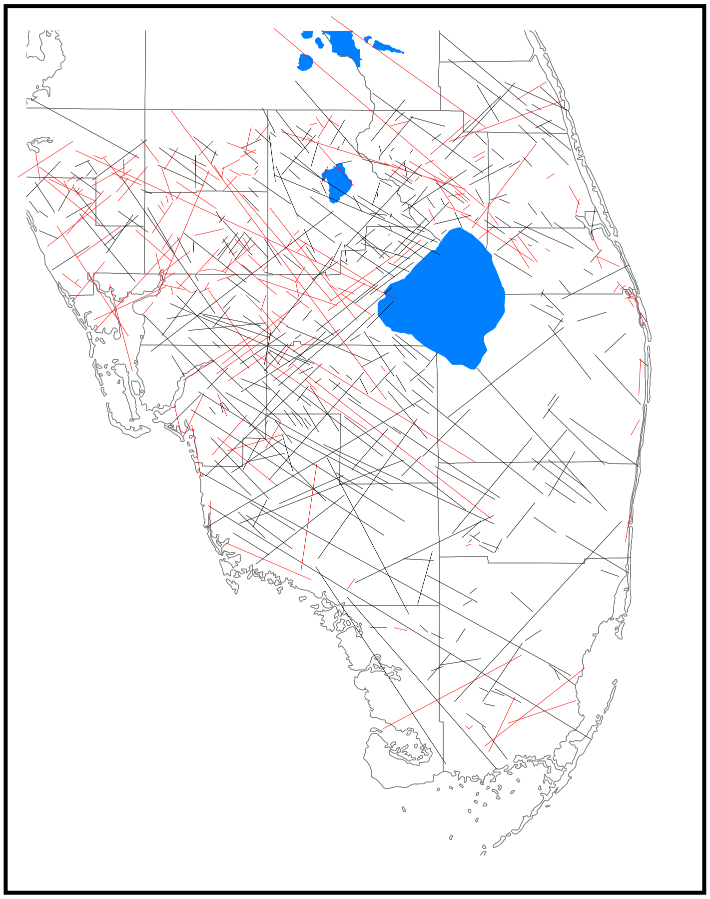


**Figure 3-7 -- Lineament map of south Florida.** Figure from USACE (2004).

Six Landsat multi-spectral scanner (MSS) false color images were assembled to create a mosaic covering south Florida having a resolution of about 98 feet (30 meters). The images were manipulated to show various MSS band combinations, with bands 4, 5 and 7 showing the best contrast for identifying lineaments. The lineament analysis was performed using ArcMap™ geographic information system (GIS) and mapping software to map the lineaments as a coverage layer.

A total of 548 lineaments were mapped in the study area. Of these, 63 are equal to or greater than 25 miles in length. Lineaments defined on Landsat imagery at CERP ASR pilot project locations were cross-checked for correspondence on digital orthophoto quadrangle aerial photos, thus adding confidence to the significance of the photo-linear. Further confidence gained by noting that the lineament study duplicated many lineaments identified by other authors.

The findings show that the regional geologic structure and hydrogeologic character tend to parallel surface lineament trends. The data suggest that many lineaments may indicate subsurface fractures or perhaps faults extending from the basement structures through the overlying rock and are reflected on the ground surface. One of the most noteworthy findings of this investigation was the concentration of northeast-trending lineaments along the northern Caloosahatchee River corridor and the northwest side of Lake Okeechobee. Here, lineaments seem to correlate to a deep basement feature or other deep geologic structure. Water quality in the FAS degrades significantly south of these features.

Other noteworthy findings were: 1) lineaments coinciding with a mapped fault and in areas of higher chloride concentrations and higher UFA groundwater temperatures in the northeast study area; and 2) the northwest-trending lineaments in the southwest portion of the study area, which appear to correlate with naturally occurring upward leakage through semi-confining and confining units, and inferred faulting and structure in the FAS, Hawthorn Group, and SAS. The lineament study was a useful contribution to the ASR Regional Study. However, additional data are required to incorporate extensive lineament structure and orientation into the ASR Regional groundwater model.

### 3.6.3 Borehole Fracture Analysis/Image Logging

Results from the Phase I regional groundwater model showed that the initial conceptualization for the model, and by extension, our understanding of the FAS flow system at that time, significantly under-predicted the heads in southeast Florida. The Phase I model was unable to produce a reasonable match for predevelopment heads in the Upper Floridan and APPZ south of Lake Okeechobee. The groundwater modeling team investigated this problem by using the model to evaluate alternate conceptualizations of the flow system (USACE, 2006). One of the more promising alternatives was the application of regional anisotropy, increasing the permeability in the FAS along the axis of the peninsula, to direct water more rapidly southward. Results from the surface lineament analysis encouraged the hypothesis of preferential orientation of flow in the FAS. The following analysis of geophysical log data from the test well drilling determined that data were insufficient to support anisotropy as a contributing factor for model calibration.

The groundwaterflow-system within the FAS is highly complex. The FAS contains both primary and secondary permeability. The secondary permeability ranges from pin-point vugs to caverns, but much of it appears to be associated with enhanced dissolution along bedding and fracture planes. The degree to which natural fracturing governs the nature of flow within the FAS is poorly understood. In an effort to better characterize the relationship among fractures and secondary permeability, anisotropy, and productivity, borehole image logs were run on number of wells shown on **Figure 3-9.** These data were interpreted using methods for fracture analysis.

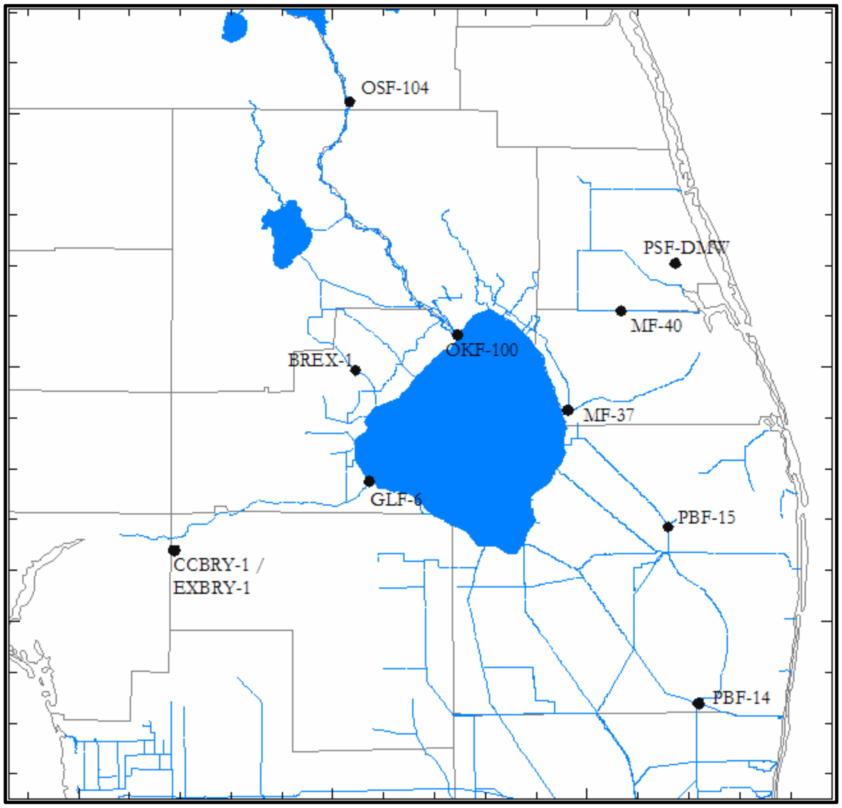
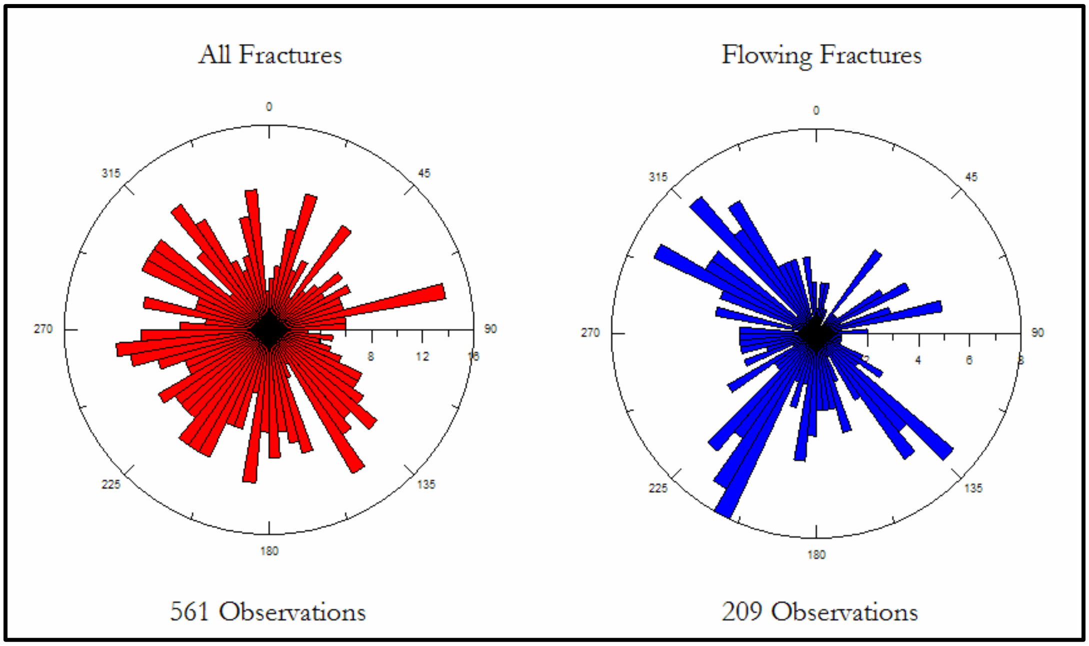


**Figure 3-8 -- Locations of wells used for the borehole fracture analysis.**

Several types of specialty geophysical imaging logs were run and evaluated by independent experts from Schlumberger™ or Petris Technology Inc™. These logs produce electronic pictures of the rocks and fluids encountered by a drilled borehole:

- OBI - Optical Borehole Imager: produces high resolution optical image of the borehole wall that is fully oriented in 3-d space
- FMI - Full bore Formation Micro-Imager: produces high resolution electrical resistivity image of the borehole wall that is fully oriented in 3-d space
- UBI - Ultrasonic Borehole Imager: produces high resolution acoustic reflection amplitude and travel time image of the borehole wall that is fully oriented in 3-D space

The resulting borehole images were analyzed to identify the presence, orientation and dip of planar features (bedding planes and fractures) within the borehole log. The individual well analyses from Petris and Schlumberger were compiled, and each feature tagged according to its formation, hydrogeologic unit, and flow status (based on correlation to flow log results). In addition to frequency and dip angles, the strike orientation (dip azimuth + 90°) of the observed fractures were summarized to determine if preferential orientations existed that might lead to directional anisotropy in the permeability of the FAS. **Figure 3-10** presents the strike orientations for all of the observed fractures in this study.


All Fractures

Flowing Fractures

**Figure 3-9 -- Strike orientation of all fractures from the image log dataset.**

The polar coordinate plots represent fracture strike orientation in units of degrees from north. The length of the bar represents the frequency of occurrence of fractures at that orientation. When all fracture orientations are combined, the orientations looked fairly random. But when the display included only fractures with observed productivity, some patterns began to emerge. These patterns are resolved further if the orientation data sub-set is grouped by aquifer. The following general observations were made from the sub-set data:

- There are distinct trends in fracture orientation within the aquifers of the FAS.
- The trends are clearest within productive intervals.
- The trends are not the same in different aquifer units.
- Increasing complexity in fracturing tends to increase with depth

Based on USACE (2006), the fracture orientation data from the UFA lent itself best to application of regional anisotropy to improve model calibration **(Figure 3-10).** Here, the dominant strike orientation for flowing fractures within the UFA is overlain on a map of the estimated pre-development head in that unit (Bush and Johnston, 1988). The alignment between the orientation of dominant strike, and the orientation of the groundwater “high” that runs down the peninsula was intriguing, and constituted sufficient support to pursue this avenue of investigation during the early phases of model calibration. The data do not, however, support regional application within the entire UFA. Both wells OSF-104 and

PBF-14, for example, showed no indication of fracturing within this unit. There are also inherent biases in the current log data-set which restrict its interpretation, and the extent to which it can be extrapolated beyond the borehole scale. Two critical biases were identified in the data-set which affect comparisons of fractures between different aquifers:

- There are significantly more data in the shallow FAS than in the deeper hydrogeologic units.
- Flowing intervals within each borehole were defined based on production logging under conditions of artesian flow. This depends on an upward head gradient to induce flow into the well, something generally not found in the LFA.

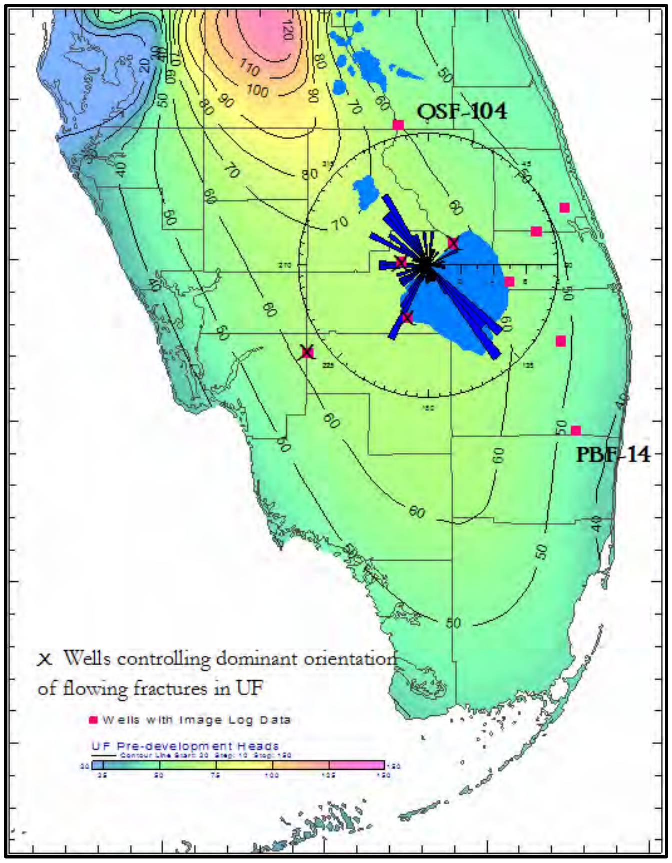


**Figure 3-10 -- Flowing fracture orientation in the UFA and estimated pre-development heads.**

Because of these biases, the image log data-set, if viewed in isolation, would lead to the conclusions that; 1) there is a greater intensity of fracturing within the UFA than in the lower permeable units, and 2) that most fractures within the LFA are un-productive. We know from other data that these conclusions are incorrect. Neither of these difficulties is insurmountable, but both require additional field data collection to correct. Problem (2) requires different, and more costly test design to rectify, while problem (1) is a simple matter of acquiring more sample data. The difficulty with making regional extrapolations also is a problem of sample size. As depicted in **Figure 3-10,** data from only four wells contributed to the strike orientation displayed. Of those wells, 75 percent of the fractures were from a single well, OKF-100, at the KRASR system.

The objective of this task was to evaluate the presence and orientation of preferential flow paths due to fracturing in the FAS, and whether data were sufficient to support the application of a regional coefficient of anisotropy in regional model calibration. Results from the logging and analysis clearly indicated preferential orientation of water producing fractures in certain wells, but the available data are insufficient for regional extrapolation. Due to this conclusion, anisotropy was not used in the final calibrated regional model. Acquisition and interpretation of additional image log data is promising for future study of preferential flow in the FAS.

### 3.6.4 Clewiston APT Evaluation for Anisotropy

The lineament and borehole image log analyses focused on the question of anisotropy in the FAS. In an effort to better understand the degree to which anisotropy might affect aquifer responses, the question was approached from an additional direction. The City of Clewiston had recently installed a 4-well FAS wellfield. The orientation of the wells, and wellfield location in the data-poor interior offered the opportunity for further evaluation of the anisotropy question, while acquiring much needed hydraulic property data for the regional modeling. A 5-day APT was performed and analyzed at the City's new multi-well FAS wellfield (Water Resource Solutions, 2007). Well configurations during the test are shown in **Figure 3-11.**

The APT was accomplished by pumping PW-3 at a constant rate of 1,100 gpm for a period of five days. The water level changes in the pumping well and three observation wells (designated as PW-1, PW-2 and PW-4) were measured using vented pressure transducers. The production zone consists primarily of microfossiliferous peloidal limestone of the Ocala Limestone Formation. The open-hole interval of the production wells extends from 700 to 1,250 ft bls, however, lithologic descriptions and geophysical logging information suggested the main flow zone was from 700 to 800 ft bls.

The transmissivity, storage, and leakance values of the aquifer were calculated using multiple methods. Results from the analyses indicated that the average transmissivity of the aquifer was about 22,700 $ft^2$/day. The average storage coefficient of the aquifer is 3.0 $x10^{-4}$, and the average leakance of the aquifer was about $4.2x10^{-4}$ $day^{-1}$**.**

The common methods used to derive hydraulic coefficients from APT data assume that the aquifer is isotropic, i.e, the hydraulic conductivity of the aquifer is the same in all directions. In reality most aquifers are anisotropic. The hydraulic conductivity in the direction of flow (Kx) tends to be greater than that perpendicular to flow (Ky). The ratio Kx: Ky or Tx: Ty (if the thickness of the aquifer is constant) is referred to as the anisotropy ratio. In this study, Hantush's method (1966) was used to determine the anisotropy of the aquifer at the project site on a horizontal plane.

Figure 3-11 -- Well configurations during the Clewiston APT.

Using the above-referenced analysis, the results indicated that the principal axis of anisotropy (x-axis) is at an angle (θ) of about 95° from the straight line joining the pumping well PW-3 and the observation well PW-1, and the minor axis of anisotropy (y-axis) is 90° to this axis **(Figure 3-12)**. The ratio of anisotropy (Tx/Ty or m) was calculated to be 7.04. The transmissivity value along the x-axis (Tx) was about 73,000 ft$^2$/day and the transmissivity value along the y-axis (Ty) was about 10,500 ft$^2$/day. This evaluation was a helpful demonstration to the groundwater modeling team, when evaluating various potential orientations and magnitudes of anisotropy to insert into the model during calibration.

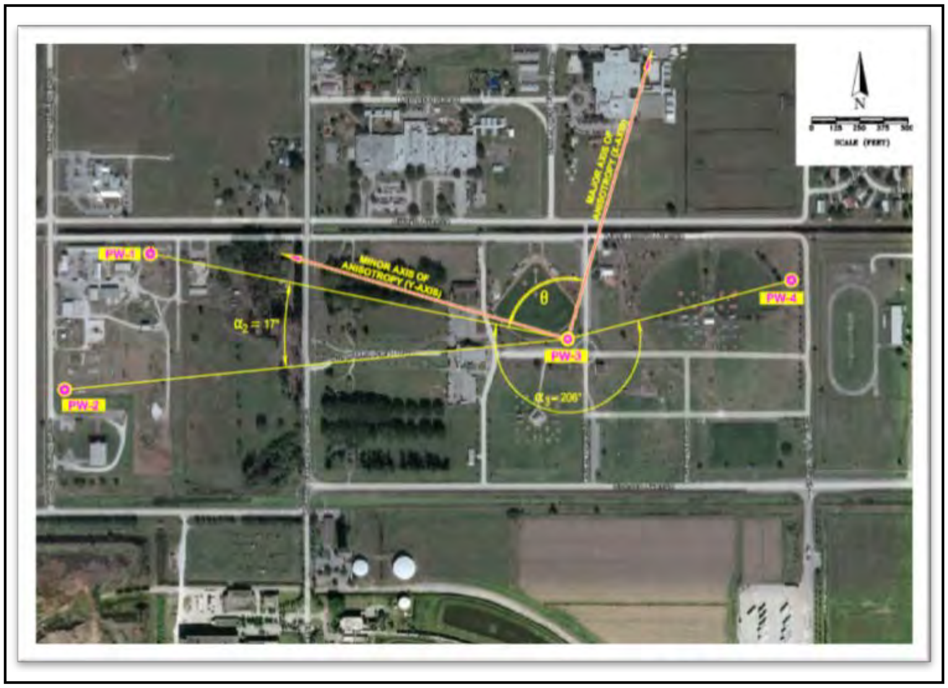


Figure 3-12 -- Primary axes of anisotropy within the Clewiston wellfield.

## 3.7 Geophysical Characterization of the FAS

### 3.7.1 Analysis of Existing Seismic Reflection Data

Numerous seismic reflection geophysical surveys were performed in southern Florida by oil companies since 1960, with most of the surveys conducted from the 1970s through the 1990s. These surveys targeted oil producing zones at depths of approximately 10,000 to 14,000 feet bls. Within the past decade, advances in the field of geophysical data processing have made it possible to reprocess and reanalyze some of this older, existing seismic data to provide geologic and potentially hydrogeologic information for the lower portion of the Hawthorn Group and FAS occurring at depths of approximately 500 to 2,500 bls. Given the many seismic lines that traverse areas for which no other data were available, it was prudent to investigate the possibility of reprocessing available seismic reflection data in the hopes that the seismic data could "fill in" data gaps, where information from wells was otherwise not available.

A seismic data coverage map was obtained from Seismic Exchange, Inc. (SEI) for a large area of Florida, extending from north of Lake Okeechobee to the southern tip of Florida. **Figure 3-13** presents a map area showing some of the seismic lines that were available for purchase or "lease", if the data had the potential to be re-processed for imaging the FAS. A senior geophysicist assessed general data parameters of several of the existing seismic lines for review, and an area just south of Lake Okeechobee was selected for further evaluation. Thirteen lines were selected for further assessment, based on general proximity to Lake Okeechobee and line orientation (URS, 2003). Data acquisition parameters for each line were obtained from SEI for comparison and assessment. Each line was evaluated for the geophone interval, shot interval, fold, and cost to lease. From this review, five lines were chosen for subsequent visual review of sample sections from SEI.

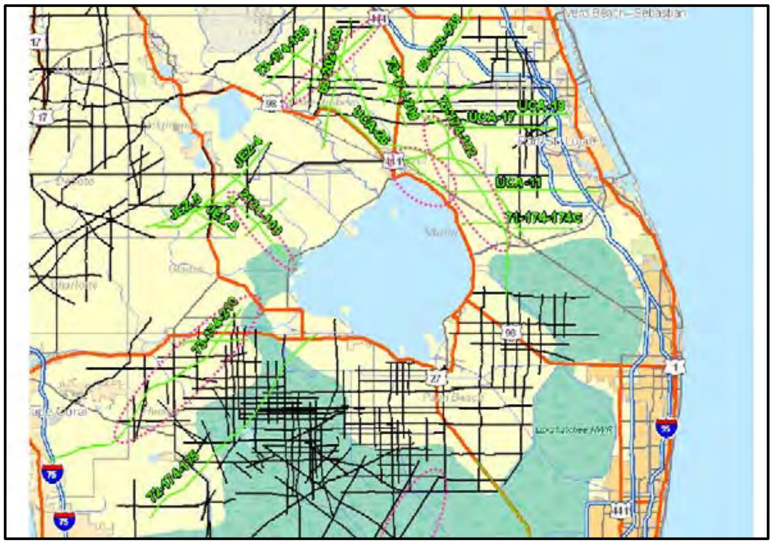


Figure 3-13 -- Available seismic lines in an area of south Florida.

After securing the data from their Houston office, SEI met with URS for data review. The review consisted of examination of one hard copy of each line. This hard copy review was limited to what SEI provided to protect confidentiality of data that might subsequently be purchased or leased for oil exploration. The project team could not obtain multiple copies with various display parameters unless the data were leased. As a result, some expertise was required to estimate the value that additional reprocessing would likely produce for a given data set. Based on review of the hard copy seismic sections, two seismic lines were recommended for subsequent lease and reprocessing. One of the lines utilized dynamite as the seismic source with an east-west orientation, and the other line used a vibroseis source also with an east-west orientation. Both lines had favorable acquisition parameters that could be processed to enhance shallow data resolution (URS, 2003). For future consideration, the lines chosen for interpretation represent some of the better seismic data that were available in the area.

The seismic data consisted of portions of two 2-D seismic lines acquired in the 1980s by SEI. The original acquisition parameters targeted potential oil-producing zones from 10,000 to 14,000 feet bls. One line was acquired using a dynamite source and recorded p-wave seismic data. The other line was acquired with vibroseis, using a truck-mounted controlled source vibrator, and also recorded p-wave seismic data. The reprocessing sequence included a variety of programs that are normally applied to common midpoint (CMP) seismic data. After initial analysis the exact sequence steps were designed. During various steps the processing analyst reviewed the results to ensure optimum data quality. Processing programs have many functions including sorting data traces into CMP format, applying static and velocity functions, editing and removing unwanted noise, enhancing frequency content, scaling data for presentation, plotting data, and a variety of other data analysis techniques.

The reprocessed seismic lines were delivered to the project team that then gave consideration to overall value of the data, and its potential usefulness in filling in data gaps in the FAS interval of south Florida. Although the reprocessed data gave indications of structural attributes, definition of actual hydrogeologic features within the FAS was beyond the resolution of the seismic profiles. This exercise was a successful demonstration of the potential to acquire and reprocess existing, older seismic data. However, the cost of the data, confidentiality issues, and subsequent reprocessing fees outweighed the usefulness of the data for purposes of regional ASR evaluation. In the future, as seismic reprocessing techniques evolve, this type of evaluation might warrant reconsideration.

### 3.7.2 Seismic Survey of Lake Okeechobee

The preliminary hydrogeologic framework revealed that the largest single data gap in evaluating the hydrogeology of the FAS was beneath Lake Okeechobee. Therefore, a marine seismic reflection survey was conducted to identify structural trends that could pose obstacles to regional-scale CERP ASR implementation. Seismic reflection uses the principles of seismology to estimate the properties of the Earth’s subsurface from reflected seismic waves. **Figure 3-15** presents the configuration of the seismic surveys that were conducted in the Lake. Interpretations of these seismic lines were compiled for Lake Okeechobee and tributaries (CH2M Hill, 2006) and the Townsend Canal (Walker Marine Geophysical Co, LLC, 2004).

Marine surveys are conducted using vessels capable of towing seismic cables known as streamers. Modern surveys use multiple streamers deployed in parallel to record data suitable for the interpretation of the structures beneath the seabed. A single vessel may tow up to 10 or more streamers, each approximately 6 kilometers in length, spaced 50 to 150 meters apart. Hydrophones are deployed at regular intervals within each streamer. These hydrophones are used to record sound signals that are reflected back from structures within the rock. To calculate where subsurface features are located, navigators compute the position of both the sound source and each hydrophone group that records the signal. Accurate positioning is achieved by using a combination of acoustic networks, compasses and Global Positioning System (GPS) receivers.

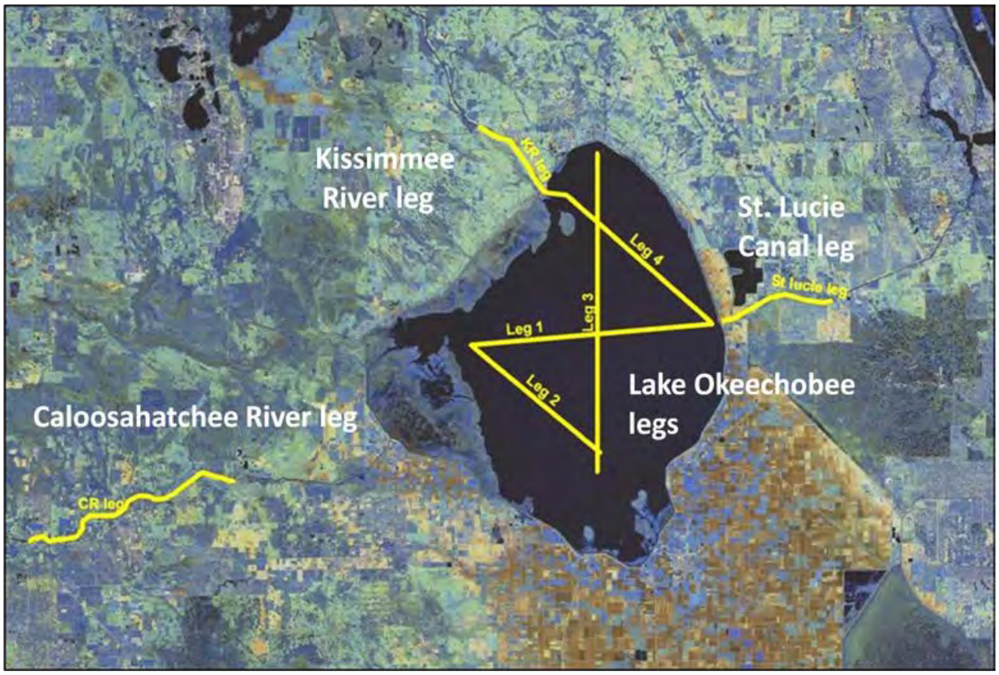


**Figure 3-14 -- Location of seismic surveys conducted in Lake Okeechobee.**
Figure redrawn from USACE (2006).

**Figure 3-16** shows the seismic reflection data from Leg 4 of the Lake Okeechobee seismic reflection survey. After reviewing the various seismic lines, the most significant geological **observation made was** that the formations beneath Lake Okeechobee are generally flat lying, with an apparent dip (fault) and thickening of beds in a southward direction. This was good news to the extent that the FAS is continuous beneath the lake, and no obvious structural hazards were indicated by the seismic lines.

The second most significant geologic feature is the erosional unconformity in the Hawthorn Group seen in the western portion of Lake Okeechobee. This feature appears to show erosion of up to 400 feet through flat lying beds with re-deposition of mostly non-flat lying material. Some apparent "paleo" channels are visible in the re-deposited material.

A third feature interpreted by the lines is the presence of significant lateral disruptions in the profiles that are caused by softer material near the surface. Fracture zones and/or faulting may also have caused these anomalies. Other velocity anomalies probably exist in the deeper beds; however, they are difficult to discern because of the generally discontinuous nature of the reflections in this zone.

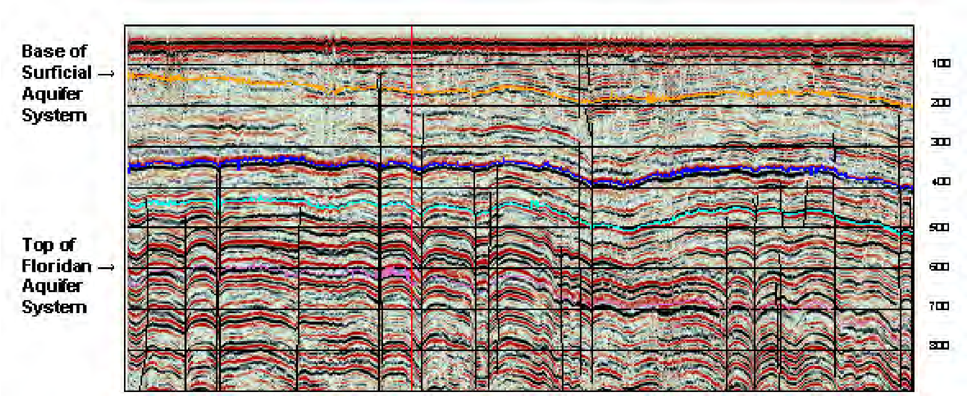


**Figure 3-15 -- The Leg 4 seismic line from Lake Okeechobee seismic survey (see Figure 3-15).** Figure redrawn from USACE (2006).

### 3.7.3 Cross-Well Tomography at Two ASR Pilot Sites

Understanding the continuity of local flow zones in an aquifer is needed to simulate the flow and transport in a groundwater model. Tomography is a tool that can be used to assess that continuity. Seismic tomography is similar to a computed tomography (CT) scan, but instead of using X-rays to create an image, seismic waves are used to digitally map a profile of the Earth. In cross-well tomography, a tomograph is used to measure an acoustic signal transmitted from a one well to a receiver located in a neighboring well to create a map of the properties of the geologic formations between the wells, as shown in **Figure 3-17**. These data can used to map the distribution of porosity and permeability between the two wells.

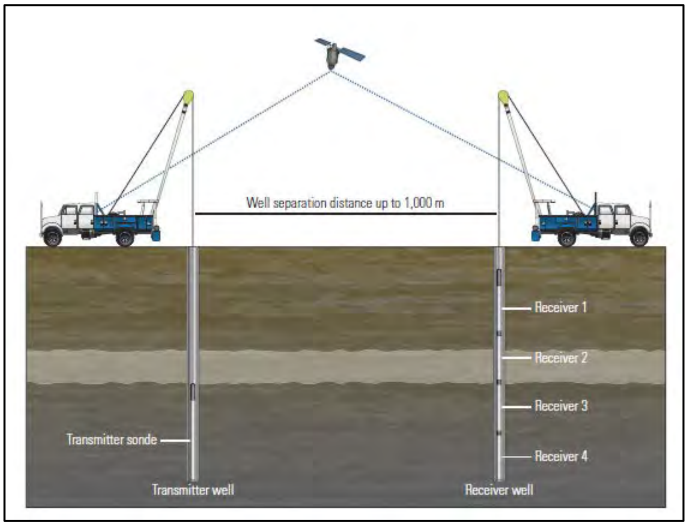


**Figure 3-16 -- Diagram showing data acquisition for the cross-well tomography investigation.**

At the Port Mayaca ASR pilot site, tomography was conducted between the ASR well and the storage zone monitor well MF-37, located 1,200-ft north-northeast of the proposed ASR well EXPM-1 (Southwest Research Institute, 2007). The tomograph profile was integrated with geophysical log data to relate the tomography data with hydrogeologic parameters. The relationships between the tomograph and geophysical log data were used to generate high-resolution profiles showing the distribution of porosity and permeability between the wells. **Figure 3-18** shows the aquifer permeability at Port Mayaca using cross-well tomography. Warmer colors (toward red) indicate greater permeability, whereas cooler colors (toward blue) represent lesser permeability. These data could be used for local-scale groundwater modeling at the Port Mayaca ASR system, and will be re-evaluated when the results of cycle testing are available from this pilot project. The data will also be useful when additional wells are installed at the site, to guide the depth to which additional storage and monitoring intervals should be constructed.

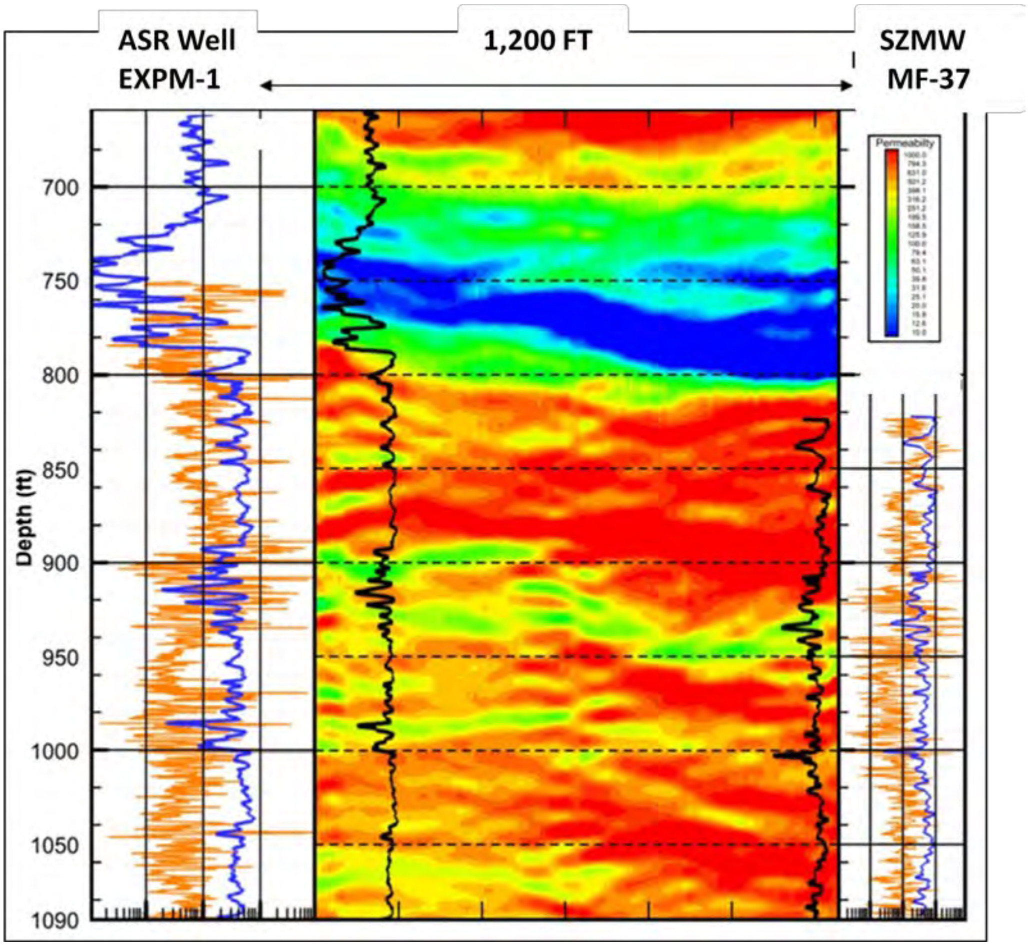


**Figure 3-17 -- Results of tomography survey at the Port Mayaca ASR pilot site.**

Cross-well seismic measurements were conducted at the Hillsboro ASR pilot site between the ASR well (PBF-13) and the 330-ft SZMW (PBF-10R) using a TomoSeis advanced piezo-ceramic X-series source and a 10-level hydrophone system (Parra et al., 2006). The survey depth interval was from 550-ft to about

1225-ft bls and covered a series of flat-lying limestones with some interbedded sandstones. The sweep length was 1.2 seconds at a sampling rate of 125 microseconds from 200 to 2000 hertz (Hz). Source and receiver depth sampling spacing was 2.5 ft; resulting in about 38,300 recorded traces. Actual reflection coverage below the total depth for each well was limited by well spacing, as well as the deepest source and receiver locations in each well. The vertical resolution of the reflection data for this profile was about 2 ft. The reflection image was inverted for impedance using the band-limited method (a feature of the Hampson-Russell STRATA software (CGG, Houston TX). **Figure 3-19** shows the tomographic image between the two wells at depths from 750-ft to 1550-ft bls. The Vp and density logs were overlain on the impedance image, and the image shows good correlation with the well logs. In particular, the impedance clearly shows the main boundaries of the upper and lower productive horizons that correspond to the high impedance zones identified in red.

Cross-plots of impedance with permeability and porosity were used to derive empirical relationships (or impedance cross plot fit equations) for permeability (*k*) and porosity (ϕ) for depths of 950 to 1250 ft. These relationships were used to convert the impedance to produce the overlaying permeability and porosity images **(Figure 3-19).** These images show continuous and discontinuous flow units. The lateral continuous flow unit observed in yellow, between 1020 to 1040 ft bls, has an average permeability of 2000 millidarcies (md), and an average porosity of 30 percent (observed in blue in the porosity image at a depth of about 1020 ft). This flow zone was delineated as a continuous reflector in the reflection image.

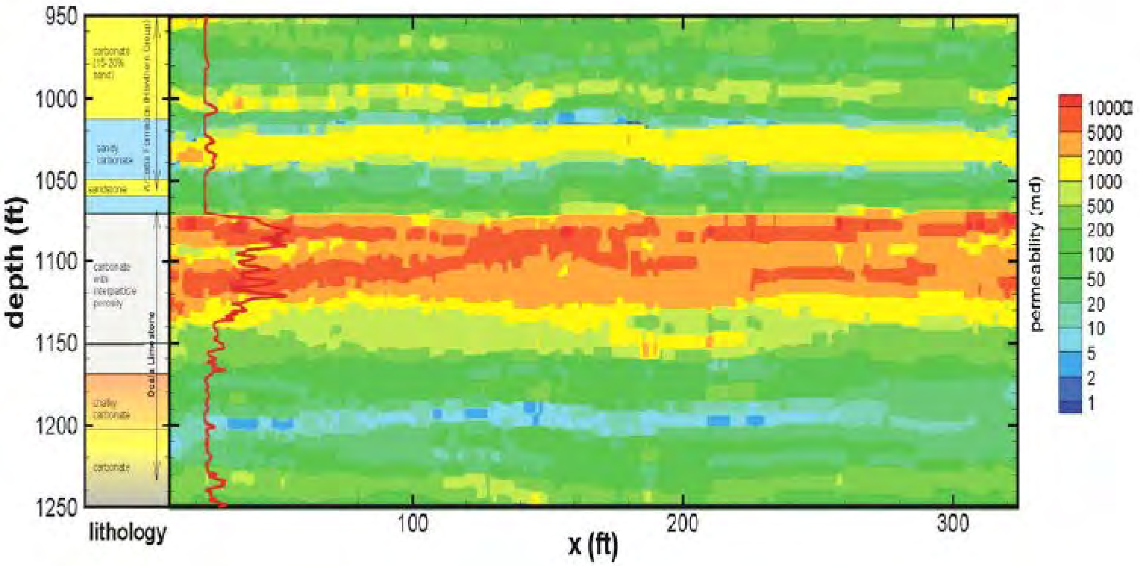


**Figure 3-18 -- Tomographic image from cross-well seismic data at the Hillsboro ASR system.**
Figure redrawn from Parra et al. (2006).

# 4 Geotechnical Investigations

## 4.1 Introduction

An important component of the ASR Regional Study was to determine the magnitude and extent of pressure-induced changes that could potentially result from the recharge of up to 1.67 billion gallons of water per day into the FAS and the overlying Hawthorn Group confining unit. Specifically, this analysis was intended to determine the potential for ASR to induce fractures, subsidence, or over-pressuring within these formations.

The magnitude of the increase or decrease in piezometric pressure within the UFA during recharge and recovery cycles is highly dependent upon numerous factors such as aquifer transmissivity, well spacing, and aquifer porosity. During ASR recharge, increases in hydraulic head of 100-ft to 200-ft (equivalent to 40 to 100 pounds per square inch (psi) near the pumping wells are possible based upon both analytical and numerical models (Brown et al., 2005). Conversely, during ASR recovery, decreases in static head of similar magnitudes are possible. Pressure-induced changes might present planning and engineering constraints that limit ASR development.

Piezometric heads within the FAS range from approximately 60-ft relative to the National Geodetic Vertical Datum 1929 (NGVD29) north of Lake Okeechobee to 50-ft NGVD29 in central Palm Beach County (Sepúlveda, 2002; USACE and SFWMD, 2004). Increased heads substantially higher than those in the current regional flow system could also lead to changes in groundwater flow direction or velocity. For ASR design purposes, the pressure-induced changes may also constrain wellhead design or pump selection.

Hydraulic fracturing originally was developed during the 1930s and 1940s by the oil industry as a means to enhance production of oil wells. During these early years of development, hydraulically induced fracturing was thought to occur when the hydraulic pressure at any specific point in the well exceeded the pressure due to the weight of the overburden at that point. Since these early developments, it has been shown through research and field application efforts that hydraulically induced fracturing can be initiated at pressures ranging from much lower to somewhat higher than the local overburden pressure and that it is related to rock strength parameters and alignment and magnitude of in-situ stresses. As reported by Driscoll (1986), hydraulic pressures that caused fracturing ranged from a low of 0.5 psi/ft of depth in poorly consolidated coastal plain sediments to 1.2 psi/ft of depth for crystalline rock. Bouwer (1978) indicated that hydraulically induced fracturing could be initiated at a pressure as low as 50 percent of the overburden pressure, but more typically the pressure should not exceed 67 percent of the overburden pressure in order to reduce fracturing potential. Recent oil industry guidelines discussed by Ehlig-Economides and Economides (2010) indicated that almost all reservoirs will hydraulically fracture within a range from 0.71 to 0.82 psi/ft of depth.

As a rough guide, drilling professionals estimate the injection pressure required to induce fracturing in a borehole as a value of 1 psi/ft of depth plus an additional 1,500 psi (Sterrett, 2007). Overall, these general hydraulically induced fracturing criteria envelope a wide range of pressures that could initiate the onset of fracturing for wide ranges of in-situ states of stress and rock matrix types. Therefore, it is necessary to calculate site-specific hydraulic pressures that may initiate the onset of hydraulically induced fracturing based on FAS rock matrix mechanical properties and in-situ stress conditions. The following subsections describe the development of a geotechnical evaluation of hydraulic fracturing potential in the context of regional ASR implementation.

## 4.2 Desktop Evaluation of Hydraulically Induced Fracturing

ASR system operation can increase or decrease aquifer pressure, with the potential to induce rock fracturing during recharge and subsidence during recovery. An initial desktop evaluation was completed to estimate the potential for hydraulically induced fracturing of the FAS rock matrix and subsidence due to consolidation of the Hawthorn Group (Brown et al., 2005). Results of that analysis are summarized in the following subsections.

### 4.2.1 Potential for Rock Fracturing

ASR cycle testing will result in changing head in the FAS. A hydrologic model was developed to simulate head changes and resultant hydraulic pressures that could occur during ASR system operation. Results of 337 aquifer performance tests (APTs) performed in the UFA were compiled to characterize the variability of aquifer hydraulic properties throughout the south Florida region. The mean transmissivity was 13,000 $ft^2$/day for tests in the UFA, which is considerably lower compared to the UFA of central and northern Florida. There, transmissivities range between 50,000 and 250,000 $ft^2$/day (Miller, 1997). The mean storage coefficient and the mean leakance values are 0.0005 (n=168) and 0.00005 (n=104), respectively. The storage coefficient ranged between approximately 0.005 and 0.00005. The leakance value ranged between approximately 0.001 and 0.00001 per day.

After a reasonable range of hydrogeologic parameters was determined for the study area, modeling was conducted using both analytical solutions and the numerical MODFLOW model (McDonald and Harbaugh, 1988). The initial analytical solution evaluations, developed by Hantush and Jacob (1954) and Walton (1962), considered a leaky confined aquifer under steady-state conditions. The evaluation included one ASR well recharging or recovering from the UFA at 5 MGD. This evaluation showed changes in head of up to 120-ft for the average transmissivity of 13,000 $ft^2$/day, and only a 25-ft change for a high transmissivity condition of 50,000 $ft^2$/day. A MODFLOW model simulated effects on head at an ASR system consisting of five ASR wells. Two wellfield designs were simulated where each consisted of a centrally placed well surrounded by four wells spaced at approximately 1,000-ft and then again at 2,000-ft. Each of the five wells was operated at a recharge or recovery pumping rate of 5 MGD, for a total well field production rate of 25 MGD. Using the average transmissivity of 13,000 $ft^2$/day, and running the model to steady-state conditions, the maximum head increase at the centrally located well exceeded 130-ft. A maximum head increase of 90-ft to 100-ft was shown using the 2,000-ft well field spacing scenario. These simulations showed that well spacing is an important factor to be considered in ASR design.

### 4.2.2 Fracturing Due to Shear Stress

Using the simulated UFA hydraulic heads determined by the analytical model and the numerical MODFLOW model, the potential shear stresses induced by ASR recharge could be estimated. The critical shear stresses that occur in the limestone matrix were estimated using a Mohr stress envelope analysis. The expected normal total stress on the critical failure surface was calculated using classical solids mechanics equations.

The calculated shear stresses indicated that failure of the limestone matrix is unlikely if actual ASR system operations are similar to those simulated in this study (i.e., aquifer pressures are kept to levels determined during modeling). Generally the computations revealed that the expected shear stresses will be six to eight times less than the allowable failure stress level. Even if lower limestone cohesion values are chosen (e.g., results from new compressive testing), failure stresses will not be exceeded through normal ASR system operations. Obviously, well spacing is an important consideration to minimize pressure changes in the UFA and consequently, it is an important aspect for evaluating hydraulic fracturing issues. Therefore, closer well spacings may drive UFA pressures higher during ASR operation. These higher pressures (or lower pressures during recovery) can increase the actual shear stresses so that the stress-state could approach the allowable rock shear stress of a limestone. If the limestone matrix fails due to high shear stresses, preferential flow pathways may form in the aquifer increasing hydrodynamic dispersion, diffusion, and potential buoyancy stratification. These changes would likely result in poor ASR system performance. Again, various design constraints should be optimized to develop the most efficient ASR well cluster system while minimizing the possibility of limestone matrix failure due to shear.

### 4.2.3 Hydraulic Fracturing

Hydraulic fracturing was the second possible failure mechanism to be investigated. The petroleum industry routinely uses hydraulic fracturing to enhance the permeability of a rock formation around an oil recovery well. Consequently, much research of this topic (related to the oil industry) is already available in the literature. Hubbert and Willis (1957) describe critical recharge stresses necessary to create new matrix fractures and extend existing fractures. They also noted that new fractures would propagate perpendicular to the least principal stress. Basically, the pressure increase required to hold open and extend an existing fracture should be equal to or greater to the least principal stress. In areas of normal faulting, the least principal stress is normally horizontal while in areas of high tectonic activity, the least principal stress may be oriented on the vertical (Hubbert and Willis, 1957). Therefore, in tectonically quiescent areas of the United States (such as Florida), the fractures caused by excess pore-water pressure would likely be in the near-vertical orientation.

Hubbert and Willis (1957) developed a relationship for the water pressure required to initiate new fractures or enlarge existing ones. This relationship was utilized to evaluate potential for hydraulic fracturing at the various ASR system sites. The analysis concluded that if heads are limited to 250-ft or less in the study area, hydraulic fracture initiation is unlikely. The value of 250-ft was chosen as an upper limit on hydraulic heads that could be reasonably developed in the UFA during the recharge phase of an ASR cycle test.

### 4.2.4 Fracturing Due to Aquifer Dilatancy

The third desktop evaluation of potential rock fracturing mechanism in the UFA was an analysis of dilatancy potential. All materials dilate (or change in volume) in response to shearing strains (Domenico and Schwartz, 1998). As the rock matrix dilates due to the increased fluid pressures, microscopic fractures may form. Pore volume increases can lead to the formation of microfractures that may increase the local-scale hydraulic conductivity of the UFA. The onset of dilatancy can occur at one-third of the allowable shear stress for a rock matrix. Handin et al. (1963) noted that in sedimentary rocks (including limestone), the ratio of the fluid pressure to the confining pressure should not exceed 0.8.

The analysis of dilatancy indicated that the ratio value would be exceeded north of Lake Okeechobee when the total UFA head is approximately 183-ft (NGVD29). In the central Lake Okeechobee region, the ratio may be exceeded when the total UFA head is approximately 225-ft NGVD29. In the south Lake Okeechobee region, the ratio may be exceeded when the total UFA head is approximately 275-ft. This analysis does appear to provide a useful guide to constrain the anticipated fluid pressures that could occur during ASR system operation.

The analysis completed during this initial evaluation clearly demonstrated that pressure-induced hydraulic fracturing of limestones in the UFA, or total limestone matrix failure, is highly unlikely if aquifer pressures are constrained to the maximum defined in the Underground Injection Control permit (typically 66 percent of the casing pressure test, or 66 psi for a 100 psi test).

### 4.2.5 Subsidence Evaluation

Groundwater extraction is one of the most common causes for land subsidence. The greatest magnitude of subsidence occurs where significant water-level declines are coupled with confining units that are thick and composed of compressible materials. In addition to the compressibility properties of the sediment there are two factors that control the extent of land subsidence: the magnitude of water-level or hydraulic head decline, and the duration of that decline. The first factor controls the driving force of subsidence, while the second controls the probability of subsidence. Land subsidence takes place only as fast as the pore water can be squeezed out of the sediment layer. It usually takes decades for extensive subsidence to take place, as demonstrated through documented cases of subsidence worldwide. Based on the evaluation in this study, because it is difficult for pore water to drain from a low permeability clay unit (Hawthorn Group sediments) the time required for the estimated subsidence to be complete, could be decades. This is the case only if ASR wells are pumped continuously over that period. No ASR well is anticipated to be pumped constantly as envisioned in CERP. The ASR wells will be operated in an alternating manner of recharge, storage, and recovery. Therefore, it is likely that land subsidence induced by ASR operation will be insignificant, and should not pose any ASR development constraints.

### 4.2.6 Desktop Study Conclusions

The desk-top study results indicate that only a few of the possible pressure-induced changes examined have the potential to constrain ASR development in south Florida. First, practical limitations involving basic pump availability, pipe pressure limitations, and electricity demand will constrain the total allowable head (or pressure) at each ASR wellhead. Second, pressure-induced change limitations outlined here will slightly constrain ASR operations.

For ASR wells located north of Lake Okeechobee, it is recommended that the average hydraulic head of well clusters be limited to a maximum of 183-ft NGVD29 (80 psi) or less. This threshold exceeds the typical ASR wellhead pressures observed during the recharge phase of cycle testing at KRASR. Maximum ASR wellhead pressures observed during recharge at KRASR were approximately 60 psi during cycle test 1, and decreased to approximately 25 psi during cycle test 4 (USACE and SFWMD, 2013). The maximum ASR wellhead pressure allowed by the Underground Injection Control (UIC) permit is 66 psi at this location.

For ASR wells located east or south of Lake Okeechobee, it is recommended that the average hydraulic head of well clusters be limited to a maximum of 225-ft NGVD29 (97.5 psi) or less. Analysis of allowable thresholds south of Lake Okeechobee suggest permissible hydraulic head up to 275-ft NGVD29. However, under this scenario, pressures greater than 100 psi would be generated, which would require specialized well casing and piping materials to be installed at significantly higher cost. Maximum ASR wellhead pressures observed during the recharge phases at HASR, located southeast of Lake Okeechobee generally were less than 66 psi (USACE and SFWMD, 2013), so specialized well casing materials are not required for ASR operation.

Brown (2007) completed complementary work to further refine estimates of potential subsidence due to ASR system operations. Specifically, a more sophisticated analysis was completed using a stochastic approach where key variables were assigned to a model using standard probabilistic distributions to determine the magnitude and duration of subsidence. The model was based upon an ASR system that exhibits typical geologic and hydrogeologic conditions. The model was run for 20,000 iterations using a classic Monte Carlo simulation and resulting probability density functions were plotted and analyzed. Considering all factors, it was predicted that after 50 years of ASR operation the amount of subsidence would not be significant and likely less than 4-in. Subsidence occurred only in close proximity of the ASR well field.

## 4.3 Geotechnical Evaluation of Fracturing Based on Rock Core Analysis

Geibel and Brown (2012; **Appendix B**) expanded the original work of Brown et al. (2005) to determine the critical threshold of water pressure that marks the onset of hydraulically induced fracturing of the UFA rock matrix and the overlying Hawthorn Group sediments at proposed CERP ASR systems. Brown et al. (2005) suggested that additional mechanical rock property data be collected and analyzed to support a refined evaluation of hydraulically induced fracturing of the FAS rock matrix. A geotechnical evaluation was conducted, to include collection and analysis of additional geotechnical data from core samples, for seven proposed ASR system locations: Caloosahatchee River, Moorehaven, Kissimmee River, Port Mayaca, Hillsboro, Seminole-Brighton, and Paradise Run **(Figure 2-1)**.

### 4.3.1 Background

To understand the potential for and orientation of hydraulically induced fracturing, the in-situ state of the regional stress field is considered. In a geologic unit a stress field exists composed of three principal stress components, the maximum ($\sigma_1$), intermediate ($\sigma_2$), and minimum ($\sigma_3$). Under nearly flat ground that is not subjected to significant tectonic forces, such as that exhibited at the proposed ASR locations, $\sigma_1$ will be oriented in the vertical direction while $\sigma_2$ and $\sigma_3$ will be oriented in the horizontal direction and be compressive in nature (Goodman, 1980). Based on the directional distribution of the in-situ regional stress field $\sigma_2$ is near or equal in magnitude to $\sigma_3$ allowing for two-dimensional stress analysis (Rahn, 1986). In addition to the principal stresses, shear and normal stresses also are present and acting upon the rock matrix as driving or resisting forces, respectively, for fracture initiation.

Other factors that may influence UFA rock matrix stability include: (1) resultant stress intensity on the well borehole wall due to decreasing pressure in the well, (2) magnitude redistribution of pre-drilling in-situ principal stress field, (3) chemical dissolution of FAS rock matrix, and (4) fatigue failure of the well borehole wall due to cyclic ASR operations. Effects, whether positive or negative, from these factors on the initiation of hydraulically induced fracturing will be very minimal and confined to rock matrix at and very near the well borehole wall. Although present, they are minor components of potential induced fracturing and are of limited concern.

Hydraulically induced fracturing of the overlying Hawthorn Group sediments, if realized, would be the result of vertical upward propagation of fractures initiated within the FAS. A fracture propagation arrest model based on geologic formation elasticity, and in-situ stress factors that influence the arrest of propagating hydraulic fractures was applied to address fracturing concerns of the Hawthorn Group sediments.

### 4.3.2 Methodology

Three primary evaluation methods were used to determine critical threshold water pressures at which the potential onset of hydraulically induced fracturing will occur at a specific point in the UFA. Two additional evaluation methods were utilized to determine hydraulically induced fracturing potential to check the outcomes of the three primary methods. A typical ASR system will recharge or recover water directly into or out of the UFA, thereby imparting hydraulically induced fracture driving stresses to the aquifer. Stress due to the weight of overburden is the primary stress that resists hydraulically induced fracturing. Within the UFA, stress from overburden is least at the top of the aquifer. This will render the top of the UFA most vulnerable to the onset of hydraulically induced fracturing making it the point of interest for the evaluation methods. For the three primary methods, a factor of safety (FS) of ten percent was applied to the results to account for assumptions applied to the evaluations and to define "safe" ASR system design and operational water pressure thresholds above which caution should be exercised.

#### 4.3.2.1 Shear Method

The shear method involves an analysis of shear stresses that develop as a result of the principal stresses acting at the evaluation point of interest. Ultimately, the shear strength of the UFA rock matrix and the shear stress acting on a critical failure plane are determined and compared. If the imposed shear stress is greater than the shear strength of the UFA rock matrix, the potential exists for hydraulically induced fracturing along some critical failure plane within the rock matrix. Fracturing due to shear may be induced at the well borehole wall or at any point within the FAS where hydraulic pressure conditions favor failure.

#### 4.3.2.2 Tensile Method

Hydraulic fracturing at a particular point on a well borehole wall will be induced when the pressure of the fluid in the well exceeds the minimum principle stress ($\sigma_3$) by an amount equal to the tensile strength of the rock. After a fracture is induced into the borehole wall, a small localized heterogeneous stress field is formed at its tip and controls its propagation. The fracture geometry and loading configuration, termed the stress intensity factor, control the magnitude of the stress field. Microfractures will develop within the stress field when its magnitude is sufficient, and the density of the microfractures increases as the magnitude of the stress field increases. The fracture toughness of the rock matrix is a resisting force against fracture propagation. Fracture toughness is related to rock matrix properties such as strength, composition, and temperature, and during laboratory rock specimen testing, the applied rate of loading and magnitude of the confining pressure. At a critical stress intensity level, where the stress intensity factor is equal to or greater than the fracture toughness, the hydraulic fracture will propagate as the individual microfractures coalesce to form a macrofracture within the fracture tip stress field (Pollard and Aydin, 1988). An induced hydraulic fracture plane will be generated and propagate parallel to the principal stress axes of $\sigma_1$ and $\sigma_2$ and will therefore be perpendicular to the $\sigma_3$ stress axis. However, the orientation and propagation of fractures also can be influenced by anisotropy or planar in-homogeneities in the rock (i.e., bedding, schistosity, cleavage, joints, etc.) and by nearby stress fields produced by propagating fractures (Smith, 1989; Pollard et al., 1982).

#### 4.3.2.3 Microfracture Method

The microfracture method provides a way to evaluate the hydraulically induced microfracturing potential of FAS rock matrix due to water-pressure conditions. Handin et al. (1963) suggested that abnormally high pressure results in dilatancy effects within the rock matrix. Dilatancy is the change in volume of a material when subject to shearing or other deformation forces. As the rock matrix dilates due to increasing pressure, the pore volume increases and may materialize in the form of microfractures (Palciauskas and Domenico, 1980). The resultant force causing the dilatancy effect on the pore space of the rock matrix is oriented parallel to the principal horizontal stress axes $\sigma_2$ and $\sigma_3$ and perpendicular to the vertical stress axis $\sigma_1$. Therefore, resulting microfractures are oriented and propagate in a similar way to hydraulic fracture orientation and propagation described under the tensile method. Upon the development of microfractures, the excess pressure that initiated the dilatancy effect tends to be relieved (Keith and Rimstidt, 1985). However, if pressure continues to increase and cannot be sufficiently relieved by the existing microfracture network or other means, the microfractures will expand, and/or additional microfractures will develop. As individual microfractures propagate or their density increases, they can combine and lead to well-developed macrofracture planes (Sherman, 1973; Jaeger et al., 2007).

#### 4.3.2.4 Check Methods

Two check methods were implemented to assure predictive values are not grossly over or under represented using the three primary evaluation methods described above. Goodman (1980) presented a method based on the Mohr Coulomb linear failure criterion in terms of principal stresses at peak load condition. The pressure in pores and fissures required to initiate fracture of intact rock can be determined similar to the shear method. Calculation of pressure is based on an initial state of stresses, defined by $\sigma_V$ and $\sigma_H$ at some evaluation point of interest, and rock matrix strength and internal friction characteristics. A second check method is presented by Bouwer (1978), in which the initiation of hydraulically induced fracturing has the potential to occur either at a well borehole wall or within the FAS, similar to the tensile and microfracture methods, when the fluid pressure at the evaluation point of interest is equal to 50 to 67 percent of $\sigma_V$.

### 4.3.3 Conceptual Model: Fracture Propagation Arrest Model

A criterion for successful ASR operation is to minimize the potential to hydraulically induce fracturing of the Hawthorn Group, which confines the storage zone at most proposed CERP ASR systems. Fracturing of Hawthorn Group sediments could result in uncontrolled migration of recharge water, and could reduce the percent recovery during ASR operation. In addition, fracturing of the Hawthorn Group would result in vertical propagation of fractures initiated within the UFA. Gudmundsson and Brenner (2001) present a model of hydraulically induced fracture propagation arrest based on a function of three factors: discontinuities, variations in the modulus of elasticity (E) within or between geological layers, and stress barriers. Any single or combination of these three factors has the potential to redistribute the fracture, promoting a hydraulically induced stress field at the tip of a propagating fracture. The propagating fracture could then potentially be redirected and ultimately become arrested.

A discontinuity is a feature that exhibits low or negligible tensile strength, such as a defined contact between two differing geological materials. A preexisting discontinuity will prevent the stress perturbation associated with the propagating crack tip from being transmitted across the discontinuity. Therefore the hydraulic fracture will propagate along the plane of the discontinuity rather than to penetrate across the discontinuity. A value of E is a measure of the stiffness of the rock, and greater values of E indicate greater stiffness. Hydraulic fracture propagation has a tendency to be arrested at the contact of two geological materials exhibiting substantially different values of E (Gudmundsson and

Brenner, 2001). A stress barrier is a zone in which the compressive or tension stresses, aligned perpendicular to the direction of hydraulic fracture propagation, are greater or less than those observed in adjacent zones (Gudmundsson and Brenner, 2001). A stress barrier will result in the hydraulic fracture tip stress to redistribute and dissipate in such a manner that it penetrates only a short distance within the rock mass hosting the stress barrier. This redistribution of hydraulic fracture tip stress limits the distance of fracture propagation into the rock mass hosting the stress barrier, followed by arrest.

### 4.3.4 Laboratory Testing and Results

Mechanical and elastic properties of the UFA rock matrix that are used in fracturing and fracture propagation arrest modeling include the angle of internal friction (Φ), cohesion (C), and the E. Components Φ and C are determined from Mohr stress envelopes while E is determined from stress-strain curves. In order to develop the Mohr stress envelopes, unconfined and confined compressive strength laboratory testing results of FAS rock core specimens were utilized, and if available, tensile strength laboratory results were also incorporated into the evaluation. Additionally, during laboratory testing, axial strain readings were recorded, which were then coupled with associated stress readings to develop stress-strain curves, allowing values of E to be determined for the rock specimens.

All rock specimens were collected using air rotary core-drilling techniques. Rock specimens for geotechnical analysis were obtained by sub-sampling cores in the laboratory, so that each sub-sample had a typical diameter of 2.2-in. All rock specimens were from the Ocala Limestone and the Suwannee Limestone, and their lithologies consisted of intact, fine-grained, slightly muddy limestone with very few shells and vugs. Rock specimen preparation was completed to meet shape, length-to-diameter ratio, and crystal size-to-diameter criteria in accordance with ASTM method D 4543 (ASTM, 2008).

Strength and strain testing of the rock specimens followed ASTM method D 7012 (ASTM, 2013) requirements and was completed under approximate in-situ stress and temperature conditions that would be encountered during ASR operation. A stiff testing machine coupled with a servo system was used to conduct the tests. The servo system automatically regulated the stress rate applied by the testing machine to achieve a constant strain rate of 0.03 percent/minute. This practice significantly reduced the chance for catastrophic failure of the rock specimen at or just beyond its ultimate strength, allowing stress-strain readings to be compiled substantially beyond the ultimate strength of the specimen. Overall, testing results were valid and exhibited minimal data-use uncertainty based on adherence to rock specimen preparation criteria prescribed in ASTM method D 454f3 (ASTM,2008). No discernible effects on UFA rock matrix strength due to moisture content and temperature control of specimens, a reasonably applied strain-controlled loading rate, stability of the testing machine, and appropriate rock specimen failure modes were exhibited during strength testing.

All mechanical rock properties presented in Brown et al. (2005) were compiled and included in the data set developed to determine properties to be used in the hydraulically induced fracturing evaluation methods. Arithmetic mean values of 28.9° and 332 psi were determined for Φ and C, respectively, to be used in the hydraulically induced fracturing evaluation methods. Testing results of eighteen samples for

E ranged from 0.33 x $10^6$ to 17.4 x $10^6$ psi at confining pressures ranging from 0 to 210 psi. These data served as the basis for the fracture propagation arrest model.

**Table 4-1** shows the predicted maximum allowable total head (TH) and wellhead pressures that could initiate hydraulically induced fracturing utilizing the primary evaluation methods at each proposed ASR system. Hydraulically induced fracturing, under the primary methods, can be initiated at the well borehole wall or anywhere within the UFA when the critical threshold level is reached at any point in the hydraulic pressure field. However, the mechanics of hydraulically induced fracturing under the tensile method require that the critical threshold level be reached within the well borehole to initiate fracturing of the well borehole wall. The mechanics for the shear and microfracture methods require the total pressure to remain at or above the critical threshold level within the initiated fracture to impart its propagation. Hydraulically induced fracturing will not be initiated nor propagated at any pressure below the critical threshold level. To reach the critical threshold level, recharge of water into the UFA is required. However, fracture initiation and propagation can still occur during recovery if the TH remains at or above the critical threshold level.

**Table 4-1 -- Predicted Water Pressure Thresholds Above Which Hydraulically Induced Fracturing May Be Induced at the Top of the UFA.**

| ASR System | Shear Method | | Tensile Method | | | | Microfracture Method | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | TH (ft NGVD) | Pressure* (psi) | TH (ft NGVD) | Pressure* (psi) | TH (ft NGVD) | Pressure* (psi) | TH (ft NGVD) | Pressure* (psi) | TH (ft NGVD) | Pressure* (psi) |
| | FS/No FS | FS/No FS | FS | FS | No FS | No FS | FS | FS | No FS | No FS |
| Caloosahatchee R. | >>400 | >>164 | 309 | 125 | 343 | 139 | 220 | 86 | 244 | 97 |
| Moore Haven | >>400 | >>167 | 455 | 190 | 505 | 212 | 321 | 133 | 357 | 148 |
| Kissimmee River | >>400 | >>168 | 301 | 125 | 334 | 139 | 210 | 85 | 233 | 95 |
| Port Mayaca | >>400 | >>164 | 412 | 169 | 458 | 189 | 296 | 119 | 329 | 133 |
| Hillsboro | >>400 | >>168 | 503 | 213 | 559 | 237 | 356 | 149 | 395 | 166 |
| Seminole-Brighton | >>400 | >>163 | 360 | 146 | 400 | 163 | 260 | 102 | 289 | 115 |
| Paradise Run | >>400 | >>165 | 308 | 125 | 342 | 140 | 218 | 86 | 242 | 97 |

TH = total head; NGVD = National Geodetic Vertical Datum, 1929; ft=feet; psi=pounds per square inch; FS = factor of safety applied at 10 percent; >> = significantly greater than. *Pressure is calculated for ground surface (below TH) to aid in well head design. 1 ft = 0.3048 m; 1 psi = 0.006895 MPa.

The shear method results indicated that it is highly unlikely that hydraulically induced fracturing due to shear failure will occur under any probable ASR operational condition, either at the well borehole wall or within the FAS. The tensile method results indicate that hydraulically induced fracturing due to failure of the well borehole wall is possible if ASR operations increase the TH to the predicted critical threshold levels. Likewise, the microfracture method results indicate that hydraulically induced fracturing due to microfracture development is possible if ASR operations increase the TH to the predicted critical threshold levels. Results of the hydraulically induced fracturing check methods indicate that predictive values derived from the primary shear, tensile, and microfracture methods do not grossly over- or under-estimate the critical threshold levels at which fracturing is induced.

The UFA contains natural discontinuities such as open vugs, fractures, fractures filled with material of negligible tensile strength, joints, bedding planes, and a horizontal contact zone with the overlying Hawthorn Group sediments. Should a hydraulically induced fracture be developed and propagate within the UFA, it is highly likely that it will align with one of these discontinuities and be contained within the rock matrix of the UFA. Should the fracture encounter the horizontally oriented contact zone between the UFA and Hawthorn Group, it will likely propagate along the zone as the hydraulic fracture tip stress will be redistributed and align with the contact zone, following the discontinuity arrest model presented by Gudmundsson and Brenner (2001). The hydraulic fracture will propagate until the fracture tip stress is reduced to a level not conducive to overcoming fracture-resisting stresses and FAS discontinuity strength.

Vertical propagation of a hydraulically induced fracture from the UFA into the Hawthorn Group is unlikely. The Hawthorn Group sediments exhibit significantly lower stiffness values compared to the UFA rock matrix. Therefore, the fracture tip stress of a vertically propagating fracture initiated in the FAS is likely to be effectively redistributed and dissipated at the contact with the overlying Hawthorn Group. Dissipation of the tip stress at the Hawthorn Group contact would occur, consistent with the variation of stiffness arrest model presented by Gudmundsson and Brenner (2001). Significant stress barriers do not exist within the UFA or Hawthorn Group, therefore fracture propagation arrest due to this characteristic is not likely.

### 4.3.5 Geotechnical Evaluation Conclusions

Three primary failure methods (shear, tensile, and microfracture) were evaluated as mechanisms for hydraulically induced fracturing. Brown et al. (2005) suggested that additional rock matrix testing be completed to refine the mechanical properties of the rock needed to complete the geotechnical evaluation. Additional rock testing was completed to define UFA rock matrix mechanical properties, similar to those properties determined the desktop evaluation completed by Brown et al. (2005). These mechanical rock properties along with in-situ stresses were characterized, and were the basis to determine the pressure values that would induce hydraulic fracturing at the top of the UFA. Shear method results indicate that an extremely high pressure in the UFA is required to initiate fracturing by shear failure. Tensile method results indicate that a relatively moderate pressure is required to initiate fracturing by tensile splitting of the well borehole wall. Microfracture method results indicate that a moderately low pressure is required to initiate microfracturing. It is unlikely that extremely high pressure values will be achieved during ASR operation; therefore, hydraulic fracturing due to shear failure is not a concern. However, moderate pressure values can potentially be achieved, initiating hydraulic fracturing due to tensile splitting of the well borehole wall. More likely, moderately low pressure values causing microfracture initiation may be achieved within maximum ASR operational limits. Two additional hydraulically induced fracturing check methods were applied and produced results consistent with the tensile and microfracture primary methods, providing for increased assurance of the predictive pressure values that may induce fracturing.

Hydraulically induced fracturing can be initiated at and propagate from the well borehole wall for all three fracture mechanisms, while the ability to initiate and propagate hydraulic fracturing away from the borehole wall and within the FAS can be achieved by shear failure and microfracture development. Hydraulically induced fracturing is not a concern at any pressure below the critical threshold level that may result from practical ASR operation. If the critical water pressure threshold is met for the top of the FAS, fracturing is more likely to occur there rather than in deeper portions of the FAS, as increasing overburden stress with depth will largely negate fracture-inducing stresses. If hydraulically induced fracturing of the FAS rock matrix is initiated, it will likely be vertically oriented; however, orientation and propagation may be influenced by anisotropy, planar inhomogeneities, or alignment of the principal stresses in the FAS. The potential for hydraulically induced fracturing of the Hawthorn Group, due to vertically upward propagating fractures initiated in the FAS, is very unlikely. Fractures initiated in the FAS would be arrested at or re-directed along the discontinuity formed by the interface of the FAS and Hawthorn Group. If the fracture were able to propagate through the discontinuity and into the Hawthorn Group sediments, the softer nature of these lithologies would dissipate stress and arrest its propagation. Results and conclusions of hydraulic fracturing initiation and propagation potential developed under Brown et al. (2005) are compatible with results and conclusions developed under Geibel and Brown (2012).

# 5 Surface Water and Groundwater Quality Controls on ASR System Performance

Organic and inorganic constituents in surface water can affect geochemical reactions in the storage zone. Geochemical reactions, particularly those related to arsenic mobilization, differ at ASR systems that recharge lightly treated surface water (CERP systems) compared to those that recharge potable or treated drinking water (**section 5.8**). Native groundwater quality, with regard to inorganic constituents, will influence the percent recovery of stored water, particularly during early cycles. Surface water and groundwater compositions are characterized in the following sections, then interpreted to define important water quality changes that can improve or degrade ASR system operations. **Table 5-1** shows the descriptive statistical compilation of all water quality constituents compiled from the four sites.

## 5.1 Surface Water Quality Characteristics and Suitability for ASR Recharge

The following section addresses a major concern for regional ASR implementation, which is to characterize surface water quality of Lake Okeechobee and tributaries, and to evaluate these as suitable sources of recharge water for ASR operations. As discussed extensively in the CERP ASR Pilot Project Technical Data Report (USACE and SFWMD, 2013), source water quality at CERP ASR systems must comply with UIC regulations and Safe Drinking Water Act (SDWA) criteria with minimal pre-treatment, particularly without chemical addition. Surface water quality characteristics should not promote fouling of the filter and UV disinfection system, well and aquifer clogging, or otherwise impede recharge at the 5 MGD pumping rate at a typical CERP ASR system.

Surface water quality constituents that are most likely to impede ASR operations are: total and dissolved organic carbon (TOC, DOC) and its proxy indicator color; iron, turbidity, and total alkalinity. Elevated color, iron, and turbidity values will reduce ASR system performance by clogging filter beds and the well bore with inorganic precipitates or biofilms. These processes were observed at the CERP ASR pilot systems during cycle testing. Low total alkalinity concentrations will promote carbonate dissolution, most likely near the well bore. Limited dissolution can improve permeability and result in recharge pumping at lower wellhead pressures.

This evaluation shows surface water quality characteristics and interpretations at four proposed CERP ASR systems using data compiled for the period of record 2000 to 2014. Water quality samples were collected at structures close to each CERP ASR system: at S39 (Hillsboro); S78 (Caloosahatchee River); S308 (Port Mayaca where Lake Okeechobee discharges into the St. Lucie Canal); and S65E (5 miles north of the Kissimmee River ASR (KRASR) system). Water quality data were obtained from the SFWMD database DBHYDRO for each structure, with additional analyses obtained at the ASR wellhead during four recharge phases at KRASR. To evaluate regional variations in selected water quality constituents, datasets from each site are compared statistically. To evaluate temporal changes, particularly wet-dry season variations, selected constituent concentrations are superimposed on flow rate plots for each corresponding channel. Wet and dry seasons begin on the median historical date of May 20 and October 17 respectively, unless actual season dates defined by the National Weather Service (Miami) are known.

**Table 5-1 -- Descriptive Statistics of Surface Water Quality Characteristics Compiled at Structures Located Near Four Proposed CERP ASR Systems.**

| Constituent | Unit | Structure S65E - Kissimmee River | | | | | | Structure S78 - Caloosahatchee River | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Median | 25 %ile | 75 %ile | Mini-mum | Maxi-mum | No. of Samples | Median | 25 %ile | 75 %ile | Mini-mum | Maxi-mum | No. of Samples |
| | | Major Inorganic Constituents | | | | | | | | | | | |
| pH | std units | 7.0 | 6.7 | 7.4 | 5.5 | 9.1 | 393 | 7.6 | 7.3 | 7.8 | 6.4 | 8.5 | 82 |
| Spec. Conductan. | µS/cm | 185 | 153 | 217 | 1.3 | 607 | 393 | 501 | 435 | 570 | 47.5 | 713 | 82 |
| Tot. Alkalinity | mg/L as CaCO3 | 38 | 30 | 44 | 14 | 68 | 406 | 129 | 111 | 158 | 76 | 200 | 82 |
| Calcium | mg/L | 16.9 | 13.5 | 19.6 | 8.0 | 32.2 | 109 | 51.5 | 42.5 | 64.8 | 29.2 | 88.7 | 81 |
| Magnesium | mg/L | 3.9 | 3.3 | 4.7 | 2.1 | 7.3 | 109 | 10.0 | 8.6 | 11.8 | 6.1 | 18.1 | 81 |
| Sodium | mg/L | 12.7 | 11.0 | 14.8 | 6.7 | 23.8 | 109 | 29.2 | 23.4 | 35.3 | 15.5 | 73 | 80 |
| Potassium | mg/L | 3.0 | 2.5 | 3.5 | 1.5 | 233 | 110 | 6.4 | 5.4 | 7.1 | 0.1 | 8.6 | 82 |
| Chloride | mg/L | 22.7 | 19.1 | 26.5 | 11.4 | 63.3 | 390 | 51.5 | 42.0 | 62.3 | 27.0 | 133 | 81 |
| Silica | mg/L | | | | | | | 7.6 | 5.5 | 9.0 | 2.7 | 12.5 | 81 |
| Sulfate | mg/L | 11.4 | 8.8 | 14.4 | 3.9 | 38.3 | 391 | 29.3 | 23.4 | 37.3 | 4.4 | 61.0 | 82 |
| Tot. Diss. Solids | mg/L | 139 | 112 | 170 | 80 | 237 | 36 | | | | | | |
| Turbidity | NTU | 2.9 | 2.2 | 4.0 | 0.1 | 26.7 | 401 | 3.33 | 2.5 | 4.8 | 1.1 | 24.9 | 75 |
| Color | PCU | 118 | 77 | 166 | 29 | 467 | 388 | 68 | 49 | 107 | 31 | 249 | 81 |
| | | Organics, Nutrients, and Trace Inorganic Constituents | | | | | | | | | | | |
| Diss. Org. Carbon | mg/L | 18.0 | 16.0 | 21.4 | 11.8 | 39.7 | 344 | | | | | | |
| Total Org Carbon | mg/L | 18.0 | 16.0 | 20.9 | 11.7 | 36.9 | 348 | 1.2 | 0.91 | 1.6 | 0.53 | 1.9 | 5 |
| Total Kjeldahl N | mg/L | 1.08 | 0.99 | 1.19 | 0.62 | 2.35 | 406 | 1.28 | 1.17 | 1.41 | 0.86 | 2.72 | 298 |
| Total Ammonia | µg/L | 34 | 19 | 68 | < 5 | 541 | 395 | 38 | 20 | 76 | < 9 | 278 | 81 |
| Nitrite + Nitrate | µg/L | 54 | 14 | 158 | < 5 | 755 | 389 | | | | | | |
| Nitrate | µg/L | 46 | 10 | 149 | < 2 | 575 | 361 | | | | | | |
| Total Phosphorus | µg/L | 71.5 | 55 | 106 | 31 | 435 | 408 | 96 | 77 | 132 | 36 | 840 | 299 |
| ortho-Phosphorus | µg/L | | | | | | | 61 | 41 | 97 | 7 | 468 | 79 |
| Iron | µg/L | 347 | 77.3 | 166 | 92 | 1,040 | 57 | 81 | 57 | 149 | 36 | 300 | 9 |
| Arsenic | µg/L | < 1.5 | | | | | 5 | <1.5 | | | | | 3 |
| Mercury | µg/L | < 0.2 | | | | | 5 | | | | | | |

| Constituent | Unit | Structure S39 - Hillsboro Canal at WCA-1/2 | | | | | | Structure S308 - Port Mayaca | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Median | 25 %ile | 75 %ile | Mini-mum | Maxi-mum | No. of Samples | Median | 25 %ile | 75 %ile | Mini-mum | Maxi-mum | No. of Samples |
| | | Major Inorganic Constituents | | | | | | | | | | | |
| pH | std units | 7.70 | 7.40 | 7.90 | 6.75 | 8.50 | 245 | 7.95 | 7.70 | 8.10 | 5.60 | 9.08 | 391 |
| Spec. Conductan. | µS/cm | 588 | 411 | 743 | 160 | 1,202 | 246 | 462 | 403 | 552 | 239 | 3,500 | 394 |
| Tot. Alkalinity | mg/L as CaCO$_3$ | 127 | 96 | 170 | 42 | 347 | 211 | 116 | 102 | 132 | 63 | 228 | 332 |
| Calcium | mg/L | 38.2 | 27.4 | 50.1 | 14.5 | 92.7 | 130 | 43.0 | 37.1 | 53.3 | 26.9 | 86.1 | 65 |
| Magnesium | mg/L | 11.7 | 6.9 | 17.0 | 3.1 | 29.5 | 133 | 10.9 | 10.1 | 12.3 | 6.3 | 17.0 | 64 |
| Sodium | mg/L | 54.0 | 34.4 | 71.3 | 14.3 | 115 | 135 | 34.5 | 29.4 | 43.9 | 15.9 | 61.5 | 62 |
| Potassium | mg/L | 4.8 | 2.9 | 6.7 | 0.8 | 12.6 | 135 | 6.2 | 5.2 | 6.7 | 3.5 | 9.3 | 65 |
| Chloride | mg/L | 85.2 | 55.0 | 111 | 23.7 | 170 | 227 | 51.7 | 40.3 | 69.6 | 14.6 | 111 | 272 |
| Silica | mg/L | 8.1 | 4.4 | 12.4 | 1 | 12.6 | 128 | 9.7 | 8.2 | 10.7 | 6.4 | 43.8 | 39 |
| Sulfate | mg/L | 24.1 | 12.1 | 42.9 | 1.8 | 83.3 | 146 | 30.3 | 21.1 | 28.5 | 15.0 | 59.2 | 57 |
| Tot. Diss. Solids | mg/L | | | | | | | | | | | | |
| Turbidity | NTU | 1.3 | 0.9 | 2.1 | 0.4 | 11.1 | 243 | 34 | 16.9 | 70.8 | 2.5 | 386 | 375 |
| Color | PCU | 76 | 65 | 94 | 43 | 200 | 114 | 35 | 31 | 50 | 170 | 250 | 278 |
| | | Organics, Nutrients, and Trace Inorganic Constituents | | | | | | | | | | | |
| Diss. Org. Carbon | mg/L | 21.6 | 18.0 | 25.0 | 9.9 | 35.9 | 94 | 16.5 | 15.1 | 21.2 | 13.0 | 22.0 | 8 |
| Total Org Carbon | mg/L | 22.0 | 1.4 | 25.5 | 9.5 | 36.5 | 94 | 13.4 | 12.7 | 14.0 | 11.3 | 25.3 | 103 |
| Total Kjeldahl N | mg/L | 1.39 | 1.16 | 1.59 | 0.77 | 2.71 | 245 | 1.37 | 1.19 | 1.68 | 0.88 | 4.57 | 388 |
| Total Ammonia | µg/L | 16 | 11 | 23 | < 5 | 167 | 214 | 19 | 9 | 44 | < 5 | 50 | 372 |
| Nitrite + Nitrate | µg/L | 9 | 5 | 18 | < 4 | 875 | 237 | 29 | 132 | 428 | < 4 | 963 | 377 |
| Nitrate | µg/L | 10 | 5 | 36.5 | < 4 | 734 | 89 | 235 | 123 | 383 | 6 | 916 | 153 |
| Total Phosphorus | µg/L | 20 | 14 | 30 | 8 | 132 | 243 | 172 | 128 | 242 | 67 | 908 | 385 |
| ortho-Phosphorus | µg/L | 4 | 2 | 6 | < 2 | 75 | 247 | 63 | 49 | 83 | 2 | 579 | 390 |
| Iron | µg/L | 19 | 11 | 44 | 6 | 104 | 33 | 991 | 599 | 1,744 | 170 | 7,148 | 55 |
| Arsenic | µg/L | | | | | | | 3.2 | 1.7 | 5 | 1.5 | 41 | 13 |
| Mercury | µg/L | | | | | | | | | | | | |

Note: Values with "less than" (<) are the minimum detection limit for that constituent. PCU, Platinum Color Units; NTU, Nephelometric Turbidity Units.

In this evaluation, two important meteorological phenomena occurred during the period of record that affects some water quality trends. First, a record number of hurricanes transited or made landfall across south Florida during the 2004 and 2005 hurricane seasons, resulting in high lake levels and high flows through the Caloosahatchee and St. Lucie Rivers. Second, a record drought occurred in 2007 through August 2008, resulting in record low lake levels (8.8-ft NGVD29, August 2008). Tropical Storm Fay (August 2008) initiated rising lake levels and ended the drought. The following evaluation builds on earlier summaries of regional surface water quality (PBS&J, 2003) that guided filter selection for the ASR pilot projects.

## 5.2 Variations in Surface Water Color Values and Total Organic Carbon Concentrations

Color results primarily from dissolved organic matter in the absence of suspended particulates. In south Florida surface waters, humic and fulvic acids are released by degradation of plant material, and these compounds are major components of TOC and DOC. Iron intensifies the color value due to complexation with humic and fulvic acids to form colloidal-sized particles. Particle size characterization at the Port Mayaca and Hillsboro sites showed that particle sizes range between 0.1 and 8 µm, approximately the size of pollen (USACE, unpublished data). There are fewer DOC and TOC analyses compared to color, so color will serve as a proxy for organic carbon for operational and seasonal water quality interpretations. Organic carbon concentrations exert a significant influence on groundwater geochemical reactions in the storage zone, as discussed in **Section 5.8.2**. Organic carbon characteristics and effect on groundwater geochemistry are considered in **Section 5.6.2.4.**

### 5.2.1 Regional Variation in Color Values and Total Organic Carbon Concentrations

Color values in surface water samples throughout south Florida generally are great enough to require regulatory relief (water quality criteria exemption, WQCE), and therefore can decrease UV disinfection performance by limiting light penetration **(Table 5-1; Figure 5-1)**. The greatest and most variable values of color were measured in the Kissimmee River. It is likely that any ASR system would require a WQCE for operations because color values almost certainly will exceed the SDWA secondary criterion for color (15 PCU) during some part of the year. High color values can cause fouling of the filter, the UV disinfection system, and the ASR well bore. These problems were observed during cycle testing at both KRASR and HASR pilot systems; however, biofilm production was reduced by monthly chlorination of influent lines and the filter during the recharge phase.

The datasets for total organic carbon consists of fewer samples, but these data show similar distributions observed in the color datasets (**Table 5-1; Figure 5-1),** with the exception of the Caloosahatchee River site. There are only 5 samples that define the total organic carbon concentration range for this site, so these may not be representative for this watershed.

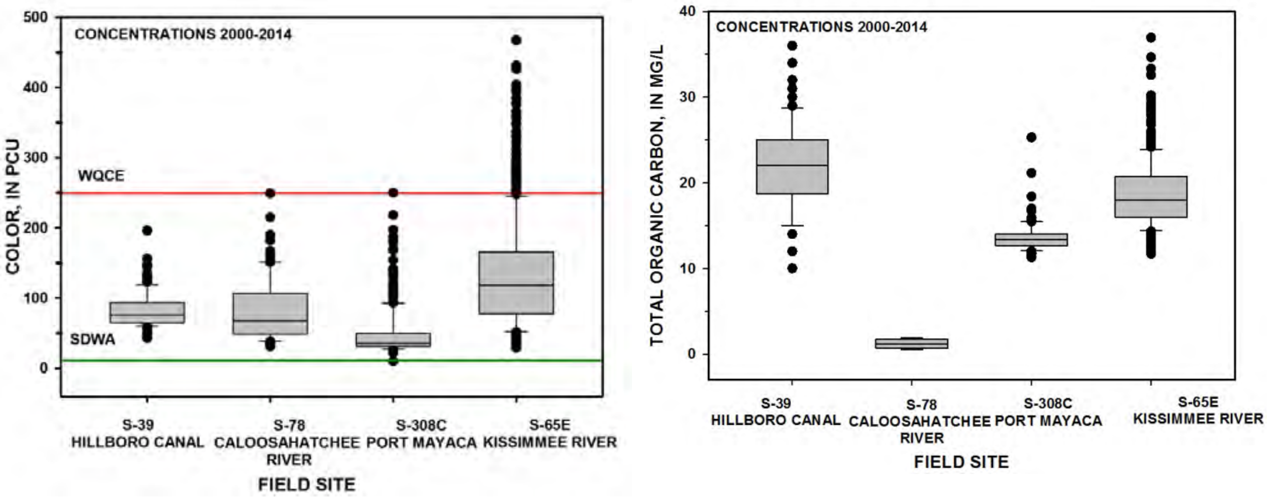
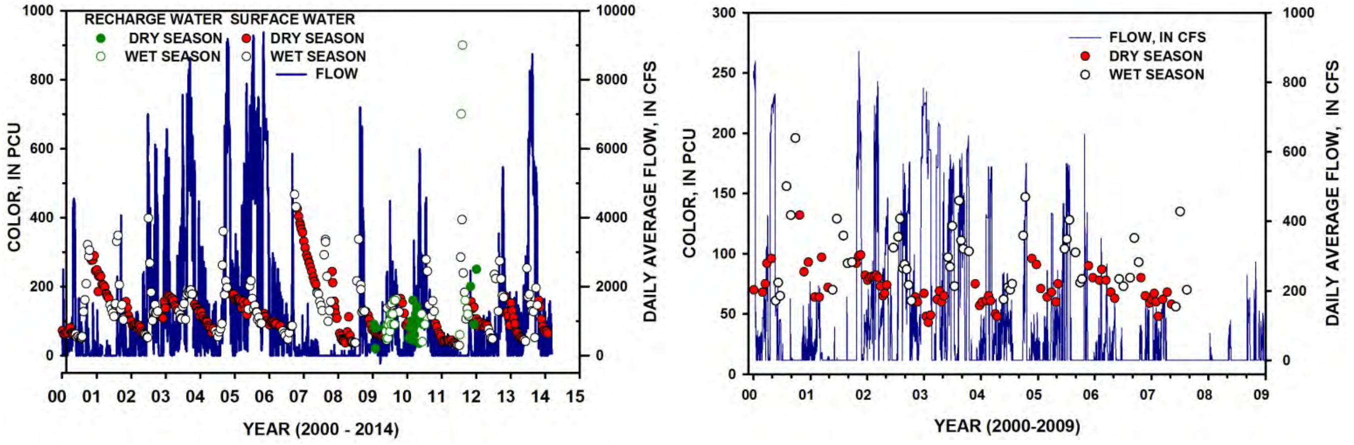


**Figure 5-1 -- Box plots comparing median, 25th and 75th percentile, and outlier values of color and total organic carbon at four proposed CERP ASR locations.** WQCE, water quality criterion exemption value for color is 250 PCU; SDWA, Safe Drinking Water Act secondary criterion for color is15 PCU.

### 5.2.2 Temporal Variations in Color Values

Color values exhibit a saw-toothed trend throughout the period of record, with highest values measured during wet seasons, followed by declining values through dry seasons and during the 2007-2008 drought. These trends are observed most clearly on the Kissimmee River and the Hillsboro Canal **(Figure 5-2 A, B).** Fewer data are available on the Caloosahatchee River, so trends are not well-resolved **(Figure 5-2C)**. Stream flow at the Port Mayaca structure is complicated because water can flow east (positive values) or west (negative values, into Lake Okeechobee) depending on gate position **(Figure 5-2D).**

Highest color values tend to occur during wet season flows, which is when the recharge phase occurs at an ASR system. Expansion of CERP ASR facilities will require water quality criteria exemptions if Lake Okeechobee and tributary surface water is recharged. High color values were a documented cause of reduced performance of UV disinfection systems at KRASR (USACE and SFWMD, 2013). Expansion of CERP ASR facilities in the Lake Okeechobee region will require more robust disinfection technology than was available in 2002-2004, when the CERP ASR pilot systems were designed.


A. S65E on the Kissimmee River

B. S39 on the Hillsboro Canal

C. S78 on the Caloosahatchee River

D. S308 at Port Mayaca

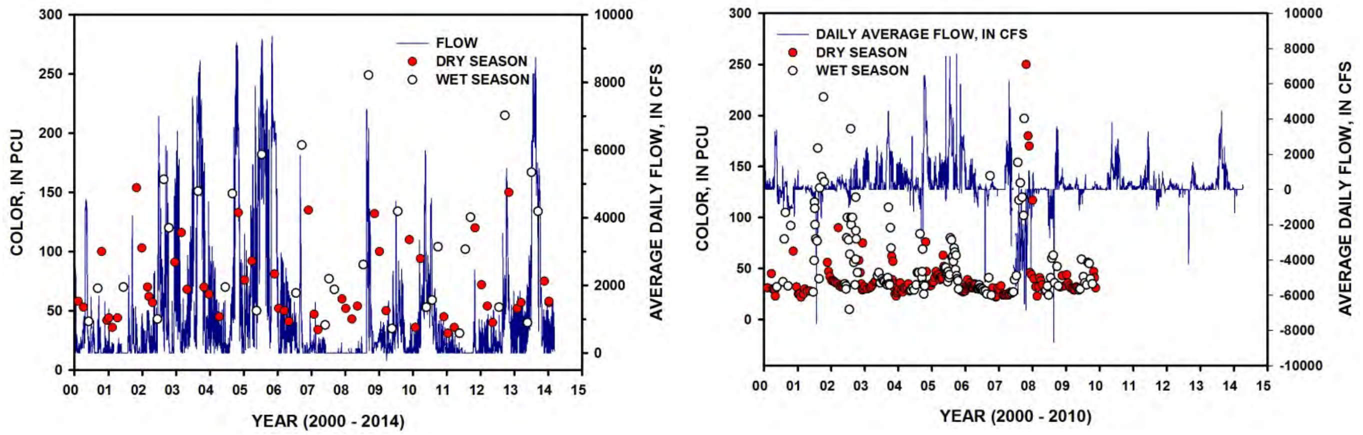


**Figure 5-2 -- Time-series plots showing wet and dry season color values (PCU) superimposed on flow rates (cfs) at four water control structures located near existing or proposed CERP ASR systems.**

## 5.3 Variations in Surface Water Iron Concentrations

Iron normally will precipitate as ferric oxyhydroxide solids in oxic surface water having near-neutral pH, due to its extremely low solubility product ($K_{sp}$; $10^{-37}$ to $10^{-44}$; Schwertmann, 1991). However, ferric (FeIII) iron will bind with humic acids (a component of DOC) in acid-to-neutral surface water, and thus remain in solution (Tipping et al., 2002 and others). The presence of iron and carbon in recharge water has important implications for geochemical reactions, including arsenic mobility in the FAS, as discussed in **Section 5.8.** Therefore, it is important to characterize the spatial occurrence and temporal trends of iron in surface waters that recharge ASR systems.

### 5.3.1 Regional Variations in Iron Concentration

Iron concentrations in surface water samples throughout south Florida often are great enough to require regulatory relief (WQCE), and can increase the potential for well and aquifer clogging due to mineral precipitation or enhancement of iron-reducing bacteria in biofilms (Pavelic et al., 2007; Bustos Medina et al., 2013). It is likely that ASR systems located in the Kissimmee Basin and along the St. Lucie Canal would require a WQCE for operations because iron concentrations almost certainly will exceed the SDWA secondary criterion for iron (300 µg/L). The greatest and most variable iron concentrations were measured at the Port Mayaca structure, located where Lake Okeechobee discharges into the St. Lucie Canal **(Figure 5-3)**. There, the relationship between iron and turbidity is highly correlated ($r^2$ = 0.94; P<0.0001), so that high iron concentrations probably correspond to the occurrence of iron-rich flocs in surface water.

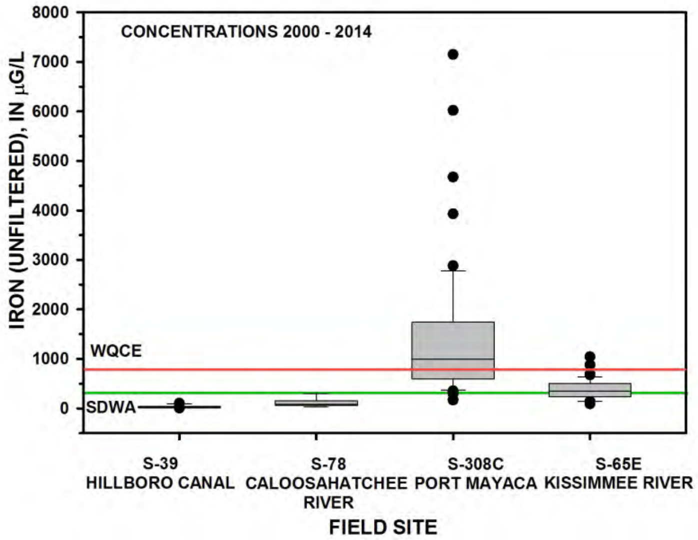


**Figure 5-3 -- Box plots comparing median, 25th and 75th percentile, and outlier iron concentrations among four proposed CERP ASR locations.** WQCE, water quality criteria exemption value (800 µg/L); SDWA, Safe Drinking Water Act criterion (300 µg/L).

The presence of iron-rich flocs could require more intensive pre-treatment (particularly filtration) in order to prevent well clogging. Iron concentrations at the Hillsboro Canal and Caloosahatchee River structures generally are lower, showing maximum iron concentrations at or below the SDWA criterion.

### 5.3.2 Temporal Variations in Iron Concentration

Iron concentrations are not measured as frequently in surface water as other analytes, so trends in iron concentration over time are not well resolved. Only at Port Mayaca S308 do iron concentrations differ statistically between wet and dry season samples. There, the median iron concentration in the dry season (1,525 µg/L, n=27) is significantly greater than the wet season value (648 µg/L, n=28; P=<0.001). Lower iron concentrations in the wet season would pose fewer operational issues during recharge.

## 5.4 Variations in Surface Water Turbidity

High turbidity values can challenge the pre-treatment process at an ASR facility. Turbid water can cause the formation of lumps and films in filter media, clog screens, reduce light penetration in the UV disinfection system, and over time, cause clogging of the ASR well bore. Lake Okeechobee is shallow with a large fetch. Tropical storms, particularly during the 2004 and 2005 hurricane seasons, resuspended bottom sediments and increased turbidity, resulting in significant ecological impacts to the lake (Rogers and Allen, 2008; Wang et al., 2012). Characterizing the spatial and temporal variations of turbidity in Lake Okeechobee and tributaries will provide better guidance for future ASR system designs. There is no regulatory criterion for turbidity in groundwater, but ASR system operation and compliance is better when recharge water shows low turbidity values.

### 5.4.1 Regional Variations in Turbidity

The statistical correlation between iron and turbidity is strong at the Port Mayaca structure, so this location also shows the greatest and most variable turbidity values **(Figure 5-4)**. ASR systems constructed along the St. Lucie Canal or eastern portions of Lake Okeechobee likely will require robust filtration components to pre-treat recharge water during high flow events.

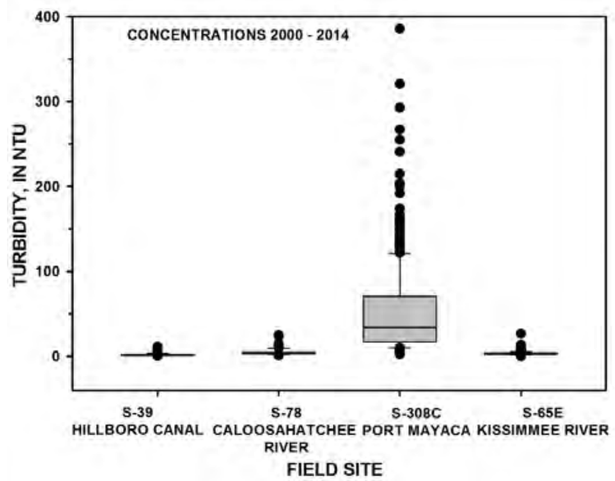
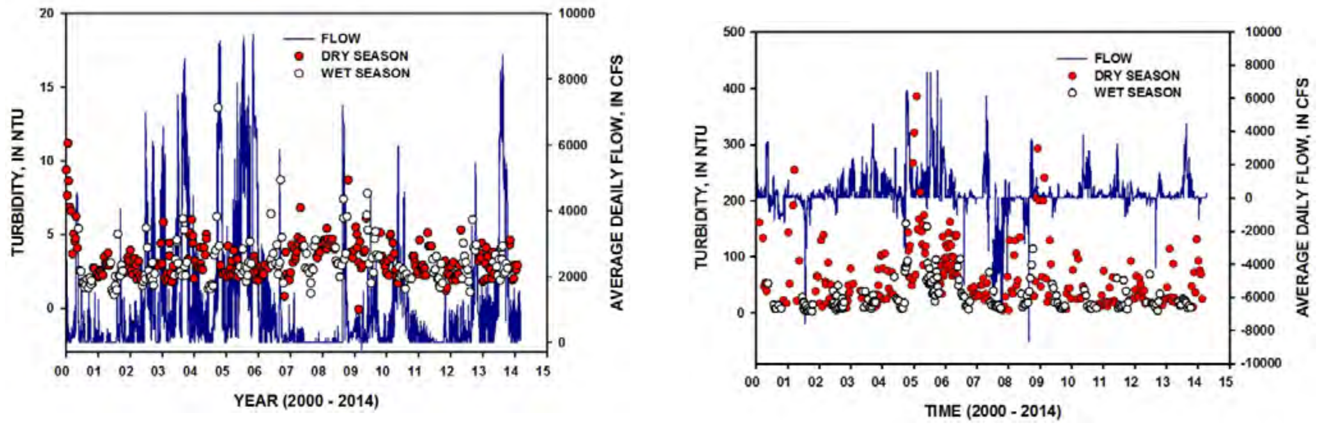


**Figure 5-4 -- Box plots comparing median, 25th and 75th percentile, and outlier turbidity concentrations among four proposed CERP ASR locations.**

### 5.4.2 Temporal Variations in Turbidity

Despite having large turbidity datasets for each site, turbidity trends over time are not well-defined. Elevated turbidity values probably result from a combination of wind and high flows, and it is difficult to separate the influence of these two factors. Also, the range in turbidity values at all sites other than Port Mayaca is small (0.1 to 27 NTU; **Table 5-1**) so that turbidity variation over time is subtle, except during major storm events.



A. S65E on the Kissimmee River

B. S308 at Port Mayaca

**Figure 5-5 -- Time-series plots showing wet and dry season turbidity values (NTU) superimposed on flow rates (cfs) at two water control structures located near existing or proposed CERP ASR systems.**

## 5.5 Variations in Surface Water Alkalinity

Alkalinity concentrations do not exert a significant influence on mechanical operations of an ASR system. The pH values of most surface waters are between 7 and 8 **(Table 5-1),** values low enough to preclude scaling as a significant process. However, recharge of low alkalinity surface water into a limestone aquifer can result in dissolution and increased permeability, particularly near the well bore where recharge water has not yet attained equilibrium with respect to calcium carbonate. Dissolution of aquifer material will be discussed in **Section 5.7.**

### 5.5.1 Regional Variations in Alkalinity

Kissimmee River surface water typically shows the lowest and least variable alkalinity concentrations because carbonate rock, the source of dissolved bicarbonate and carbonate ions, is buried beneath a veneer of silicate sands and silts. As surface water flows southward, more lime rock is exposed at the surface, resulting in greater dissolved carbonate species concentrations, and hence greater carbonate alkalinity **(Figure 5-6)**.

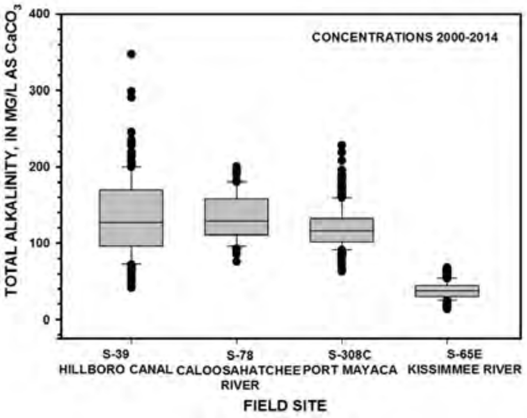


**Figure 5-6 -- Box plots comparing median, 25th and 75th percentile, and outlier alkalinity concentrations among four proposed CERP ASR locations.**

### 5.5.2 Temporal Variations in Alkalinity

There is no statistically significant difference in alkalinity concentrations between wet and dry season samples at all proposed CERP ASR system locations. However, the Kissimmee River does show alkalinity variation with longer duration (interannual) weather patterns **(Figure 5-7).** Broadly interpreted, alkalinity values are lower during wet periods (e.g. 2003 to 2005), and higher during dry periods or droughts (e.g. 2000-2001, 2006-2008). Recharge is most likely during wet periods of seasonal or interannual duration characterized by lower alkalinity values.

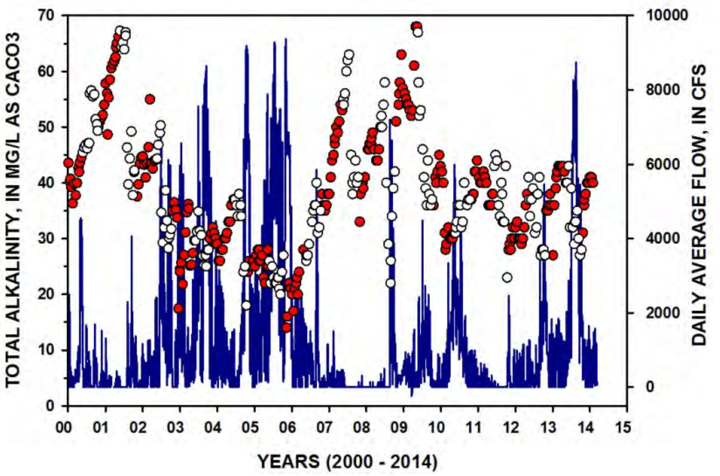


**Figure 5-7 -- Time-series plots showing interannual trends in alkalinity concentrations, super-imposed on flow rates (cfs) at the S-65E structure on the Kissimmee River.**

## 5.6 Regional Groundwater Quality Characterization and Suitability for ASR Cycle Testing

Characterization and evaluation of groundwater quality changes that result from ASR cycle testing in the FAS is one of the greatest sources of uncertainty identified by the National Research Council (2002) and the ASR Issue Team (1999). Quantitative evaluation of groundwater quality changes during ASR cycle testing requires: 1) geochemical characterization of native Floridan Aquifer System (UFA and APPZ) throughout south Florida, which serve as storage zones; 2) geochemical characterization of source (surface) water composition from different waterways; and 3) intensive sampling during ASR cycle testing at CERP ASR pilot systems to identify dominant geochemical reactions that induce water quality changes. The primary objective of this section is to identify those areas in south Florida where the Floridan Aquifer System and source (surface) water show characteristics that are most appropriate for ASR system development, from a groundwater quality perspective. In addition, results of related projects conducted for water-quality improvement during ASR cycle testing will be summarized.

Characterization of FAS groundwater quality was accomplished using newly acquired and existing data in the SFWMD Regional Floridan Groundwater (RFGW) Network, introduced in **Section 3.3.** For the ASR Regional Study, a broader suite of constituents was analyzed during RFGW sampling events in April and September 2005, and these data supplement the RFGW analytical program. For this analysis, water-quality data from 49 UFA wells and 16 APPZ wells were compiled, representing a period of record generally between 2004 and 2013. Data quality control consisted of calculating charge balance errors, and evaluating relationships between pH and alkalinity. Samples having charge balance errors greater than 8 percent were eliminated from the data set. Samples having pH values greater than approximately 8.5 and low alkalinity and calcium concentrations also were eliminated from the dataset, as this characteristic suggests calcium carbonate precipitation as water travels up the well bore during sampling. Water quality constituent concentrations are color-coded on maps to represent "low, moderate, or high" concentrations. With the exception of sulfate, chloride, and total dissolved solids (TDS) constituents, low concentrations range between minimum and the 25th percentile range of all UFA mean concentrations; moderate concentrations range between the 25th and 75th percentile; and high concentrations range between the 75th percentile and the maximum concentration. Chloride and sulfate concentrations are grouped according to the SDWA water quality criterion (250 mg/L). Low concentrations range between the minimum and 250 mg/L for all UFA mean concentrations; moderate concentrations range between 250 mg/L and the 75th percentile; and high concentrations range between the 75th percentile and the maximum concentration. Similarly, TDS concentrations are grouped according to levels that govern UIC permitting criteria for Class V (e.g. ASR) wells. Low TDS concentrations range between the minimum and 3,000 mg/L; moderate concentrations range between 3,000 and 10,000 mg/L; and high concentrations range between 10,000 mg/L and the maximum.

### 5.6.1 Native Groundwater Quality of the Upper Floridan Aquifer

Groundwater quality in the UFA ranges from fresh to brackish with respect to chloride, sulfate, and total dissolved solids concentrations. As groundwater flows southward from the Polk County recharge area, inorganic constituent concentrations generally increase as water reacts with carbonate rock. Maximum concentrations of major constituents approach those of seawater. Concentrations of barium, strontium, silica, iron, and manganese exceed that of seawater. Other than iron and manganese, all trace metal concentrations generally are below detection. The existence of detectable dissolved organic carbon in the UFA is surprising, considering that groundwater at Lake Okeechobee is approximately 25,000 years old (Morrisey et al., 2010). The redox environment of the Upper Floridan Aquifer is sulfate-reducing as indicated by the absence of dissolved oxygen, negligible nitrate concentrations, low concentrations of redox-active iron and manganese, the presence of dissolved sulfide, positive detections of sulfate-reducing bacteria in field test kits, and redox potentials ranging between -280 and -320 mV. Descriptive statistics for inorganic constituents in UFA samples are shown in **Table 5-2.** More detailed discussion of the conceptual hydrogeologic model can be found in **Sections 3.1** and **3.2.** Regional groundwater flow simulations are discussed in **Chapter 7.4.**

### 5.6.2 Regional Water Quality Variations in the Upper Floridan Aquifer

The main axis of groundwater flow occurs from the north at areas of highest head (130 to 140-ft NGVD29) in Polk County, southward toward Lake Okeechobee, and further towards the Gulf and Atlantic coasts. A smaller potential recharge area exists in northwestern Highlands County, characterized by heads of 100 to 110-ft NGVD29 (USACE, 2011). The hydraulic gradient in the UFA is greatest along this axis to the region north of Lake Okeechobee. The gradient declines in the region of Lake Okeechobee, southwest Florida and toward the Gulf and Atlantic Coasts. A smaller potentiometric high exists southwest of Lake Okeechobee, resulting in a “saddle” in the Caloosahatchee River valley. Estimated (Bush and Johnston, 1988) and model-computed (USACE, 2011) pre-development head contours depict recharge areas and hydraulic gradients of the regional flow system in the semi-confined and confined portions of the UFA **(Figure 5-8).** The regional pattern of groundwater flow away from the recharge area controls native groundwater quality, as longer flow paths allow greater reaction between groundwater and carbonate rock that includes the UFA. **Figures 5-9** through **5-11** show the spatial distribution of selected constituent concentrations in the UFA.

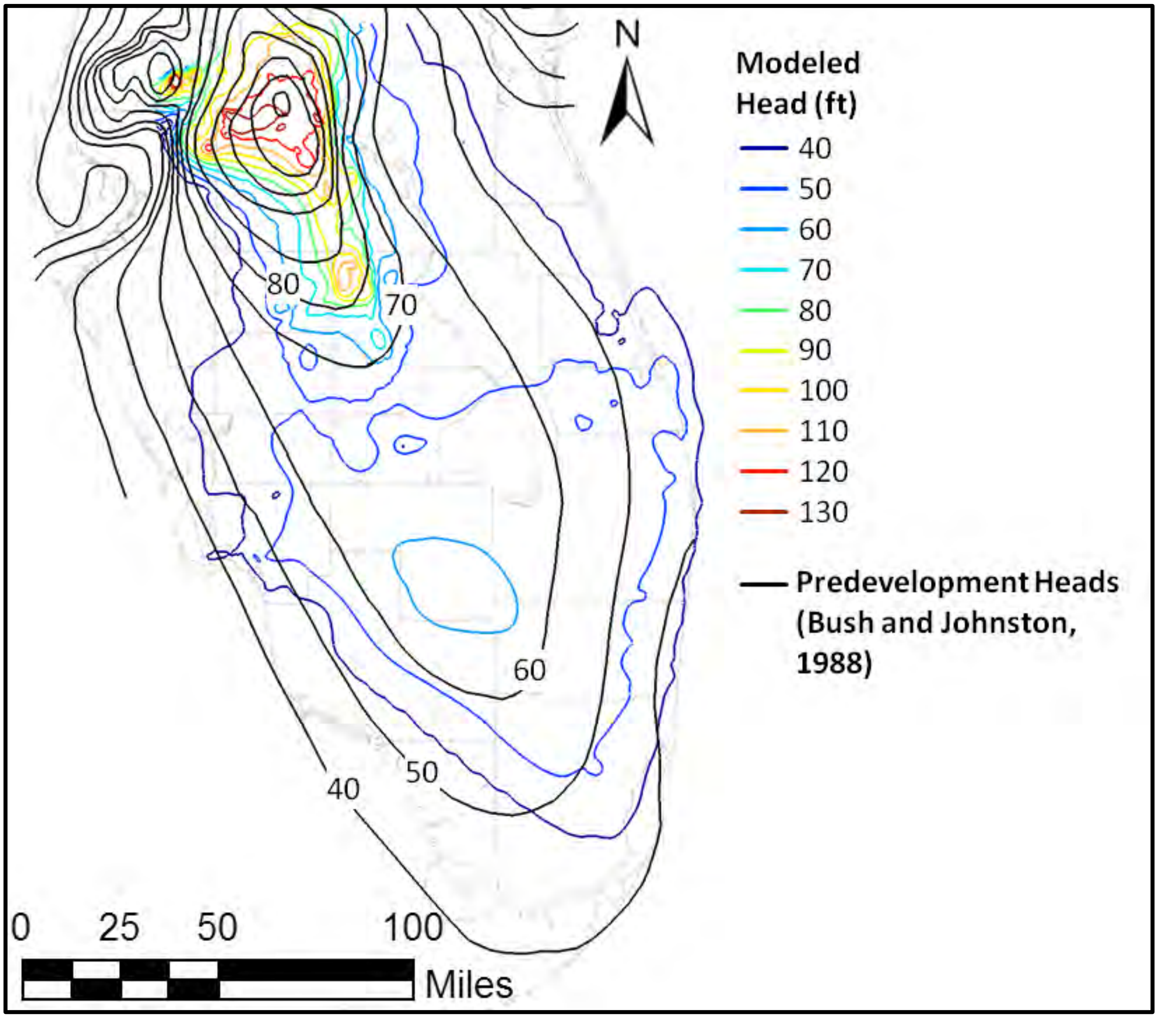


**Figure 5-8 -- Estimated and model computed pre-development head contours of the Upper Floridan Aquifer.** Figure redrawn from USACE (2011).

**Table 5-2 -- Descriptive Statistics of Major and Trace Inorganic Constituents in Native Upper Floridan Aquifer Samples.**

| Constituent | Unit | Mean | Median | 25 percentile | 75 percentile | Minimum | Maximum | Sample Number |
|---|---|---|---|---|---|---|---|---|
| **Major Constituents** | | | | | | | | |
| pH | std units | 7.73 | 7.77 | 7.49 | 7.93 | 7.06 | 8.37 | 46 |
| Specific Conduct. | µS/cm | 4,910 | 3,570 | 1,070 | 6,340 | 258 | 43,540 | 47 |
| Total Alkalinity | mg/L CaCO3 | 122 | 129 | 91 | 150 | 15.6 | 190 | 49 |
| Temperature | ° C | 26.3 | 26.1 | 24.7 | 28.1 | 22.3 | 32.0 | 46 |
| ORP | mV | -307 | -308 | | | -278 | -344 | 5 |
| Tot. Diss. Solids | mg/L | 3210 | 2,030 | 665 | 4,270 | 148 | 29,350 | 47 |
| Calcium | mg/L | 107 | 103 | 52.0 | 140 | 25.3 | 419 | 49 |
| Magnesium | mg/L | 114 | 79.7 | 37.0 | 146 | 5.7 | 961 | 49 |
| Sodium | mg/L | 832 | 511 | 82.5 | 1,162 | 3.6 | 8,460 | 49 |
| Potassium | mg/L | 30.9 | 18.2 | 6.0 | 41.6 | 1.0 | 309 | 49 |
| Chloride | mg/L | 1,480 | 917 | 133 | 2,060 | 4.8 | 15,460 | 49 |
| Silica | mg/L | 13.1 | 11.0 | 7.6 | 15.6 | 2.5 | 45.5 | 34 |
| Bromide | mg/L | 5.1 | 4.1 | 0.24 | 8.5 | 15 | 0.02 | 21 |
| Fluoride | mg/L | 1.1 | 0.94 | 0.65 | 1.3 | 0.22 | 3.5 | 21 |
| Sulfate | mg/L | 446 | 323 | 176 | 509 | 8.1 | 4,500 | 47 |
| Sulfide | mg/L | 1.9 | 1.6 | 0.78 | 2.8 | 0.05 | 4.3 | 16 |
| Diss. Org. Carbon | Mg/L | 0.73 | 0.71 | 0.27 | 0.88 | 0.10 | 2.1 | 15 |
| **Trace Constituents** | | | | | | | | |
| Aluminum | µg/L | < 30 | | | | < 30 | 38 | 17 |
| Antimony | µg/L | < 2.3 | | | | < 2.3 | 4.7 | 3 |
| Arsenic | µg/L | < 1.0 | | | | < 1 | 4 | 20 |
| Barium | µg/L | 34.3 | 27.5 | 22.6 | 40.8 | 8.9 | 117 | 28 |
| Beryllium | µg/L | < 0.12 | | | | < 0.12 | < 0.12 | 3 |
| Boron | µg/L | 498 | 450 | 165 | 7.5 | 17 | 1,800 | 16 |
| Cadmium | µg/L | < 1 | | | | < 1 | 0.98 | 23 |
| Chromium | µg/L | < 0.83 | | | | < 0.83 | 0.95 | 23 |
| Cobalt | µg/L | < 0.71 | | | | < 0.71 | 0.88 | 15 |
| Copper | µg/L | < 1.7 | | | | < 1.7 | 6.1 | 24 |
| Iron | µg/L | 111 | 64.0 | 31.7 | 180 | < 27 | 450 | 32 |
| Lead | µg/L | < 2.2 | | | | < 2.2 | < 2.2 | 24 |
| Lithium | µg/L | 34.9 | 22.0 | 14.0 | 40 | 3.1 | 150 | 15 |
| Manganese | µg/L | 12.9 | 9.7 | 5.6 | 16.6 | <1.4 | 65 | 15 |
| Mercury (ultrace) | ng/L | 5.6 | 6.5 | 1.9 | 9 | < 5 | 9 | 16 |
| Methyl Mercury | ng/L | 0.65 | 0.06 | 0.03 | 0.3 | < 0.03 | 4 | 16 |
| Nickel | µg/L | < 1.8 | | | | < 1.8 | 1.9 | 20 |
| Selenium | µg/L | < 6.2 | | | | < 6.2 | 7.8 | 17 |
| Silver | µg/L | < 1.0 | | | | < 1.0 | < 1.0 | 3 |
| Strontium | µg/L | 11,990 | 11,490 | 4,895 | 17,150 | 320 | 2,900 | 34 |
| Thallium | µg/L | < 9.8 | | | | < 9.8 | 12 | 17 |
| Zinc | µg/L | < 6.5 | | | | < 6.5 | 21.5 | 20 |

Note: Values with "less than" (<) are the minimum detection limit for that constituent. ORP, oxidation-reduction potential.

#### 5.6.2.1 Total Dissolved Solids and Chloride

Total dissolved solids and chloride concentrations increase due to water-rock interactions as groundwater travels away from the Polk County recharge area. Lowest TDS and chloride concentrations occur in UFA wells located in the Kissimmee Basin and along the Caloosahatchee River **(Figure 5-9)**. From a water quality standpoint, ASR systems constructed in these areas would show the greatest percent recoveries because mixing recharge water with fresher, native groundwater would dilute already low native TDS and chloride concentrations. For example, the Kissimmee River ASR pilot system (at OKF-100U, native chloride concentration 195 to 226 mg/L) showed percent recoveries ranging between 94 and 106 percent (USACE and SFWMD, 2013) without exceeding the 250 mg/L SDWA criterion for chloride during four cycle tests. ASR systems that show less contrast between recharge water and native groundwater are less likely to exhibit density-dependent groundwater flow, which can also potentially reduce percent recovery. Although ASR system performance is better where the UFA is fresh, regulatory permitting requirements will be more stringent because aquifers characterized by TDS concentrations less than 10,000 mg/L are classified as underground sources of drinking water (USDW) in the SDWA.

The highest chloride and TDS concentrations in the UFA are shown in wells near the Atlantic and Gulf coasts, although these concentrations are lower than modern seawater concentrations (TDS greater than 35,000 mg/L; chloride greater than 19,800 mg/L). Elevated TDS and chloride concentrations in the UFA may be the result of saltwater intrusion and mixing during Pleistocene high sea-level stands (Reese and Memberg, 2000). From a water quality standpoint, ASR systems located in these areas would show lower percent recoveries particularly during early, smaller volume cycle tests. Fresher recharge water will “float” on denser native saline water due to buoyancy stratification (Vacher et al., 2006). Existing potable water ASR systems in coastal Palm Beach, Broward, and Collier Counties (e.g. Broward County WTP 2A, Springtree, Fiveash, Marco Lakes) have native groundwater chloride concentrations ranging between 1,900 and 4,000 mg/L. These ASR systems showed percent recoveries generally less than 40 percent during the first three cycle tests (Reese, 2002), although percent recoveries generally improved during successive cycle tests. For example, the Marco Lakes ASR system performance improved to show 75 percent recovery after 7 cycle tests, and has expanded to 9 ASR wells with a capacity of 10.5 MGD (Poteet et al., 2013). ASR operational strategies such as creation of a mixing or buffer zone between native and recharge water, and recharging large volumes can improve percent recovery at ASR systems that store water in brackish and saline aquifers.

#### 5.6.2.2 Sulfate

Sulfate concentrations also increase as groundwater travels away from the recharge area in the UFA. The spatial distribution of sulfate concentrations is similar to that of chloride (**Figure 5-10),** with lower concentrations occurring in the Kissimmee Basin wells, and highest concentrations in coastal wells. High sulfate concentrations in native UFA groundwater can degrade recharge water quality through mixing during ASR cycle tests, possibly exceeding the secondary SDWA water quality criterion of 250 mg/L. Sulfate is also reduced to sulfide by native sulfate-reducing bacteria in the UFA. Sulfate reduction is the primary control on redox environment in the confined portions of the UFA, and also attenuates mobilized arsenic during storage (Mirecki et al., 2012) and discussed further in **Section 5.8**. Dissolved sulfide in recovered water can be removed during aeration prior to discharge into the surface water body. Dissolved sulfide was not found to exert toxic effects to freshwater organisms during cycle testing at the Kissimmee River ASR system (USACE and SFWMD, 2013). Discharge of recovered water with sulfate concentrations that exceed surface water values is a particular concern for water management in the Everglades Protection Area.

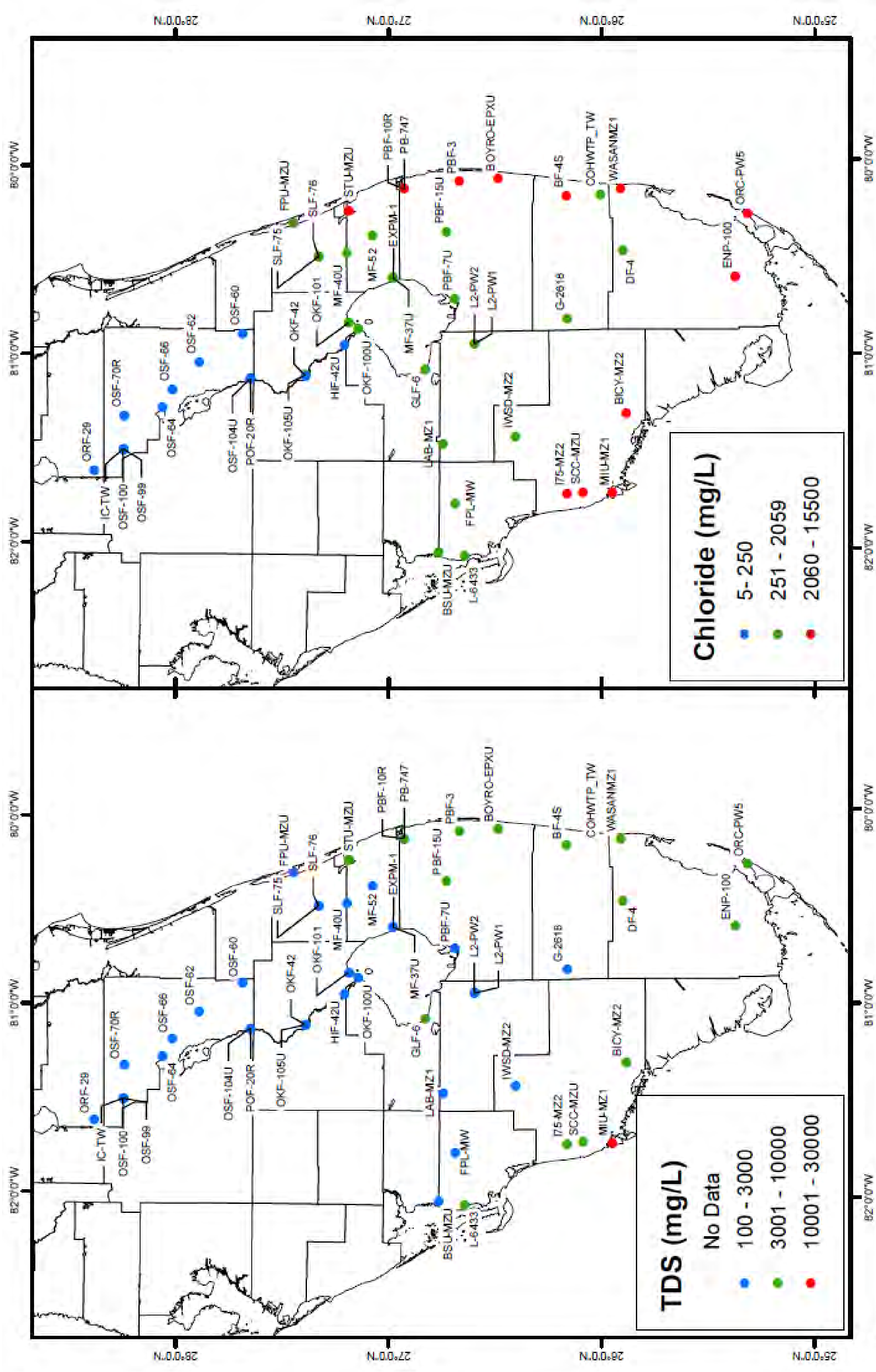


**Figure 5-9:** TDS and Chloride in the Upper Floridian Aquifer

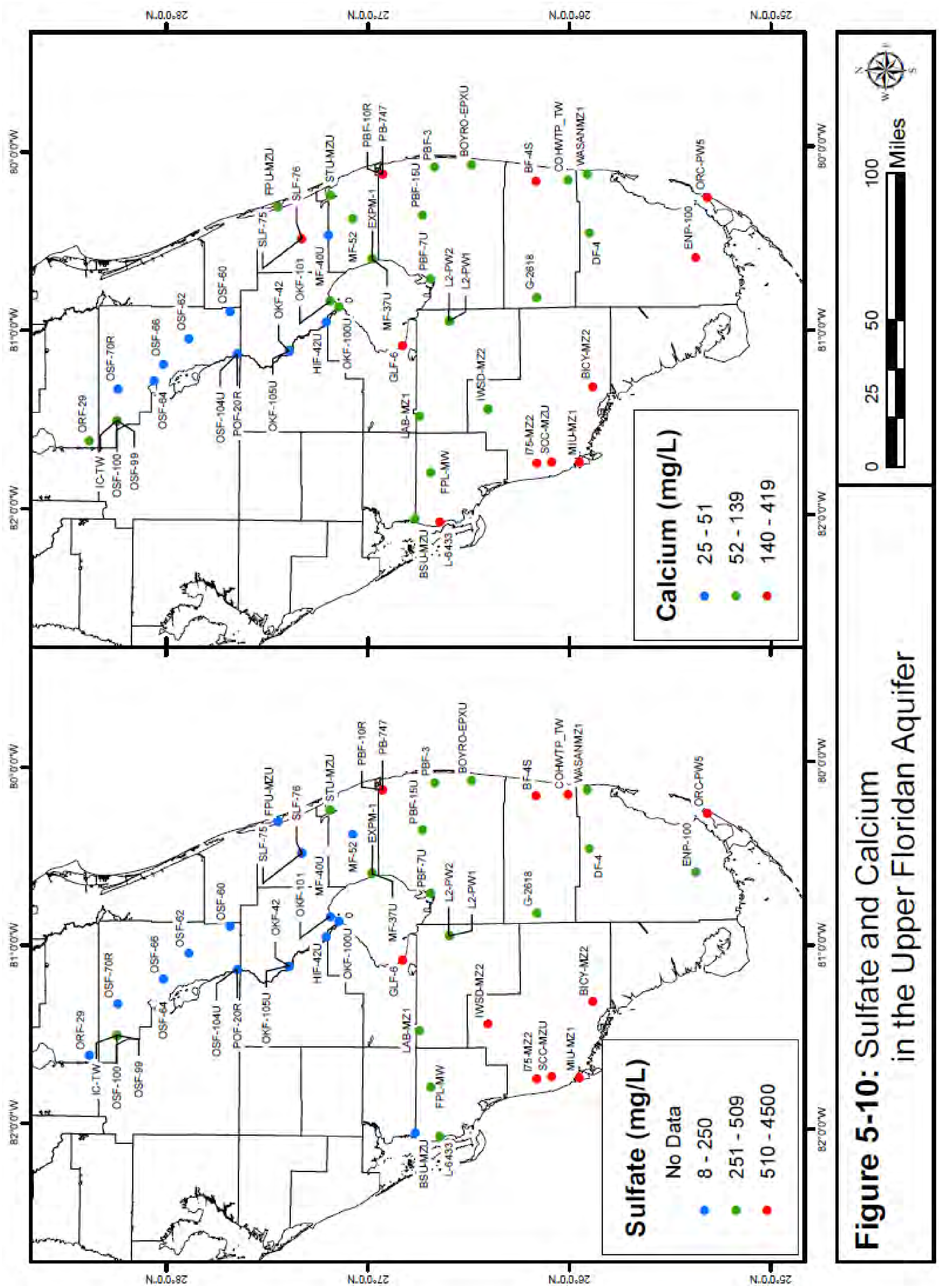


**Figure 5-10:** Sulfate and Calcium in the Upper Floridan Aquifer

1

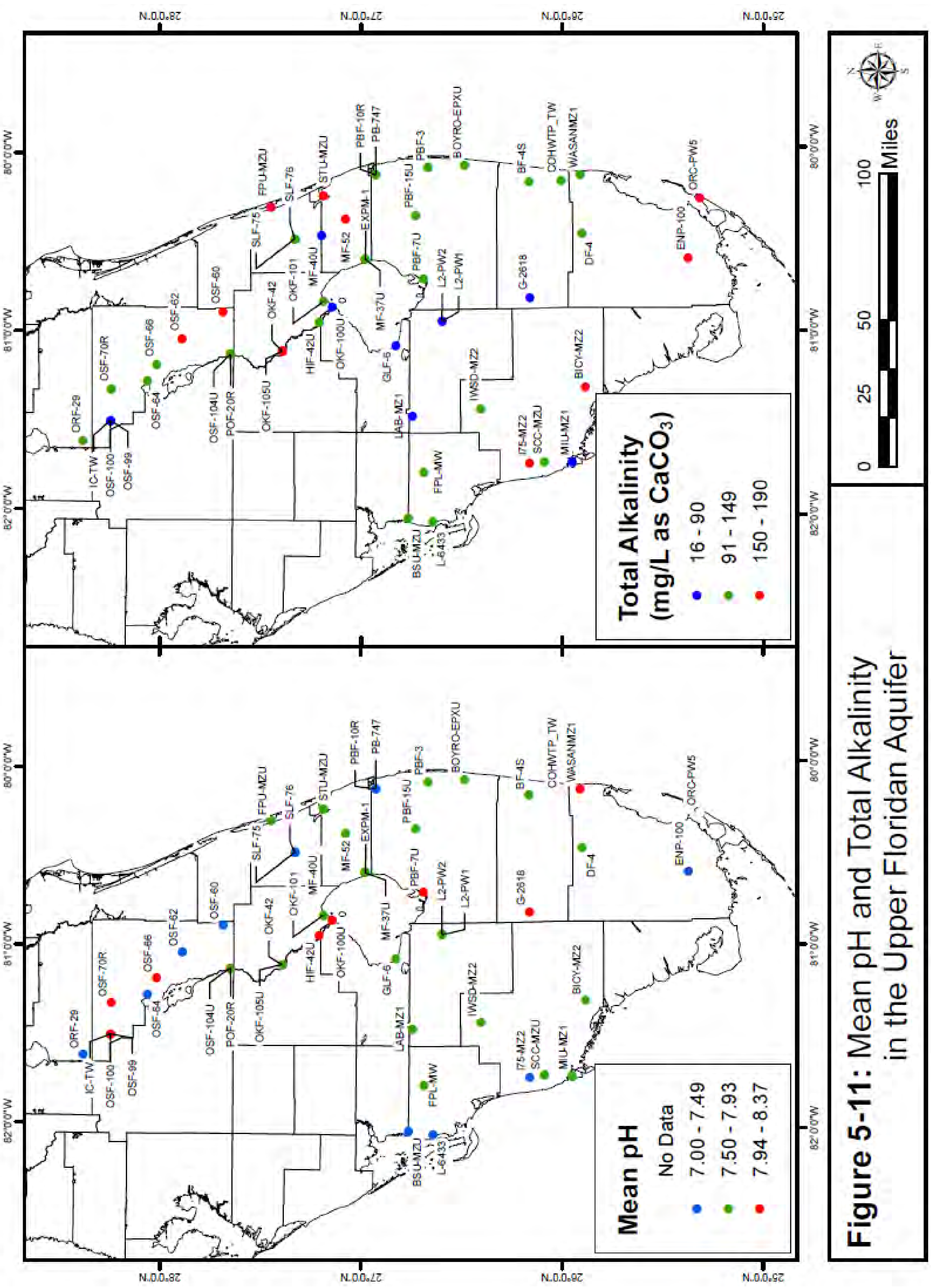


**Figure 5-11:** Mean pH and Total Alkalinity in the Upper Floridian Aquifer

#### 5.6.2.3 Calcium, Total Alkalinity, and pH

The native UFA occurs within permeable limestone units of Oligocene and Miocene age. Close to the recharge area, groundwater is undersaturated with respect to calcium carbonate, resulting in limestone dissolution and karst formation. Away from the recharge area (in the confined portions of the UFA), groundwater will equilibrate with limestone, so that dissolution will not occur. Native groundwater carbonate species distributions will shift in response to mixing with fresh, low alkalinity surface water during ASR cycle testing. However, limestone host rock serves as an effective buffer to large variations in pH and carbonate speciation during mixing.

The pH of native UFA groundwater is circum-neutral throughout the ASR regional study area **(Figure 5-11).** The equilibrium pH of water in contact with calcium carbonate and atmospheric carbon dioxide is slightly alkaline, at 8.3. More alkaline pH values are observed in down-gradient UFA wells that have reached equilibrium values of alkalinity and pH, and calcium concentrations in contact with calcium carbonate. Effects of ASR cycle testing on calcium carbonate solubility in the UFA are discussed in **Section 5.7.**

#### 5.6.2.4 Characterization of Organic Carbon in Surface and Groundwater

As cycle testing proceeded at the CERP ASR pilot systems, it became increasingly clear that the TOC and DOC phases in source (surface) water were important components of subsurface biogeochemical reactions (USACE and SFWMD, 2013). TOC and DOC were measured weekly and monthly during all phases of cycle tests at KRASR, and these data are presented in USACE and SFMWD (2013). Concentrations of TOC and DOC declined during cycle testing, most likely due to sorption to aquifer material and microbe-mediated redox reactions in the UFA. More detailed studies of microbe-mediated geochemical reactions were completed by Lisle (2014) and Harvey et al. (2014).

Lisle (2014) characterized DOC in native UFA and APPZ groundwaters, as part of a larger effort to define microbe diversity in the FAS. Microbes couple electron donor (oxidation of organic carbon) and electron acceptor (reduction of nitrate, ferric iron, or sulfate, for example) reactions to obtain energy, and these coupled reactions are specific to microbial families. As part of this study, Lisle (2014) quantified carbon utilization and biomass production in microbe communities isolated from six UFA and APPZ wells that were near the ASR pilot systems. The Lisle (2014) study is the most detailed characterization of native microbe diversity of the FAS to date.

In a related study, Harvey et al. (2014) reported characteristics of DOC fractions in Lake Okeechobee surface water samples, and the effect that these DOC fractions would have on transport of *E. coli* introduced into the FAS during ASR cycle testing. Although the transport tests were inconclusive, characterization of the DOC fractions of Lake Okeechobee surface water will be useful for other subsurface microbe studies.

### 5.6.3 Native Water Quality in the Avon Park Permeable Zone

The Avon Park Permeable Zone (APPZ) was defined by Reese and Richardson (2008) to recognize a regional sub-aquifer within the middle confining unit that separates the upper and lower Floridan aquifers. The APPZ was known previously as the Middle Floridan aquifer in southeastern Florida. Water-quality and hydraulic characteristics, and hydrostratigraphic position of the APPZ are favorable for use as an ASR storage zone, particularly north and northwest of Lake Okeechobee.

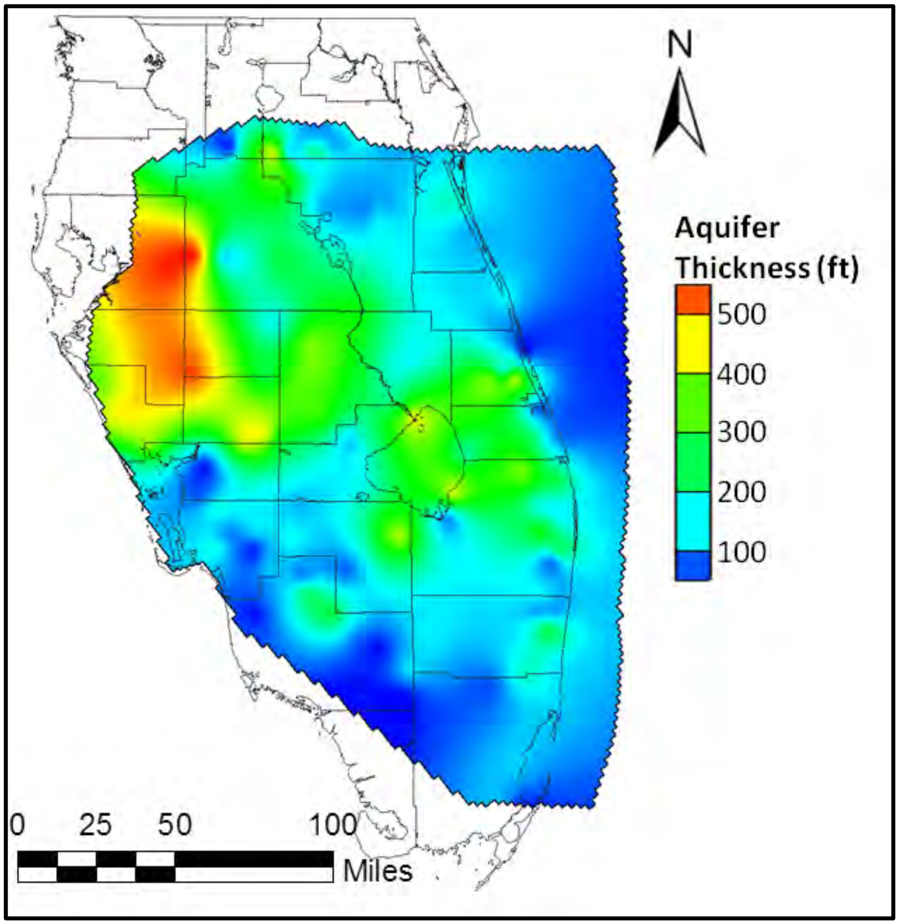


**Figure 5-12 -- Thickness of the Avon Park Permeable Zone as simulated in the ASR Regional Study groundwater flow model. Figure from USACE (2011).**

The APPZ probably has hydraulic connectivity with the upper Floridan Aquifer in the region of the primary recharge area in Polk County, which also marks the fresher portions of the APPZ. Maximum thickness (greater than 200-ft) of the APPZ occurs in a wide band extending from Hillsborough County southeast to northern Palm Beach County **(Figure 5-12).** The APPZ is thin or absent in most of Miami-Dade, Monroe, and Collier Counties. The APPZ occurs at depths of approximately 1,800 to 2,100-ft in western Lee and Charlotte Counties, coincident with the occurrence of a permeable zone having brackish water quality. Lithologies at the base of this zone are composed of dolomite and evaporites (Reese, 2000). Groundwater quality samples from the BSU-MZL well (Charlotte County) are the warmest, and have the highest concentrations of solutes of all APPZ samples.

### 5.6.3.1 Total Dissolved Solids and Chloride

Native groundwater quality of the APPZ generally is warmer and more saline than the UFA, with maximum concentrations of chloride and total dissolved solids approaching that of seawater **(Table 5-3).** Lowest TDS and chloride concentrations occur in APPZ wells located in the Kissimmee Basin and in Palm Beach County **(Figure 5-13)**, closest to the recharge area**.** The greatest TDS and chloride concentrations occur in wells where the APPZ is deepest, for example along an axis beneath the Caloosahatchee River in western Hendry, Lee, and Charlotte Counties.

**Table 5-3 -- Descriptive Statistics of Major and Trace Inorganic Constituents in Native Avon Park Permeable Zone Samples.**

| Constituent | Unit | Mean | Median | 25 percentile | 75 percentile | Minimum | Maximum | Number of Samples |
|---|---|---|---|---|---|---|---|---|
| **Major Inorganic Constituents** | | | | | | | | |
| pH | std units | 7.64 | 7.59 | 7.38 | 7.87 | 7.1 | 8.25 | 18 |
| Spec.Conductance | µS/cm | 10,670 | 6,741 | 3,806 | 8,190 | 465 | 51,350 | 18 |
| Tot. Alkalinity | mg/L as CaCO3 | 113 | 111 | 89.4 | 133 | 71 | 195 | 18 |
| Temperature | ° C | 26.9 | 27.1 | 24.4 | 29.4 | 19 | 32.6 | 18 |
| Calcium | mg/L | 197 | 140 | 91.2 | 240 | 37 | 671 | 18 |
| Magnesium | mg/L | 239 | 141 | 93.4 | 183 | 16 | 1,120 | 18 |
| Sodium | mg/L | 1,855 | 907 | 557 | 1,281 | 40 | 10,450 | 18 |
| Potassium | mg/L | 64.1 | 24.4 | 17.9 | 42.8 | 2.2 | 392 | 18 |
| Chloride | mg/L | 3,420 | 1787 | 935 | 2,270 | 71 | 18,900 | 18 |
| Bromide | mg/L | 0.9 | 0.75 | | | 0.27 | 1.8 | 3 |
| Fluoride | mg/L | 0.79 | 0.69 | 0.5 | 0.846 | 0.25 | 1.7 | 11 |
| Silica | mg/L | 11.2 | 11.6 | 9.9 | 13.1 | 5.6 | 15.2 | 11 |
| Sulfate | mg/L | 662 | 394 | 293 | 713 | 57 | 2,798 | 18 |
| Tot. Diss. Solids | mg/L | 6,657 | 4,008 | 2295 | 4,948 | 257 | 34,160 | 18 |
| Sulfide | mg/L | 2.1 | 1.5 | | | 0.5 | 3.9 | 5 |
| Diss. Org. Carbon | mg/L | 1.4 | 0.84 | | | 0.1 | 4.3 | 6 |
| **Trace Inorganic Constituents** | | | | | | | | |
| Arsenic | µg/L | <1 | | | | <1 | <1 | 4 |
| Barium | µg/L | 31.5 | 34.3 | 21.5 | 41 | 13.8 | 47 | 7 |
| Cadmium | µg/L | | | | | <0.24 | | 3 |
| Copper | µg/L | | | | | < 1 | 2.4 | 4 |
| Iron | µg/L | 271 | 51 | 22.4 | 194 | 4.4 | 1,680 | 8 |
| Lead | µg/L | | | | | < 10 | | 3 |
| Manganese | µg/L | 13.1 | 9.2 | 2.4 | 19.3 | 1.1 | 41.1 | 8 |
| Mercury (ultrace) | ng/L | | | | | < 0.15 | 0.98 | 2 |
| Nickel | µg/L | | | | | 1.1 | | 1 |
| Strontium | µg/L | 18,191 | 13,200 | 10,630 | 28,417 | 7,975 | 29,600 | 9 |
| Zinc | µg/L | | | | | < 20 | 34 | 4 |

Note: Values with "less than" (<) are the minimum detection limit for that constituent.

### 5.6.3.2 Sulfate

Sulfate concentration trends in the APPZ follow the same pattern shown by chloride and TDS, with highest concentrations occurring where the APPZ is deepest, in Lee and Charlotte Counties **(Figure 5-14).** Gypsum and anhydrite (calcium sulfate minerals) are interbedded with, or occur as inter-granular material with dolomites of the Avon Park Formation (Reese and Richardson, 2008). Dissolution of calcium sulfate minerals results in greater sulfate concentrations in these samples.

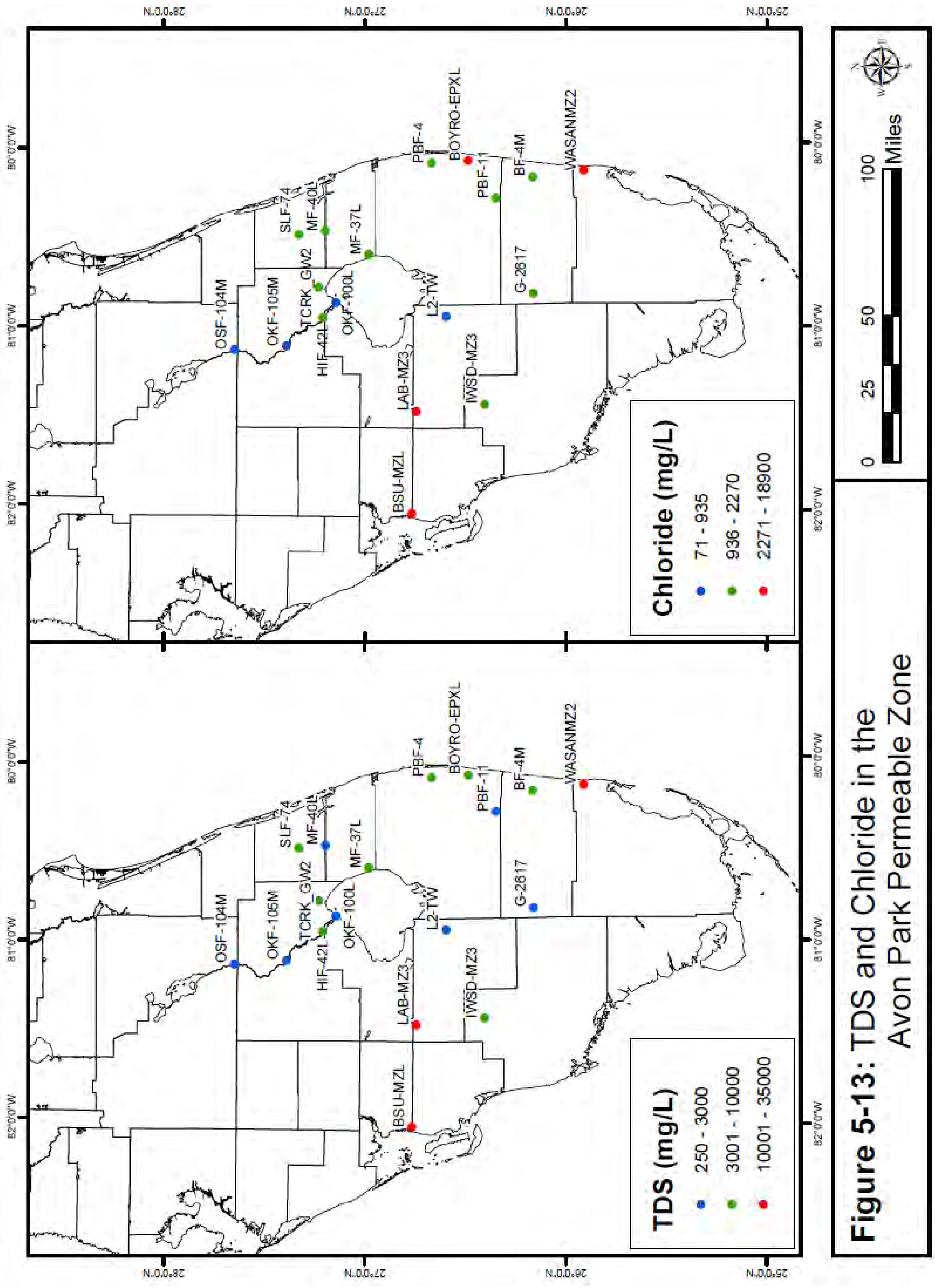


Figure 5-13: TDS and Chloride in the Avon Park Permeable Zone

1

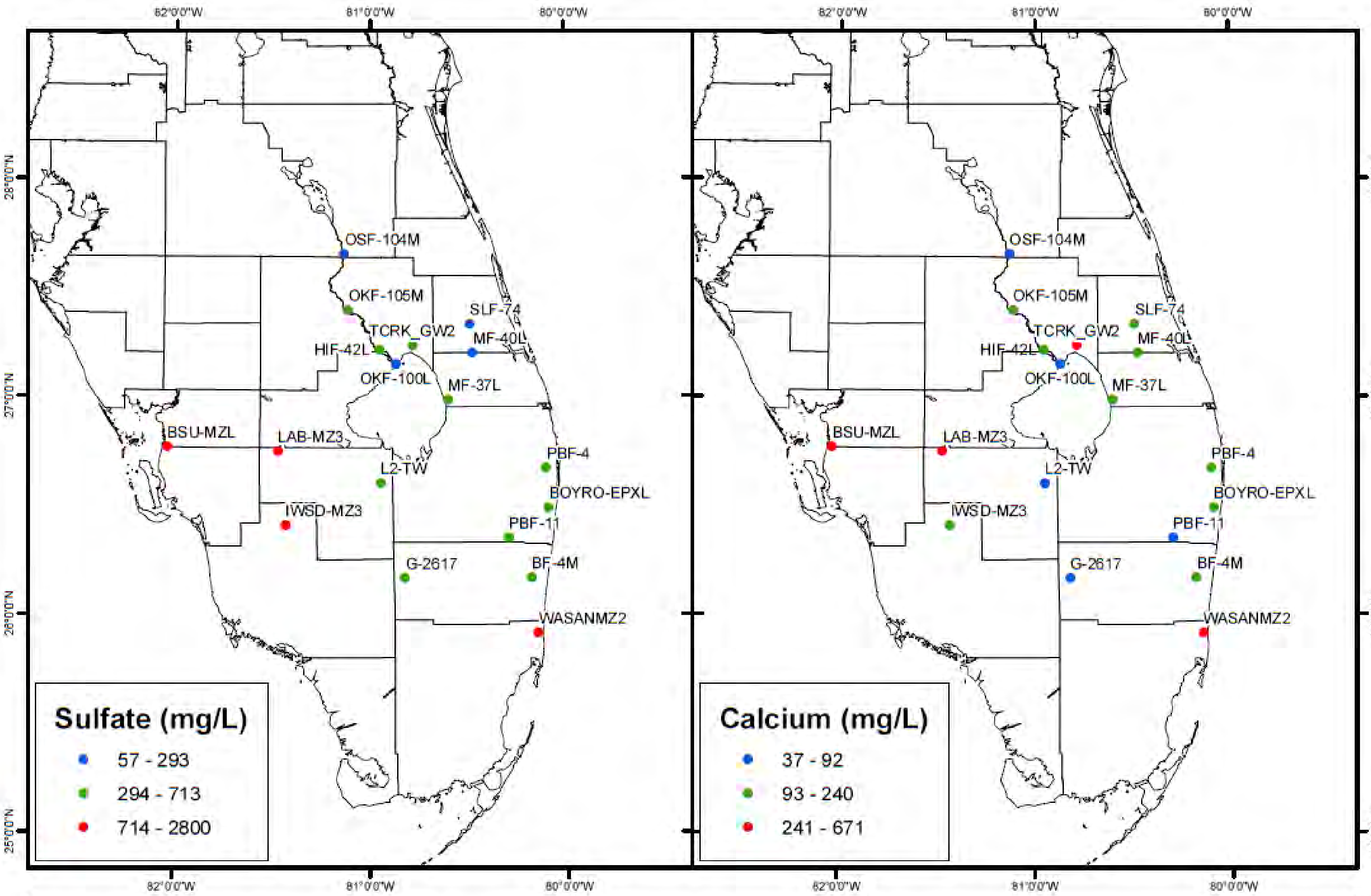


**Figure 5-14:** Sulfate and Calcium in the Avon Park Permeable Zone

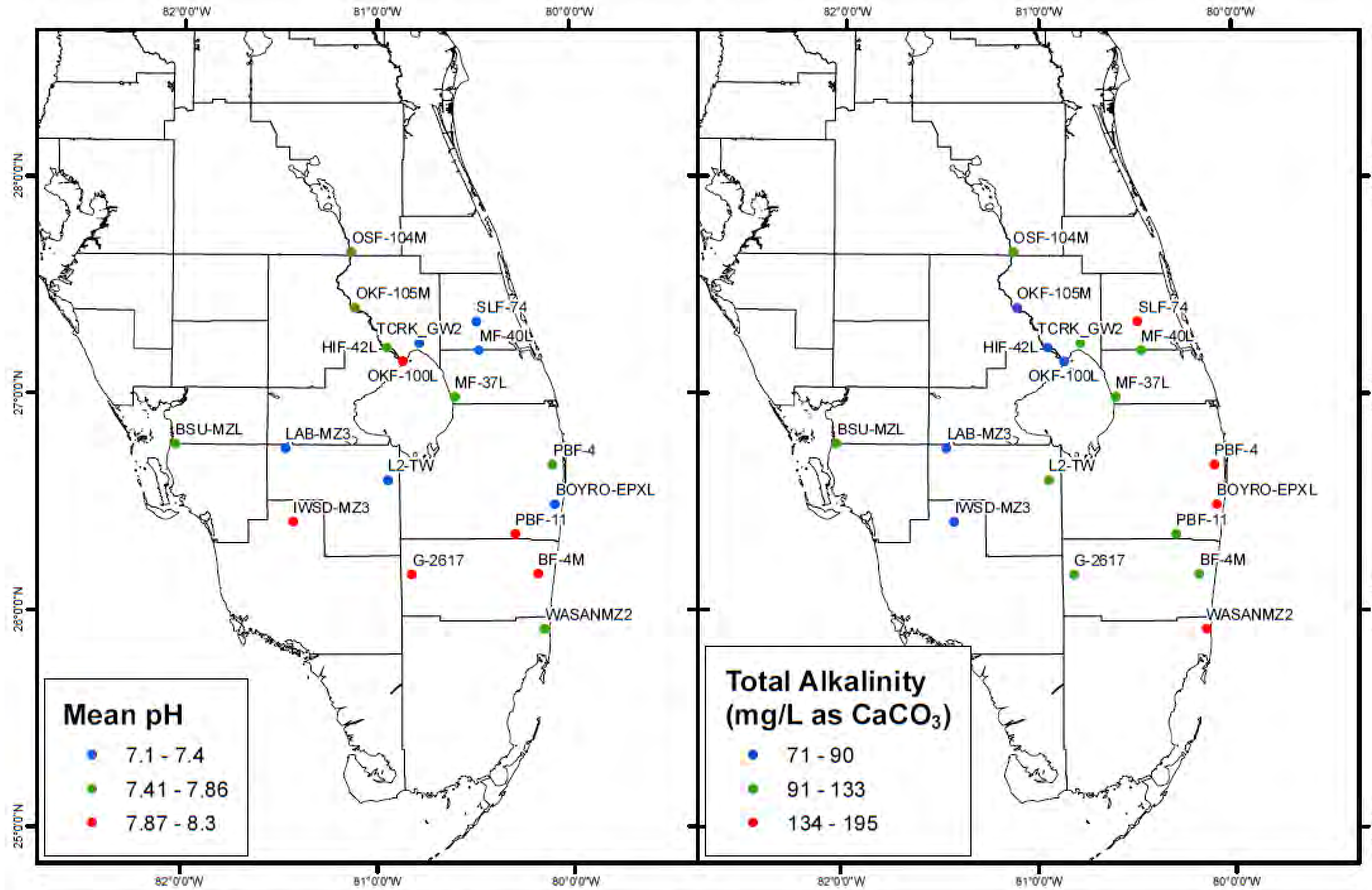


**Figure 5-15:** Mean pH and Total Alkalinity in the Avon Park Permeable Zone

### 5.6.3.3. Calcium, Total Alkalinity, and pH

The APPZ occurs within permeable carbonate rock units of Eocene age. Reactions between groundwater and carbonate rock will occur as groundwater flows away from the recharge area. The pH of native APPZ groundwater is neutral to slightly alkaline throughout the ASR regional study area **(Figure 5-15).** Most APPZ groundwater samples show moderate concentrations of total alkalinity and calcium, except where evaporates or seawater intrusion (Atlantic Coast) increase solute concentrations.

## 5.7 Geochemical Mixing Models to Evaluate Calcium Carbonate Dissolution

Surface water and native groundwater composition characteristics were defined in earlier sections of this chapter. Surface water and native groundwater data serve as end-members for geochemical mixing models. The USGS geochemical modeling code PHREEQC (v. 3.1.2, Parkhurst and Appelo, 2013) enables simulation of a wide variety of geochemical reaction and transport scenarios, which will then be compared to actual water-quality data obtained during cycle testing at KRASR.

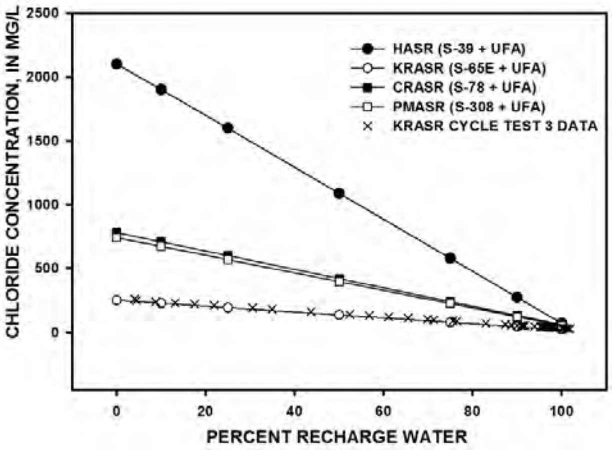


**Figure 5-16 – Conservative mixing lines at four proposed CERP ASR systems.**

Lines are based on chloride concentrations in simulated mixtures of surface water and native groundwater end-members. KRASR mixing line confirmed by cycle test 3 data from the 350-ft storage zone monitor well.

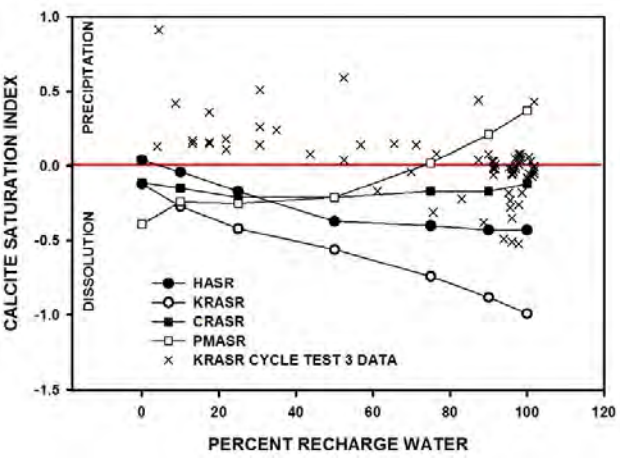


**Figure 5-17 – Calcite saturation indices in simulated mixtures at four proposed CERP ASR systems.**

Saturation indices were calculated for simulated mixtures of surface water and native groundwater end-members. Calcite saturation indices calculated from KRASR cycle test 3 data (X; 350-ft SZMW) are superimposed.

Geochemical mixing models can be developed by combining a range of proportions of two or more compositional end members, so that component concentrations are reduced only by dilution of the more concentrated end-member. Typically, chloride serves as the conservative tracer in such models. **Figure 5-16** shows conservative mixing lines based on mixtures of representative surface water with native groundwater from the Upper Floridan Aquifer at the four proposed CERP ASR systems. In this plot, steeper mixing lines indicate more saline groundwater end members. Surface water datasets are much larger than native groundwater datasets, so representative samples were chosen from each site. Each surface water sample had a chloride concentration close to the median value reported on **(Table 5-1).** Charge balance errors were calculated for samples and also simulated mixtures, and typically were below 4 percent at KRASR and PMASR. High charge balance error values in end member samples for CRASR (11 percent) and HASR (7 percent) result in greater uncertainty in slopes of the mixing lines for these systems in **Figure 5-16**. Measured chloride concentration data obtained from the 1,100-ft SZMW at KRASR during cycle test 3 also are plotted on **Figure 5-16.** The percent recharge component of each groundwater sample was calculated using a mixing model developed in PHREEQC.

Calcium carbonate dissolution and precipitation are indicated by negative or positive values of the calcite saturation index, respectively. Calcium carbonate solubility is not adequately described using a conservative mixing model because under-saturated recharge water reacts with limestone aquifer material as it flows through the storage zone. Calcite saturation indices calculated using recharge, storage, and recovery data from cycle test 3 data at KRASR differ from those predicted by the conservative mixing model **(Figure 5-17)**, confirming that calcium carbonate dissolution is a non-conservative process.

Time-series presentations of calcite saturation indices calculated from cycle test 3 data at KRASR provide a better depiction of limestone dissolution **(Figure 5-18**). KRASR recharge water shows the lowest carbonate alkalinity values, so calcium carbonate dissolution will be more extensive here compared to other proposed CERP ASR systems having higher alkalinity recharge water. As expected, negative calcite saturation indices in recharge phase samples show that dissolution occurs throughout the storage zone, even 1,100-ft away from the ASR well. Less negative and even positive saturation indices at this location suggest that recharge water is equilibrating with limestone as it flows through permeable zones. During storage, saturation indices are negative especially at 200 to 300 days into the cycle. This episode of dissolution could result from microbial metabolism of organic carbon and production of carbon dioxide. During recovery, nearly all saturation indices are positive as native water mixes with recharge water that has equilibrated with limestone.

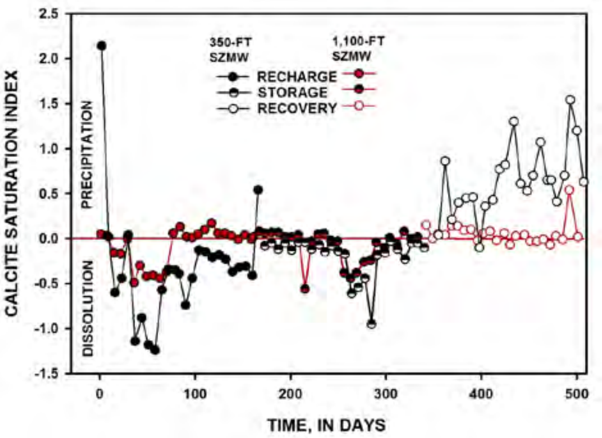


**Figure 5-18 -- Time series plot showing calcite saturation indices in samples from two storage zone monitor wells (350-ft and 1,100-ft) calculated for cycle test 3 at KRASR.**

Dissolution of limestone during recharge is beneficial from an operational perspective. Permeability is enhanced, so that recharge water can be pumped into the aquifer at lower wellhead pressures. If ASR cycle tests have a storage phase that is of long duration (one year or more), effects of limestone dissolution may only be temporary because stored water will equilibrate with limestone in the aquifer.

## 5.8 Evaluating Arsenic Mobilization on a Regional Scale

Introduction of oxygenated surface water into the FAS during the recharge phase of an ASR cycle test changes the geochemical environment of the storage zone, and drives reactions between water and rock. It is now well known that pyrite, a common iron sulfide mineral in marine limestones, will oxidize during the recharge phase, subsequently releasing arsenic that is bound within the mineral lattice (Price and Pichler, 2006; Arthur et al. 2007) Arsenic is then transported in groundwater, sometimes at concentrations that exceed the SDWA criterion of 10 µg/L. In the following sections, the potential for arsenic mobilization will be considered on a regional scale using lithological and geochemical characteristics of storage zone lithologies and native FAS groundwater.

### 5.8.1 Arsenic Distribution in Marine Limestones of the FAS

Several studies were initiated within the ASR Regional Study (Arthur et al. 2007; Fischler and Arthur, 2013) or by others in Florida (Price and Pichler, 2006; Pichler et al., 2011) to quantify the range of arsenic concentrations in marine limestone formations that include the FAS. If arsenic-rich lithologies could be identified, perhaps those intervals could be excluded from the storage zone through optimized well construction, as was done in Izbicki et al. (2008). In that study, discrete permeable zones characterized by elevated arsenic concentrations were identified using borehole flowmeter analyses. Because these zones were in the deepest portion of the well, backfilling of the open interval to exclude the arsenic-rich permeable zone resulted in lower overall arsenic concentration in produced water from that well. Similarly, if arsenic-rich lithologies were identified in representative core samples, it is possible that they could be excluded either by limiting well depth or extending the casing depth.

Detailed bulk rock analyses of samples from the Lower Hawthorn Group (Arcadia Formation), Suwannee Limestone, Ocala Limestone, and Avon Park Formation showed that the occurrence of arsenic in these marine limestones is ubiquitous, and ranges between 0.6 mg/kg and 10.5 mg/kg, which is comparable to global crustal average of 2.6 mg/kg (Pichler et al., 2011). They noted that rock samples showing hydrous ferric oxide, organic matter, clay minerals, fracture surfaces, or moldic porosity often showed greater arsenic concentration (maximum 69 mg/kg). Arsenic concentrations in pyrite minerals within the limestones (quantified by electron probe microanalysis methods) were much greater, ranging between 100 mg/kg and 11,000 mg/kg, with greatest values associated with pyrite framboids in fractures and voids (Pichler et al., 2011). Fischler and Arthur (2013) characterized lithologies and mineralogy (including pyrite occurrence) in of a smaller set of cores and rock cuttings from the same formations at HASR and KRASR. They concluded that the occurrence of pyrite in the samples was pervasive, and no apparent trend existed in relation to core, ASR study area, or lithostratigraphic unit.

Similar conclusions were reached by Arthur et al., (2007) using a different approach – analysis of leachate from sequential extraction of representative rock samples, under either oxic or sulfate-reducing redox conditions that mimic conditions of an ASR cycle test. Rock samples were obtained from the Lower Hawthorn Group (Arcadia Formation), Suwannee Limestone, Ocala Limestone, and Avon Park Formation from CRASR, KRASR, PMASR, HASR, and MHASR. In these experiments, arsenic was released during oxic phases (resembling recharge) in concentrations ranging between 1 and 816 µg/L, with greatest values in Avon Park Formation samples. Concentrations in rock leachate are not directly related to groundwater concentrations during an ASR cycle test because water:rock surface area ratios (for example) differ between bench- and field-scale experiments. Bench-scale leaching experiments did confirm the release of arsenic, as well as molybdenum and antimony, from lithologies that serve as ASR storage zones in south Florida.

The results of these investigations indicate that arsenic mobilization is likely to be an issue at any ASR system in Florida due to the pervasive occurrence of pyrite as a trace mineral in the carbonate lithologies of the FAS. Fortunately, this conclusion does not portend the end of ASR systems in Florida. An understanding of geochemical and hydrological factors controlling arsenic transport and fate has improved during the last decade, so that arsenic exceedances can be mitigated by ASR operations, and regulatory flexibility **(Appendix A)**. Geochemical factors are discussed in the following section.

### 5.8.2 Potential for Arsenic Mobilization in the FAS of South Florida

Many potable water ASR systems in Florida fell out of regulatory compliance when the SDWA criterion for arsenic declined from 50 µg/L to 10 µg/L in 2006 (2005 for Florida regulations). Many water utilities previously investing in ASR systems decided that the risk of non-compliance was too great, so chose to manage water supplies using reservoirs or other infrastructure. This regulatory change also spurred more investigations to evaluate arsenic mobilization at the field scale at both potable water and CERP ASR systems.

The pattern of arsenic mobilizations differs when cycle test data from potable versus CERP ASR systems is compared. These patterns differ primarily due to source water quality characteristics. Potable water ASR systems recharge drinking water, which typically is oxic, very low TDS, and shows very low concentrations of iron and organic carbon. Drinking water is often polished by lime softening prior to distribution, a process that lowers most major inorganic constituent concentrations. In contrast, CERP ASR systems recharge lightly treated surface water, which is oxic, and shows fairly high concentrations of iron, organic carbon, and phosphorus **(Table 5-1)**. These constituents in particular serve as nutrients and electron donors or acceptors to stimulate microbe-mediated geochemical reactions in the storage zone. The result of these geochemical reactions is that arsenic is sequestered in a newly formed iron sulfide solid during storage and recovery (Mirecki et al., 2012). During cycle tests 2 through 4 at KRASR, concentrations of arsenic in recovered water were below the 10 µg/L criterion.

The CERP ASR system KRASR served as the "applied research" system for the CERP ASR pilot project (USACE and SFWMD, 2013). A large water quality dataset was amassed during the four cycle tests completed at this facility, and interpretations of arsenic transport and fate were developed mostly from this dataset. Controls on arsenic mobility will be described below, and the validity of extrapolating these conditions to other CERP ASR systems in south Florida will be evaluated.

#### 5.8.2.1 Controls on Arsenic Mobility During ASR Cycle Tests at KRASR

Arsenic is mobilized during the recharge phase at KRASR by pyrite oxidation, similar to most other ASR systems in Florida, regardless of source water composition. Finely disseminated pyrite ($FeS_2$) is oxidized by dissolved oxygen (DO) in the source water, releasing arsenic (also molybdenum) that was co-precipitated when the pyrite mineral was formed. However, the pyrite oxidation reaction only occurs over a time and length of flowpath in the aquifer where dissolved oxygen can persist. In-situ measurements (Sea-Bird water quality probe at approximately -600 ft depth in the 350-ft SZMW) measured DO and ORP hourly during the recharge and storage phases of cycle test 1 (**Figure 5-19).** During recharge, DO was detected at low but measureable (< 0.2 mg/L) concentrations in wellhead samples from the 1,100-ft SZMW (USACE and SFWMD. 2013).

Probe measurements indicate that DO does not persist after recharge pumping ends **(Figure 5-19)**. DO concentrations decrease rapidly at the onset of storage, showing a half-life of 25 hours during cycle test 1 (Mirecki et al., 2012). Therefore, the redox conditions do exist for pyrite oxidation, but they do not persist for very long after recharge ends. DO data for potable water ASR systems are not common, but a similar half-life (1 day) was estimated for decreasing DO concentrations at the Fort Myers-Winkler Avenue potable water ASR system (Mirecki, 2004). Even though DO does not persist beyond the recharge phase, the temporary oxic condition is sufficient to promote the release of arsenic at concentrations that exceed 10 µg/L in the aquifer.

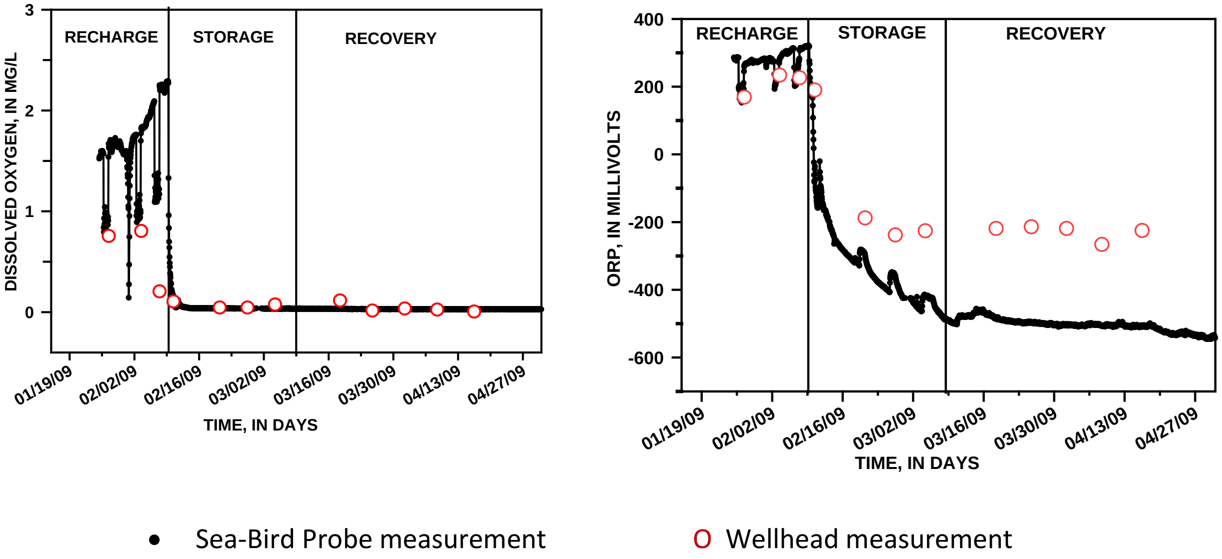


**Figure 5-19 -- In-situ measurements of dissolved oxygen and ORP in the 350-ft SZMW during cycle test 1 at KRASR.**

The aquifer redox environment evolves during the storage phase. As the storage phase proceeds, ORP continues to decline to values that are more negative than would be expected only from the absence of oxygen. Redox conditions in the storage zone evolve to sulfate-reducing conditions, as suggested by the significantly more negative (-200 to -400 mV) ORP values **(Figure 5-19)**, and increasing concentrations of dissolved sulfide (Mirecki et al., 2012). A sulfate-reducing redox environment is mediated by native microorganisms, which couple sulfate- and ferric-iron reduction with organic carbon oxidation, both readily available constituents in mixed source water and native FAS groundwater. The products of microbe-mediated reactions are dissolved sulfide and an iron sulfide solid phase (Mirecki et al., 2012). Arsenic will co-precipitate with this stable iron sulfide phase, effectively removing arsenic from groundwater. Lisle (2014) and work summarized in **Chapter 6** describes the microbiological environment of the FAS in greater detail.

Arsenic trends defined from wellhead sample data at the ASR well, and the 350-ft and 1,100-ft SZMWs are shown in **Figure 5-20.** The greatest arsenic concentrations were measured in all wells during cycle test 1. Comparison of arsenic trends in the 350-ft and 1,100-ft SZMWs show that a pulse of arsenic is mobilized through the storage zone during recharge. Most likely, arsenic is transported beyond the farthest SZMW (1,100-ft at 5 MGD pumping rate).

However, although arsenic is mobilized during recharge, declining arsenic concentrations during storage in SZMW samples indicate that geochemical reactions attenuate arsenic concentrations under static conditions. Samples obtained throughout the wellfield and at the ASR well during the recovery phases of cycle tests 2 through 4 show arsenic concentrations are always below the 10 µg/L criterion at the onset of recovery. Because each cycle test concluded with approximately 100 percent recovery by volume, it is unlikely that arsenic remained as a dissolved constituent in the aquifer.

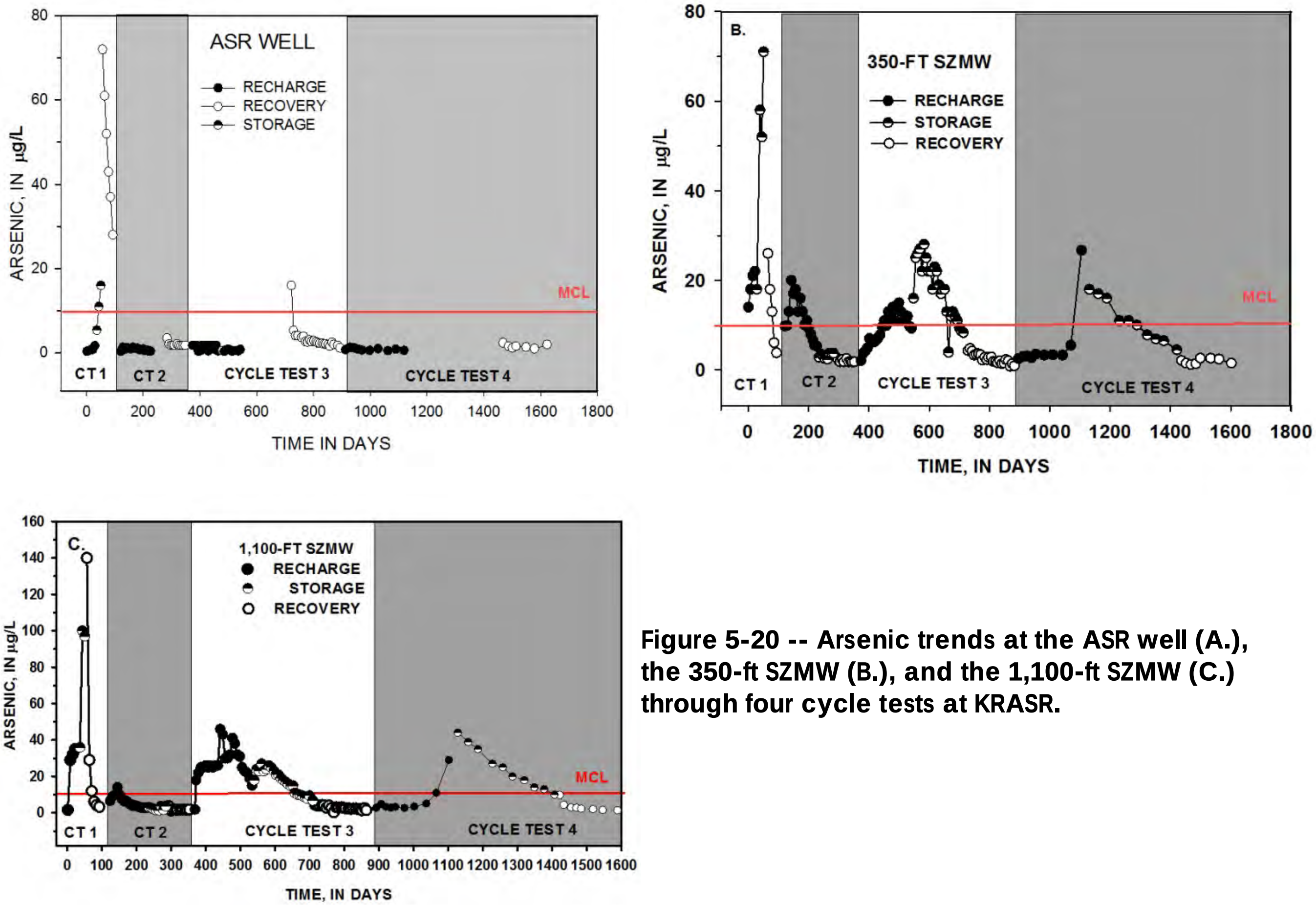


**Figure 5-20 -- Arsenic trends at the ASR well (A.), the 350-ft SZMW (B.), and the 1,100-ft SZMW (C.) through four cycle tests at KRASR.**

This reaction sequence differs from storage zone reactions at potable water ASR systems. Because drinking water has little to no iron (generally less than 30 µg/L) and organic carbon (less than 0.1 mg/L), the constituents that drive the microbe-mediated reactions defined above in the aquifer are absent. Consequently, iron and arsenic released during pyrite oxidation simply remain as dissolved complexes in groundwater. The only way to diminish arsenic concentrations at potable ASR systems is through dilution, advective transport (recovery), or removal of pyrite by aquifer pretreatment or extensive oxidation. Declining arsenic concentrations were observed over sequential cycle tests at the Tampa-Rome Avenue Park ASR system. Here, ozone-treated water is stored in the UFA. High concentrations of DO in the source water effectively oxidized the pyrite over the course of 10 cycle tests. Each cycle test was identical with regard to volume recharged and recovery, so that each new recharge volume of water repeatedly occupied the same permeable zones (CH2M Hill, 2007c).

### 5.8.2.2 Arsenic Mobilization at Proposed CERP ASR System Locations

A process for minimizing arsenic concentrations in the aquifer was defined using water quality data obtained during four cycle tests at the KRASR system (Mirecki et al., 2012). Because the KRASR system source water differs from that of a potable water system, the patterns of arsenic mobilization differ when the two systems are compared. A remaining question is whether the arsenic control process defined at the KRASR system is applicable to other CERP ASR systems that store lightly treated surface water in permeable zones of the UFA or APPZ. The approach to evaluate arsenic mobilization and control process on a regional basis is predicated on the following assumptions:

- Pyrite occurs as a trace mineral in all marine limestone units that include the UFA and APPZ. Therefore, pyrite oxidation and arsenic release during the recharge phase is expected **(Section 5.8.1).**
- Source water quality characteristics that promote arsenic control in the aquifer are moderately high iron and organic carbon concentrations **(Section 5.1, Table 5-1).**
- The native aquifer is characterized by a sulfate-reducing redox environment

The potential for arsenic control at other proposed CERP ASR systems is based on the similarity of source and groundwater characteristics compared to those at KRASR.

**Source Water Characteristics.** Surface water quality characteristics of major sources of recharge water for ASR systems were defined earlier in this chapter. It is expected that the major sources will be Lake Okeechobee, the Kissimmee and Caloosahatchee Rivers, and the St. Lucie Canal. All of these surface water sources show relatively high concentrations of TOC (**Section 5.1, Table 5-1**; **Figure 5-1)** and iron **(Section 5.1, Table 5-1**; **Figure 5-3).** The exception is for TOC and iron concentrations in the Caloosahatchee River, because the dataset consists of too few samples (n=5, n=9 respectively). Median TOC concentrations range between 13 mg/L and 22 mg/L (KRASR 18 mg/L). Median iron concentrations are more variable, ranging between 81 µg/L and 991 µg/L (KRASR 347 µg/L). All source waters (pending additional data from the Caloosahatchee River) have adequate iron and carbon to initiate geochemical controls on arsenic in the aquifer.

**Redox Environment of the Aquifer**. The redox environment of the native UFA and APPZ was estimated using RFGW native groundwater quality data applied to the Redox Processes Workbook spreadsheet of Jurgens et al. (2009). Concentrations of major electron acceptors that are needed for microbiological metabolism (DO, nitrate, manganese, iron, sulfate) and sulfide are entered, and a redox environment is assigned based on their algorithm and threshold criteria for each electron acceptor concentration. Electron acceptor concentrations and redox environment interpretation are presented for a subset of the RFGW dataset **( Table** 5-4**).** Only samples having sulfide plus all 5 electron acceptor concentrations were used in this analysis.

All groundwater samples have moderate to high concentrations of sulfate and show measureable sulfide, indicating that the process of sulfate reduction has occurred at some point in the aquifer. Of all samples analyzed, over half are interpreted as a “suboxic” redox environment, which indicates low DO conditions but additional data are required to define the dominant redox process. Generally, these samples are depleted in all electron acceptors except sulfate. If microbial metabolism is stimulated under these conditions, the aquifer evolves to become sulfate-reducing (Mirecki et al., 2012). The remaining samples do indicate sulfate-reduction, or mixed sulfate- and ferric iron-reduction are the dominant redox processes that characterize the confined portions of the UFA in south Florida. Sulfate reduction is one of the metabolic reactions that is energetically favorable for native microorganisms in the UFA (Lisle, 2014) and **Section 6.2.3**

**Conclusions.** It is reasonable to extrapolate the geochemical reactions that control arsenic mobility defined at KRASR can be applied to most proposed CERP ASR systems in other basins of south Florida. Relevant source (or surface) water characteristics, primarily iron and organic carbon, have ranges of concentrations that overlap those defined at KRASR. Native aquifer redox conditions in the UFA and also the APPZ also are similar to those at KRASR, in that they represent suboxic or sulfate-reducing redox environments. The native redox environment was characterized as suboxic prior to the initiation of cycle tests at KRASR, but it evolved to sulfate-reducing conditions during the storage and recovery phases of each cycle test, thus enabling co-precipitation of arsenic in a newly formed stable iron sulfide solid.

**Table 5-4 -- Calculation of Dominant Redox Process in the Native UFA and APPZ.** Using the method of Jurgens et al. (2009).

| Sample ID | Location | Aquifer | Dissolved $O_2$, in mg/L | Nitrate $NO_3$- , in µg/L | Manganese $Mn^{2+}$ in µg/L | Ferrous Iron $Fe^{2+}$ in µg/L | Sulfate $SO_4^{2-}$ , in mg/L | Sulfide (sum of $H_2S$, HS-, $S^{2-}$), in mg/L | Redox Assignment | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | General Redox Category | Redox Process |
| DF-4 | Miami-Dade Co., Krome Ave. | UFA | 0 | 0.021 | 16 | 27 | 510 | 0.81 | Suboxic | Suboxic |
| ENP-100 | Miami-Dade Co., Everglades NP | UFA | 0 | 0.023 | 5.8 | 180 | 470 | 1.1 | Anoxic | SO4 |
| G-2618 | Broward Co. Alligator Alley | UFA | 0 | 0.013 | 1.4 | 27 | 540 | 1.9 | Suboxic | Suboxic |
| PBF-3 | Palm Beach Co. Lake Lytal | UFA | 0 | 0.078 | 14 | 200 | 460 | 2.2 | Anoxic | SO4 |
| PBF-10 | Palm Beach Co., HASR | UFA | 0 | 0.013 | 1.4 | 27 | 900 | 2.8 | Suboxic | Suboxic |
| PBF-7U | Palm Beach Co., HASR | UFA | 0 | 0.013 | 17 | 390 | 520 | 2.5 | Anoxic | SO4 |
| MF-52 | Martin Co. at C-44 Reservoir | UFA | 0 | 0.013 | 5.3 | 190 | 230 | 3.9 | Anoxic | SO4 |
| EXPM-1 | Martin Co., PMASR | UFA | 0 | 0.01 | 2 | 48 | 260 | 2.9 | Suboxic | Suboxic |
| SLF-74 | St. Lucie Co. at C-24 canal | UFA | 0 | 0.013 | 1.4 | 360 | 220 | 3.5 | Anoxic | SO4 |
| OKF-42 | Paradise Run ASR, Okeechobee Co. | UFA | 0 | 0.049 | 1.4 | 94 | 110 | 4.3 | Suboxic | Suboxic |
| EXKR-1 | Okeechobee Co., KRASR | UFA | 0 | 0.1 | 3.8 | 28 | 200 | 0.8 | Suboxic | Suboxic |
| OSF-100 | Osceola Co. Intersession City | UFA | 0 | 0.007 | 8.1 | 52 | 64 | 0.5 | Suboxic | Suboxic |
| OSF-66 | Osceola Co. FL Turnpike | UFA | 0 | 0.02 | 1.4 | 27 | 93 | 0.66 | Suboxic | Suboxic |
| LAB-MZ1 | Hendry Co. Labelle | UFA | 0 | 0.007 | 15 | 39 | 370 | 1.3 | Suboxic | Suboxic |
| L2-PW2 | Hendry Co. L2 Basin | UFA | 0 | 0.007 | 3.5 | 59 | 330 | 1.4 | Suboxic | Suboxic |
| EXBRY-1 | CRASR, Hendry Co. | UFA | 0 | 0.1 | 10 | 110 | 250 | 1.9 | Anoxic | SO4 |
| I75-MZ1 | Collier Co. I-75 | UFA | 0 | 0.013 | 7.7 | 27 | 480 | 0.77 | Suboxic | Suboxic |
| IWSD-MZ2 | Collier Co. Immokalee | UFA | 0 | 0.026 | 17 | 375 | 500 | 0.5 | Mixed(anoxic) | Fe(III)-SO4 |
| G-2617 | Broward Co. Alligator Alley | APPZ | 0 | 0.013 | 31 | 27 | 350 | 0.43 | Suboxic | Suboxic |
| PBF-11 | Palm Beach Co., HASR | APPZ | 0 | 0.013 | 15 | 270 | 340 | 1.5 | Anoxic | SO4 |
| TCRK-GW2 | Taylor Creek ASR, Okeechobee Co. | APPZ | 0 | 0.013 | 7.5 | 46 | 280 | 2.6 | Suboxic | Suboxic |
| BSU-MZL | Charlotte Co. Burnt Store | APPZ | 0 | 0.016 | 44 | 3400 | 3000 | 0.5 | Mixed(anoxic) | Fe(III)-SO4 |
| LAB-MZ3 | Hendry Co. Labelle | APPZ | 0 | 0.042 | 17 | 27 | 1700 | 0.87 | Suboxic | Suboxic |

# 6 Fate of Microorganisms and Pathogens During ASR Cycle Testing

Both the ASR Issue Team (1999) and the NRC (2002) recognized that bacteria and pathogens in surface (or recharge) water could compromise native groundwater quality during ASR cycle testing. They recommended sampling and studies to evaluate bacteria and pathogen transport and survival in the aquifer. In addition, compliance with the UIC permit for cycle testing at KRASR and HASR required sampling for a suite of microorganisms (coliforms, enterococci, *Clostridium perfringens*, *Cryptosporidium parvum*, and *Giardia lamblia*) at the ASR wellhead and monitor wells to quantify microbe survival after passage through the UV disinfection system and in the aquifer. Data and interpretations from cycle testing at KRASR and HASR were discussed extensively in USACE and SFWMD (2013), and are summarized in **Section 2.4.4**. The following text summarizes field and laboratory studies that were conducted to quantify microbe and pathogen survival in the FAS. Due to funding limitations, evaluation of microbe transport in the FAS was not initiated.

Studies described in this chapter were conducted to satisfy three objectives: 1) to characterize microbial communities in native FAS groundwater; 2) to examine how microorganisms can alter geochemistry within the FAS; and 3) to quantify survival of surface water microorganisms and pathogens under aquifer conditions. Due to state and Federal regulatory constraints, it is not yet possible to conduct in-situ aquifer studies of microbe and pathogen survival with live microorganisms, similar to those conducted at Australian ASR systems (Pavelic et al., 1998; Gordon and Toze, 2003). In the future, perhaps regulatory approval can be obtained to conduct in-situ experiments.

## 6.1 Bench-Scale Study of Fecal Indicator Bacteria, Bacteriophage, and Protozoan Survival in Florida Surface and Groundwater

A bench-scale study (John and Rose, 2004; 2005; **Appendix D**) investigated the survival of groups of microorganisms that are used as fecal indicator bacteria (FIB) under different water quality conditions. Microbes were incubated under ranges of temperature and total dissolved solids concentrations in representative raw and sterilized surface and groundwaters. The survival (or conversely, inactivation) rates of FIBs were determined in these different aqueous matrices. This research sought to fill data gaps in published literature on environmental conditions that affect survival and inactivation of a suite of microorganisms routinely used to assess the microbiological quality of surface and groundwater. The study was limited to laboratory type (bench-scale) experiments, simulating conditions that occur in the aquifer, although with some simplifications and assumptions.

Two branches of laboratory investigations were performed for this project. Inactivation studies were conducted in artificial water (Instant Ocean; Aquarium Systems Inc., Mentor OH) matrices to isolate the effects of temperature and total dissolved solids (TDS) on test microorganisms. Inactivation studies were conducted in natural surface and ground waters that were either raw or pasteurized, to isolate the effects of temperature and native microbe community on test microorganisms.

Three groups of microorganisms evaluated: (1) two types of FIBs (fecal coliform and enterococci); (2) three types of FIB phages (DNA coliphage, F+ RNA coliphage, and PRD-1); and (3) two pathogenic encysted protozoan parasites, *Cryptosporidium parvum* and *Giardia lamblia.* Bacteriophages are viruses that infect bacteria. The PRD-1 is a large phage that infects *Salmonella* bacteria, and has been used as a tracer of septic tank contamination due to its moderate ability to be transported in aquifer environments (USEPA, 2006a). The coliphages serve as a tracer of fecal contamination in source water as cited by the Groundwater Rule of the SDWA (USEPA, 2006b).

Bench-scale microcosm experiments were performed to evaluate survival of this suite of microbial indicators of water quality over time in water samples held at 5° C, 22° C, and 30° C, and TDS concentrations of 200, 500, 1000, and 3000 mg/L. The duration of these experiments was 28 days. To compare the relative effects of factors such as TDS and temperature, or in natural water trials water type and pasteurization treatment effects, a single comparative statistic was necessary for analysis of variance (ANOVA) tests. In the scientific literature there are typically two ways of analyzing microbial inactivation data. The first method is to plot the decrease in numbers of microorganisms over time and determining the slope of a regression curve. This approach defines a first-order regression model, in which inactivation rates (k; $\log_{10}$ $d^{-1}$) are expressed as a decrease in the number of microorganisms per unit time. The second method is to express the decrease in the number of microorganisms in units of log-reductions or as a ratio or percentage. For example, the EPA regulatory criterion for public drinking water systems is to reduce the surface water concentration of *Giardia lamblia* in the finished drinking water by 3-logs (i.e., a 3-$\log_{10}$ reduction) or by 99.9 percent of its original concentration.

### 6.1.1 Results of Inactivation Experiments in Artificial Waters

Results of inactivation studies in artificial water show a statistically significant increase in first-order inactivation rates for all microorganisms except PRD-1 when temperature increased from 5°C to 30°C (John and Rose, 2004; 2005; **Appendix D**). There was no statistically significant change in first-order inactivation rates for any microorganism when TDS concentrations varied between 200 and 1,000 mg/L. When TDS concentrations increase to 3,000 mg/L, a statistically significant increase in first-order inactivation rate was observed for enterococci and F+ RNA coliphage. However, this effect was also confounded by trends in temperature for F+ RNA coliphage, such that survival was longer at higher TDS concentrations but a lower temperature of 5° C.

The dataset for enterococci inactivation rates was difficult to interpret because trends between inactivation rate versus temperature or TDS concentration were not linear. Inactivation rates on average were greatest at a TDS concentration of 1,000 mg/L but decreased at 3,000 mg/L. Although lower temperature (5°C) decreased inactivation rate, higher incubation temperatures (22°C and 30°C) showed similar 99 percent (2-log) inactivation rates. The similarity between results at 22°C and 30°C incubation temperature suggests that the increase in inactivation rate reaches a maximum toward higher temperatures for enterococci.

### 6.1.2 Results of Inactivation Experiments in Natural Waters

Surface water and FAS groundwater samples obtained from two locations in Florida were utilized for natural water inactivation studies (John and Rose, 2004). Surface water samples were obtained from the Bill Evers (Manatee County, FL) and Clear Lake (Palm Beach County, FL) reservoirs. Groundwater samples were obtained from an APPZ well (ROMP TR4-7; Manatee County, FL) and a UFA well in Lake Lytal Park (PBF-3, Palm Beach County).

There are two objectives for this study. The first objective was to compare the relative effects of temperature, water type, and background microbial community on the 2-$\log_{10}$ inactivation period and first-order inactivation rate constants. Test microorganisms include the PRD-1 phage, *Cryptosporidium parvum*, and *Giardia lamblia*. A pretreatment of the surface and groundwater by pasteurization (70°C for 30 min) was done to inactivate or reduce the concentration of native microorganisms.

The second objective was to characterize the inactivation rates using temperatures typical of the native FAS and recharged surface water. The predicted number of days for 2-$\log_{10}$ inactivation in the raw (unpasteurized) waters, at 22°C and 30°C, were quantified separately from the pasteurized and 5°C test conditions. A first-order inactivation model fit the data from all of tests using pasteurized water at the higher temperatures. The consistency in inactivation models using natural water contrasts the inactivation models from the bench-scale experiments using artificial water. Some tests conducted at 5°C required alternative, higher-order regression models for interpretation (Lisle, 2014).

Inactivation rates for all microorganisms in non-pasteurized, natural waters are compiled in **Table 6-1**. Based on comparative analyses of observed inactivation rates, several statistically significant trends were observed. Inactivation rates increased steadily with increasing temperature, and this was true in both combined raw and pasteurized comparisons. Inactivation rates typically were higher in raw surface water under raw conditions. One exception is the F+ RNA coliphage, which were quite fragile and exhibited relatively rapid inactivation rates under both conditions. The other exception was *Giardia lamblia* cysts. It is not clear why data for *Giardia lamblia* cysts showed decreasing inactivation rate with increasing temperature. It may be the method used for measuring viability was affected by the TDS concentrations or another geochemical constituent of the groundwater. The viability dyes, used for assessing cyst viability are based on the permeability of the membrane. It is conceivable the groundwater constituents affect this permeability. It is known that the dye test is not completely reliable for assessing parasite viability. The viability of *Cryptosporidium parvum* oocysts, on the other hand, is determined via cell culture and is a true measure of inactivation.

The effect of heat pasteurization to reduce native bacterial populations also had a statistically significant effect of reducing inactivation rate of seeded indicator organisms. Decreasing inactivation rates were sometimes more significant in surface water than groundwater, particularly when using enterococci and DNA coliphage test organisms.

**Table 6-1-- Inactivation Rates for Test Organisms in Natural, Non-Pasteurized Groundwater and Surface Water Samples.** Table re-formatted from John and Rose (2004).

| MICROORGANISM | NATIVE GROUNDWATER | | | | NATIVE SURFACE WATER | | | |
|---|---|---|---|---|---|---|---|---|
| | ROMP TR4-7 APPZ WELL | | LAKE LYTAL PBF-3 UFA WELL | | BILL EVERS RESERVOIR, MANATEE CO. | | CLEAR LAKE, WEST PALM BEACH CO. | |
| | 22°C | 30°C | 22°C | 30°C | 22°C | 30°C | 22°C | 30°C |
| *Crypto. parvum* | **0.001** | 0.110 | 0.042 | 0.120 | 0.045 | 0.200 | 0.066 | 0.180 |
| *Giardia lamblia* | 0.040 | 0.098 | 0.030 | 0.110 | **0.005** | **0.081** | **0.0042** | **0.076** |
| PRD-1 | 0.017 | **0.015** | **0.027** | **0.045** | 0.100 | 0.150 | 0.840 | 0.120 |
| DNA coliphage | 0.064 | 0.130 | 0.072 | 0.150 | 0.120 | 0.170 | 0.092 | 0.160 |
| Fecal coliform | 0.100 | 0.170 | 0.065 | 0.150 | 0.250 | **1.00** | 0.170 | 0.300 |
| Enterococci | 0.160 | 0.250 | 0.062 | 0.130 | 0.380 | 0.770 | 0.270 | 0.500 |
| F+ RNA phage | **0.510** | **1.600** | **0.45** | **2.400** | **0.420** | 0.630 | **0.940** | **2.00** |

Notes: 22°C and 30°C are incubation temperatures for each experiment. Slowest rates are red, fastest rates are green. All rates were converted to absolute (non-negative) values for comparison to other studies. Unit is log$_{10}$ d$^{-1}$

Inactivation rates for the different types of microorganisms were determined in natural raw water samples, specifically at temperatures typical of the FAS (22°C to 30°C). For fecal coliforms, 2-log$_{10}$ inactivation was predicted to occur over periods of 1 to 6 weeks in groundwater, and 1 to 2 weeks in surface water. Enterococci 2-log$_{10}$ inactivation ranged from approximately 1 to 5 weeks in groundwater, and approximately 1 week in surface water. A comparison of the two types of coliphage revealed that DNA coliphage was much hardier in the conditions evaluated. DNA coliphage results indicated 2-log$_{10}$ inactivation over periods of 2 to 6 weeks in both water types. In contrast, F+ RNA coliphage showed the fastest 2-log$_{10}$ inactivation of approximately 1 week or less in both surface and groundwater. As expected, PRD-1 in these conditions was the most stable with a 2-log$_{10}$ inactivation rate in the APPZ well water at approximately 6 months at 22°C or 30°C.

A comparison of inactivation rates between bacterial and viral indicators (coliforms, phages, enterococci) and the enteric parasite *Cryptosporidium parvum* indicated slower rates in *C. parvum* in the APPZ at 22°C **(Table 6-1)**. The observed decline was minimal over the course of the experiment. However, *C. parvum* inactivation rates were similar to those of the two bacterial indicators in UFA well water at 22°C and in both groundwater sources at 30°C. A 2-log$_{10}$ inactivation rate for *C. parvum* was predicted to take about 7 weeks at 22°C in Lake Lytal Park UFA water, and 2-3 weeks at 30°C in both groundwater sources. In surface water, 2-log$_{10}$ inactivation of *C. parvum* at 22°C was predicted over 4-7 weeks, and at 30°C in 1-2 weeks. *Giardia lamblia* inactivation rates were significantly lower than the bacterial indicators in ground water at 22°C and 30°C with 2-log$_{10}$ declines predicted in 7-9 weeks at 22°C and 2-3 weeks at 30°C. There was negligible inactivation of *G. lamblia* in surface water at 22°C, while 2-log$_{10}$ declines at 30°C would be predicted in 3-4 weeks. Once again, the method of analysis for *G. lamblia* may have influenced the apparent lack of inactivation since the assay relies only on cyst membrane integrity as an indicator of viability, not actual viability or infectivity. With the exception of APPZ groundwater at 22°C, inactivation rates of the *C. parvum* and *G. lamblia* were similar in groundwater at these temperatures.

Major conclusions of this study were:

- TDS concentrations in the range of 200 mg/L to 1,000 mg/L (artificial water matrix) had no statistically significant effect on inactivation rates using any test microorganism.
- Higher temperature (22°C and 30°C) in TDS-temperature experiments with artificial water increased inactivation rates of all test microorganisms, although trends using enterococci and F+ RNA coliphage were not as strong.
- Fecal coliform, enterococci, DNA coliphage, PRD-1 and *Cryptosporidium parvum* all had greater inactivation rates in surface water than in groundwater. In contrast, RNA coliphage and *Giardia lamblia* had greater inactivation rates in groundwater than surface water.
- For fecal coliform, 2-$\log_{10}$ inactivation was predicted over periods of 2 to 6 weeks in groundwater and 1 to 2 weeks in surface water; enterococci 2-$\log_{10}$ inactivation rates ranged from 1 to 5 weeks in groundwater, and about 1 week in surface water sources.
- The enteric parasites and the DNA coliphage were much more resistant than the fecal coliform or enterococci. It would take an estimated 7 months to achieve a 2-$\log_{10}$ inactivation of *Giardia lamblia* cysts in surface water; 1 to 4 months would be required for DNA coliphage and *Cryptosporidium parvum* oocysts.
- Bacterial or coliphage indicators are not adequate indicators of the human health risks potentially associated with the co-presence of the enteric protozoa due to the significantly reduced inactivation rates of the latter.
- Site-specific monitoring of sites using water containing these organisms should be required until those conditions that inhibit or enhance inactivation of the most resistant microorganisms can be better defined.

## 6.2 Field Study to Quantify Survival of Bacterial Indicators and the Functional Diversity of Native Microbial Communities in the Floridan Aquifer

In order to better define inactivation rates of microbiological indicators under aquifer conditions, a field study was initiated to expose selected microorganisms to Floridan Aquifer groundwater in above-ground, flow-through mesocosms (Lisle, 2014; **Appendix D**). In support of this objective, biogeochemical analyses of groundwater samples was completed, to characterize the geochemical environment in which ambient microbial communities currently subsist within the FAS. Members of the native microbiological communities within the aquifer were identified, to better understand their biogeochemical processes under native aquifer conditions. Biogeochemical characterization under native conditions can serve as a baseline for comparison of conditions during or after ASR cycle testing.

### 6.2.1 Experimental Design and Sampling Methodology

Inactivation rate experiments were performed using a unique flow-through mesocosm equipped with inoculated diffusion chambers **(Figure 6-1).** This above-ground, flow-through mesocosm system was constructed so that native groundwater geochemical conditions (other than pressure could be maintained). Mesocosm influent was directly connected to an FAS wellhead, enabling consistent groundwater flow through the system. No pumps were needed because all wells flowed under artesian conditions.

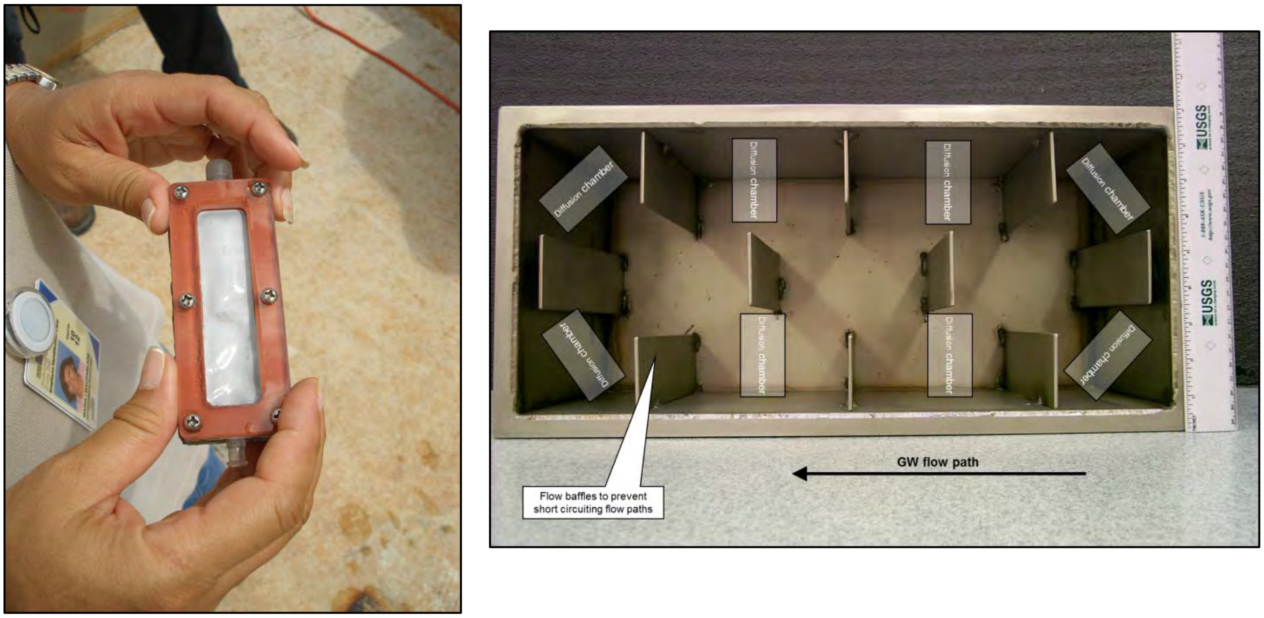


**Figure 6-1 -- Photographs showing a diffusion chamber (left), and orientation of diffusion chambers in a flow-through mesocosm (right).** Photos from Lisle (2014).

Mesocosm chambers were connected to the wellhead sampling taps at each of the wells, and water from the UFA was allowed to flow through the mesocosm and pass through diffusion chambers. Each diffusion chamber contained live populations of *Escherichia coli* or *Pseudomonas aeruginosa* strains that had originally been isolated from fresh water sources. Data on in-situ inactivation and survival of FIBs in the FAS are not readily available. The *E. coli* strain is the most recognizable member of the FIB group, and the *P. aeruginosa* strain was selected as an emerging opportunistic pathogen of public health concern in recreational waters. Both bacterial strains were grown, processed, and loaded in the diffusion chambers.

The diffusion chambers used in this study are a modified design of the McFeters and Stuart (1972) diffusion chamber. The diffusion chambers retained the bacterial suspensions using 0.02 µm pore–sized membranes. Inoculated bacterial suspensions were isolated from predation by native bacteria, while allowing the diffusion of dissolved groundwater constituents (e.g., nutrients, trace elements, gases) through the chambers. Due to access constraints and the multiple time point sampling design of the experiments, down–well deployments of the diffusion chambers were not practical. The above-ground mesocosm system design allowed easy access to the diffusion chambers while insulating the chambers from the elevated outside surface temperatures and minimizing alterations in the geochemistry of the native groundwater.

A flow-thru mesocosm was set up for each well listed in **Table 6-2**. At specific time points a set of diffusion chambers that contained either *E. coli* or *P. aeruginosa* cultures was removed from the mesocosm and processed for culturability. The *E. coli* cultures were plated on mTEC agar, *P. aeruginosa* cultures on PIA agar and both were plated on R2A agar. All plating and incubation conditions were performed as recommended by the manufacturer and defined by regulatory standards, if applicable.

To conduct the biogeochemistry study, three monitor well "pairs" were selected, so that UFA and APPZ could be utilized at a single site. Groundwater samples from each site were analyzed for a full suite of major and trace inorganic constituents, including major redox pairs (sulfate/sulfide, ferric and ferrous iron, dissolved oxygen and hydrogen, and methane), nutrients, carbon species (DOC, alkalinity, inorganic carbon), and many carboxylic acids that serve as microbe substrates. These data were used in the thermodynamic calculations to determine the available energy for bacterial survival and growth in the native aquifer water. Additionally, samples were processed and stained for determining the number of native bacteria in each groundwater site using SYBR Gold and epifluorescent microscopy. The locations of the well pairs are shown on **Figure 6-2**. Well locations and characteristics are shown in **Table 6-2**.

To conduct that native bacterial diversity study, samples were collected from the same monitor well pairs into sterile 20 liter carboys during three sampling events. A cartridge filter was then connected to each carboy and, under gravity–induced flow, allowed to filter until flow had stopped. After removing the cartridge filter, its protective housing was removed and the filter transferred to a sterile container. The filters were shipped to Second Genome, Inc. for DNA extraction, amplification and application on their proprietary PhyloChip™ G3 Array technology. The PhyloChip™ G3 microarray is capable of identifying approximately 60,000 operational taxonomic units (OTU) that represent approximately 840 subfamilies within the Eubacteria and Archaea kingdoms.

**Figure 6-2 -- Locations of FAS monitor well pairs sampled in the field inactivation study**. Image from Lisle (2014).

**Table 6-2 -- FAS Well Names and Characteristics**

| Well Name | Station Name | Florida County | Location | | Aquifer | Casing Diameter (inches) | Production Interval (bls) | Screen Type |
|---|---|---|---|---|---|---|---|---|
| | | | Latitude | Longitude | | | | |
| MZ1 | LAB-MZ1 | Glades | 26° 45' 11.42" | -81° 21' 17.72" | UFA | 18 | 670-837 | Annular |
| MZ3 | LAB-MZ3 | | | | APPZ | 7 | 1645-1759 | Open |
| 42U | HIF-42U | Highlands | 27° 13' 11.16" | -80° 57' 21.98" | UF | 24 | 560-1040 | Annular |
| 42L | HIF-42L | | | | APPZ | 14 | 1310-1540 | Open |
| 15U | PBF-15U | Palm Beach | 26° 44' 16.08" | -80° 21' 48.68" | UF | 18 | 908-1144 | Annular |
| 15M | PBF-15M | | | | APPZ | 12 | 1400-1583 | Annular |

### 6.2.2 Bacterial Indicator Inactivation Results

The colony counts for *E. coli* and *P. aeruginosa* from each of the mesocosm experiments followed a bi-phasic model **(Figure 6-3)**. This bi-phasic model describes the inactivation of bacterial communities that can be subdivided into two subpopulations. One subpopulation is more susceptible to inactivation than the other, which generates an inactivation curve with an initial steep and negative slope that represents the inactivation of the first microbial subpopulation. The curve then transitions into a tail with a significantly smaller negative slope, which represents the inactivation of the second microbial subpopulation. The two subpopulations are assumed to be independently and irreversibly inactivated with the respective inactivation rates following first-order reaction kinetics.

The *E. coli* populations had slower inactivation rates in the UFA groundwater (range: 0.217 to 0.628 $hr^{-1}$) during the first phase of the model than those exposed to APPZ groundwater (range: 0.540 to 0.684 $hr^{-1}$). These same populations had significantly slower inactivation rates during the second phase of the model, ranging from 0.006 to 0.001 $hr^{-1}$ and 0.013 to 0.018 $hr^{-1}$ for the UF and APPZ, respectively, with the APPZ rates again being greater. Published inactivation rates of *E. coli* when retained in membrane diffusion chambers similar in design to those used in this study and exposed to diverse groundwater sources range from 0.004 to 0.029 $hr^{-1}$.

The inactivation rates for the first phase of the inactivation models for *P. aeruginosa* were not significantly different between the UFA (range: 0.144 to 0.770 $hr^{-1}$) and APPZ (range: 0.159 to 0.772 $hr^{-1}$) groundwaters. The inactivation rates for the second phase of the model for this bacterial species were also similar between UFA (range: 0.003 to 0.008 $hr^{-1}$) and APPZ (0.004-0.005 $hr^{-1}$) groundwaters, though significantly slower than the model's first phase rates. There are currently no inactivation data for *P. aeruginosa* in groundwater that is geochemically similar to that in UFA and APPZ for comparison.

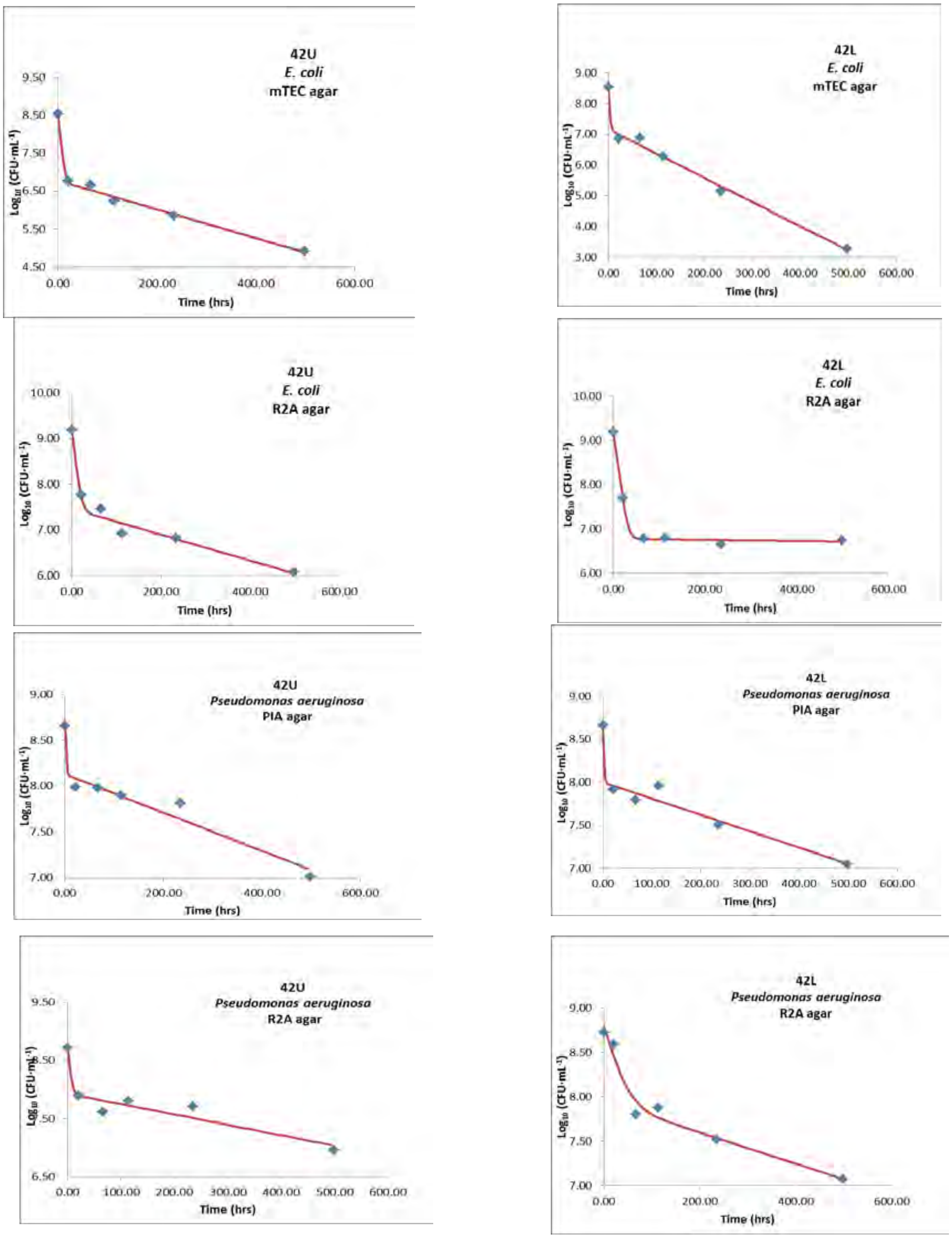


**Figure 6-3 -- Graphs showing *E. Coli* and *P. aeruginosa* inactivation curves for the 42U and 42L samples.** 42U is open to the UFA, 42L is open to the APPZ. Figure from Lisle (2014).

Inactivation rates determined in Lisle (2014) differ from those presented in John and Rose (2004) in several ways. First, the models used for inactivation rate calculations differ, with John and Rose (2004) using a linear model, while Lisle (2014) uses a bi-phasic model. Second, inactivation rates for fecal coliform (John and Rose, 2004) in bench-top experiments are much slower than those estimated for *E.*

*coli* in the field study even when rates are adjusted to the same unit ($\log_{10}hr^{-1}$; **Table 6-3**). The second phase of all bi-phasic curves of Lisle (2014) more closely approximates the linear rates calculated by John and Rose (2004). Because the field mesocosms most closely replicate aquifer conditions with regard to temperature and water quality, these higher inactivation rates serve as a better guideline for ASR operations.

**Table 6-3 -- Comparison of Coliform Inactivation Rates Between Bench Top and Field Studies.**

| Microorganism | Test Condition | Model | Rate | Unit | Reference |
|---|---|---|---|---|---|
| Fecal coliform | raw UFA water, 22°C, bench top | Linear | 0.003 | $\log_{10}hr^{-1}$ | John & Rose (2004) |
| Fecal coliform | raw APPZ water22°C, bench top | Linear | 0.004 | $\log_{10}hr^{-1}$ | John & Rose (2004) |
| *E. coli* | UFA, 29°C, field mesocosm | Biphasic, 1st phase | 0.217-0.628 | $\log_{10}hr^{-1}$ | Lisle (2014) |
| *E. coli* | UFA, 29°C, field mesocosm | Biphasic, 2nd phase | 0.001-0.006 | $\log_{10}hr^{-1}$ | Lisle (2014) |
| *E. coli* | APPZ, 28°C, field mesocosm | Biphasic, 1st phase | 0.540-0.684 | $\log_{10}hr^{-1}$ | Lisle (2014) |
| *E. coli* | APPZ, 28°C, field mesocosm | Biphasic, 2nd phase | 0.013- 0.018 | $\log_{10}hr^{-1}$ | Lisle (2014) |

To place the *E. coli* inactivation rates in a more applied context, an example that uses data from the HASR pilot system treatment facility is presented. The pumping rate for recharge water by this facility is 5 MGD. This facility has detected *E. coli* in the recharge water at a concentration ranging from below detection (<1.0 CFU 100 $mL^{-1}$) to 65 CFU 100 $mL^{-1}$. At this recharge rate and maximum *E. coli* concentration, there could be $1.23 \times 10^{10}$ *E. coli* introduced into the aquifer at the completion of a 1-day recharge event. The bi-phasic model used to calculate the inactivation rate data assumes that both subpopulations independently follow first order reaction kinetics, which permits the use of Chick's Law for calculating the times required for total inactivation of both subpopulations. The most familiar form of Chick's Law follows an exponential decay function, and is shown as follows:

$$N_t/N_0=e^{-kt}$$

Where:

$N_t$ is the concentration (CFU per milliliter) of injected bacteria at time $t$ (hours),
$N_0$ is the concentration (CFU per milliliter) of bacteria at the end of the recharge event, and
$k$ is the inactivation rate constant (per hour).

The variable $N_t$ is set at 0.9 (assuming a value of <1.0 CFU represents total inactivation), $N_0$ is adjusted for the respective subpopulations using the $f$ or $1\text{–}f$ values, and the $k_1$ and $k_2$ values from inactivation curves are used with the appropriate $N_0$ values. Solving for $t$ yields an estimate of the length of storage time required for the respective subpopulations of *E. coli* to be reduced to less than 1.0 CFU. The more sensitive subpopulation of *E. coli* ($k_1$ data) was reduced to less than 1.0 CFU in all the wells at a similar rate when using mTEC agar, ranging from 1.4 to 4.5 days **(Table 6-4).** The same subpopulation on R2A agar was completely inactivated at a generally slower rate, ranging from 1.6 to 5.6 days.

The more resistant subpopulations ($k_2$ data) were inactivated at significantly slower rates, regardless of which medium was used. Using the mTEC agar data, this *E. coli* subpopulation was inactivated after 1.5 to 3.7 months of storage in the respective aquifer zones. The R2A agar data were generally slower than the rates calculated from the mTEC agar data, ranging from 3.1 to 9.5 months for 42U, 15M, MZ1, and MZ3, and 7.1 years for 42L. The outlier in the dataset is for 15U, where a predicted > 120.6 years of storage are required to totally inactivate the more resistant *E. coli* subpopulation to less than 1 CFU **(Table 6-4 ).**

**Table 6-4 -- Estimated Storage Time to Achieve 1.0 CFU in Recovered Water at Proposed CERP ASR System Sites.** Table reformatted from Lisle (2014)

| Bacterium | Media | Inactivation Rate Curve Phase | Time | Well Designation | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 42U | 42L | 15U | 15M | MZ1 | MZ3 |
| *E. coli* | mTEC | $K_1$ | days | 3.3 | 1.4 | 4.5 | 1.8 | 1.5 | 1.7 |
| | | $K_2$ | months | 3.1 | 1.5 | 3.7 | 1.9 | 2.4 | 2.1 |
| | R2A | $K_1$ | days | 5.3 | 5.6 | 4.8 | 5 | 1.6 | 3.8 |
| | | $K_2$ | months | 4.1 | 84.8 | >247.5 | 9.5 | 3.1 | 6.7 |

### 6.2.3 Bacterial Abundance in Native FAS Groundwater

The mean bacterial abundances in all native FAS groundwaters were relatively consistent, ranging from $3.92\times10^4$ cells $mL^{-1}$ to $8.01\times10^5$ cells $mL^{-1}$. Additionally, native groundwaters from each well were collected during each sampling event and filtered or directly plated onto various media used in the inactivation experiments. None of the native groundwater samples produced colonies on the *E. coli* medium (i.e., mTEC agar), however, an average 0.7 CFU $mL^{-1}$ of *P. aeruginosa* were recovered on PIA agar and 0.7 CFU $mL^{-1}$ on R2A agar. The recovery of culturable bacteria from the native groundwaters on the non–selective PIA and R2A agars is not surprising as these ground water systems contain viable bacteria, and both media promote the recovery of heterotrophic bacteria, regardless of their identity. More importantly, the numbers of culturable bacteria on these media were not great enough to influence the colony counts of *E. coli* or *P. aeruginosa* recovered from the diffusion chambers even if a contamination event (e.g., ruptured membrane, leaky chamber gasket) were to have occurred.

### 6.2.4 Bacterial Diversity in Native FAS Groundwater

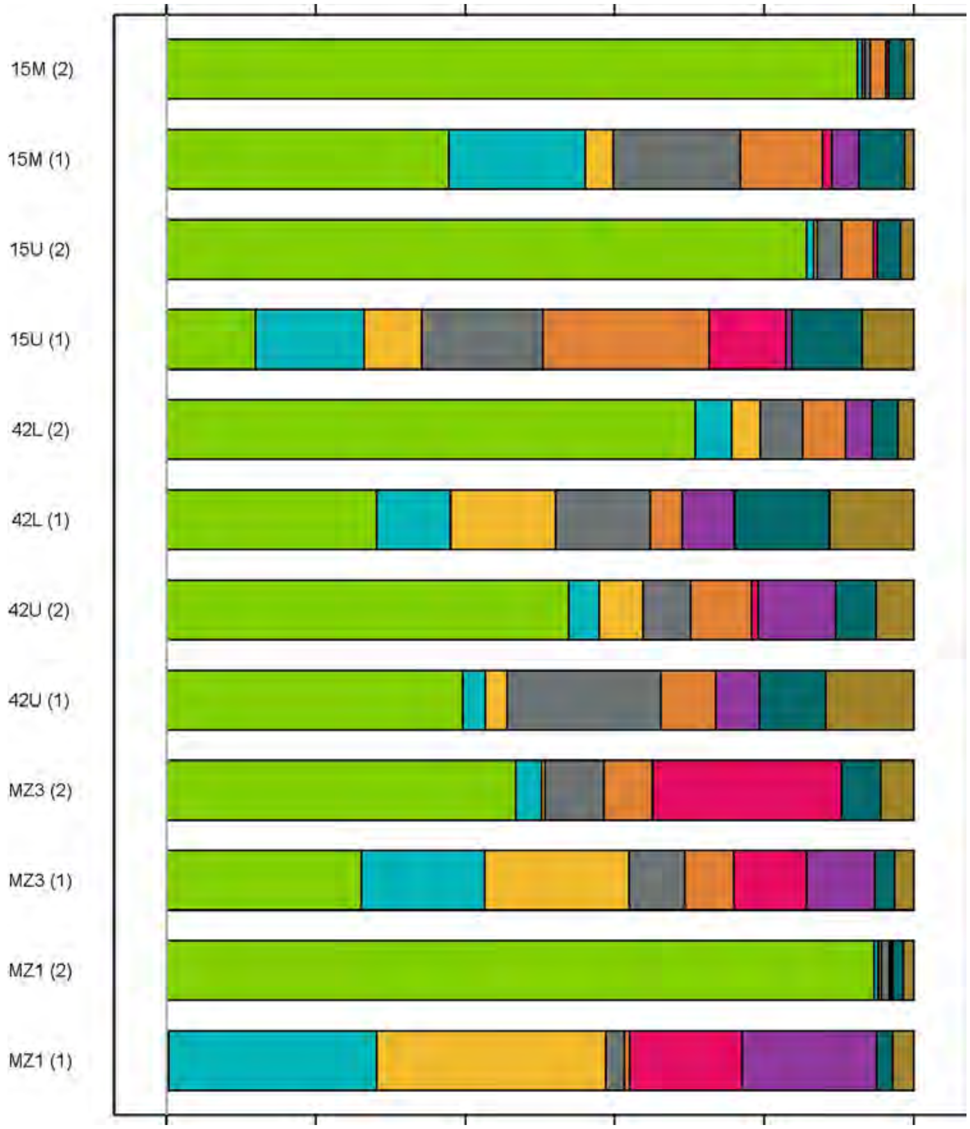
Native bacterial communities are viable and productive inhabitants of all subsurface biospheres, including the UFA. These communities are capable of aerobic, fermentative and anaerobic respiration which can significantly influence the rates of mineral dissolution/precipitation and the fate and transport of metals, nutrients, organic substrates and greenhouse gases within the aquifer. The by–products of these processes can dramatically alter the native geochemistry along a natural flow path and along a similar flow path within an artificially recharged or contaminated zone of an aquifer (Chapelle.

The first step in characterizing the types and rates of microbial processes that can alter geochemistry in an aquifer is to identify members of the native microbial community. To accomplish this, a high throughput microarray platform technology, PhyloChip™ G3, was used to characterize the functional diversity in the native aquifer bacterial communities (bacteria and archaea). Approximately 76 percent of the operational taxonomic units (OTUs) from the native bacteria in these UFA samples were categorized as "unclassified", meaning the sequence could not be definitively classified to the family, genus or species level **(Figure 6-4).**

The next step in constraining the native biogeochemistry is to use the native microbial community diversity data to corroborate the theoretical occurrence of a biogeochemical process based on energetics with the presence of one or more bacterial phylotypes capable of performing that process. The bacterial diversity in the groundwater samples was dominated by members of the Pseudomonadaceae and to a lesser extent by members of Anaerolineaceae, Desulfobacteraceae, Peptostreptococcaceae, Lachnospiraceae and Ruminococcaceae families and the phylum Euryarchaeota. The physiological capabilities of members within these groups have been shown to include the biogeochemical processes of primary and secondary fermentation, acetogenesis, and methanogenesis, and anaerobic methane oxidation, syntrophy with methanogens, ammonification and sulfate reduction. The functional bacterial diversity data support the likelihood of the energetically favorable biogeochemical reactions being present in this region of the Floridan Aquifer and provides insight into the capacity of the native bacterial communities to perform additional types of processes that would be required to sustain viability over geologic time scales and alter the geochemistry of native and recharged water.

A total of 3634 unique OTUs were detected in the groundwater samples from the six well sites, representing approximately 6.1 percent of the total OTUs on this version of the PhyloChip™ microarray. The bacterial diversity, used here and henceforth to collectively refer to eubacterial and archaeal OTUs, was similar between the two sampled depths for the 42 and 15 wells but significantly different at the MZ well site, with MZ3 (in the APPZ) having a more diverse community structure than that in MZ1 (in the UFA). The MZ3 zone has been shown to be the more unique groundwater source of the six sampled based on field, nutrient, geochemical and energetics data (Lisle, 2014).

Interestingly, the number of OTUs defined in the second sampling event increased significantly over the first event in most of the wells. For all the groundwater samples, the number of OTUs that were common to both events at each well was less than the number unique to the individual samples. For example, the 42U samples (from the UFA) had a total of 647 OTUs, of which 86 were unique to the first sample, 424 were unique to the second sample, 132 were found in both samples and 2987 OTUs were not detected in 42U but were detected in one or more of the other groundwater samples. These same relationships are similar for the other five sites.



| | Domain | Phylum | Class | Order | Family |
|---|---|---|---|---|---|
| 🟩 | Bacteria | Proteobacteria | Gammaproteobacteria | Pseudomonadales | Pseudomonadaceae |
| 🟦 | Bacteria | Firmicutes | Clostridia | Clostridiales | Peptostreptococcaceae |
| 🟨 | Bacteria | Firmicutes | Clostridia | Clostridiales | Lachnospiraceae / Ruminococcaceae |
| ⬛ | Bacteria | Chloroflexi | Anaerolineae | Anaerolineales | Anaerolineaceae |
| 🟧 | Bacteria | Proteobacteria | Deltaproteobacteria | Desulfobacterales | Desulfobacteraceae |
| 🟪 | Bacteria | Actinobacteria | Actinobacteria | Actinomycetales | Micrococcineae |
| 🟪 | Bacteria | Bacteroidetes | Bacteroidia | Bacteroidales | Prevotellaceae |
| 🟩 | Archaea | Crenarchaeota | Thermoprotei | unclassified | unclassified |
| 🟫 | Archaea | Euryarchaeota | Thermoplasmata | SAGMEG_unclassified | unclassified |

**Figure 6-4 -- OTU distributions for each well at both sampling events.**

The significant change in the bacterial diversity between the first and second sampling events cannot be explained by the introduction of new biomass and nutrients from a surface or near–surface source into this hydrologically isolated region of the UFA. The only perturbation to this ecosystem was the relatively rapid movement of groundwater near the production zones during the flushing of each well prior to sample collection. This movement of water also increases the relative concentrations of organic and inorganic carbon and nutrients delivered to the surfaces of bacterial cells associated with biofilms in the affected areas of the aquifer. The increased carbon and nutrients is assumed to promote bacterial cell growth and increase in biomass in those bacterial groups that can most rapidly respond to this stimulus. These rapidly responding groups will be numerically dominant over those bacteria who cannot respond as rapidly, whose abundances will be relatively reduced, though still present in the bacterial community. A similar response at the bacterial community diversity level would be predicted following a recharge event along with dramatic changes in the geochemistry of those same waters.

# 7 Development and Simulations using the ASR Regional Study Groundwater Flow and Solute Transport Model

The primary objective of the CERP is the "restoration, preservation, and protection of the south Florida Ecosystem while providing for other water-related needs of the region, including water supply and flood protection (WRDA, 2000)." ASR is one of the alternatives proposed by the CERP to provide long-term storage of excess water, resulting in a more stable water supply in South Florida. The original CERP recommends the construction of 333 ASR wells completed in the Floridan Aquifer System (FAS) and distributed over a large region surrounding Lake Okeechobee. In order to evaluate ASR, an intensive modeling effort was undertaken to evaluate potential impacts of CERP ASR. This chapter summarizes the distinct stages that were followed for the ASR Regional groundwater effort. Additional detail is provided in Appendix E.

## 7.1 Study Goals and Performance Objectives

The first and most important step in the modeling process is to define clear, achievable goals and objectives based on the desired end results for the models. Both the modeling team and the end user must keep the end goal in mind and have a clear understanding of the capabilities and limitations of the model. Together with the ASR Pilot Projects and the ASR Contingency Plan, the ASR Regional Study endeavored to reduce technical uncertainties associated with the proposed CERP ASR. A Project Management Plan (PMP) was prepared for the ASR Regional Study in 2003. This PMP was developed prior to any groundwater modeling work and defined general study goals to be addressed with the groundwater models. These general study goals included local, sub-regional, and regional-scale concerns including the following:

1. Regional changes in aquifer heads and flows
2. Regional changes in aquifer water quality TDS, sulfate, and chloride
3. Increased potential for salt-water intrusion caused by ASR pumping
4. Regional impacts to existing well users of the FAS
5. ASR well cluster site selection
6. ASR well cluster design and layout
7. ASR well cluster performance including estimating recovery efficiency
8. ASR well site evaluation of pressure induced changes
9. Localized transport of contaminants including heavy metals or pathogens
10. Localized ASR well pump design (dependent upon the appropriate model resolution)

Goals 7, 9 and 10 are related to local-scale issues and are not addressed in the ASR Regional Study; however, they are addressed in sub-regional models prepared for the pilot ASR systems (USACE and SFWMD, 2013). The remaining seven PMP goals were addressed by the ASR Regional Study and are discussed in this chapter. The goals fall into two major categories: (1) evaluation of regional changes to the groundwater flow and water quality, and (2) development of viable ASR well cluster designs. As the ASR Regional study evolved, a better understanding of the groundwater flow system was developed. In order to assess the viability of various CERP ASR well cluster designs, the PDT developed several performance objectives by which the regional model simulations were evaluated. These performance objectives better quantify evaluation metrics based on general study goals from the PMP and include:

1. Rock Fracturing – Determine whether or not CERP ASR would result in aquifer pressures that cause fracturing of the rock during ASR recharge. If rock fracturing were to occur, it could result in significant, permanent changes to the subsurface hydrogeologic conditions of South Florida.
2. Pump Pressure – Ensure that the pressure that any ASR well would need to overcome during recharge did not exceed 100 psi.
3. Artesian Pressure Protection Area (APPA) – Ensure that artesian flow in Martin and St. Lucie Counties was not reduced by more than 10 percent as a result of CERP ASR operations.
4. Head Impacts – Define potential reduction in water levels in wells operated by neighboring water users during the recovery phase of an ASR cycle test.
5. Water Quality Migration and Salt Water Intrusion – Evaluate whether recharge of fresh water will displace low quality water into the zone of influence of a water supply well and determine the possible effect of ASR pumping on coastal salt water intrusion.
6. Ability to Provide Storage/Recovery – Identify the volume of storage and recovered water that can be provided by ASR well clusters once the other performance measures have been satisfied.

## 7.2 Modeling Approach

In order to model the complex density-dependent groundwater flow in southern Florida and the impact of CERP ASR on the flow regime, a multi-stage approach was initiated to evaluate the proposed CERP ASR system. The following is a brief summary of the five distinct stages used for the ASR regional modeling.

***Compilation of Existing Groundwater Studies***

- Research and review of numerical modeling efforts performed in south Florida, the preliminary hydrogeologic framework, and the carbonate aquifer dispersion database study.
- Develop a summary of the parameters and methodologies used on similar groundwater modeling efforts.
- Develop recommendations for subsequent stages of the ASR regional groundwater modeling.

***Bench Scale Study***

- Evaluate available groundwater modeling codes and determine their applicability to ASR regional modeling.
- Provide a preliminary understanding of model development issues relating to resolution requirements, boundary types, and starting conditions.
- Uncover limitations and short comings of each model.
- Determine the appropriate modeling code for subsequent stages of work.

***Phase I Study***

- Identify model boundaries and test model boundary parameters.
- Identify regional flow and salt migration pathways.
- Identify the timing of salt water intrusion.
- Evaluate model run times and model sensitivity to time step sizes.
- Test hydraulic and transport parameter sensitivity.
- Compare numerical model results (WASH123D and SEAWAT).

***Phase II Calibration (Regional ASR Study Model, RASRSM)***

- Identify areas of the Phase I Study model for refinement.
- Incorporate regional-scale transient groundwater withdrawal.
- Select sites and determine refinement locations to incorporate ASR well field clusters.
- Calibrate density-dependent flow and transport results to observed measurements in major geologic units.

***D13R Predictive Simulations (RASRSM-D13R)***

- Use the Phase II Calibration model to develop a predictive tool to evaluate CERP ASR.
- Use the D13R Scenario of the South Florida Water Management Model (SFWMM-D13R) to develop pumping rates for long term ASR operational simulations on the RASRSM.
- Use the RASRSM-D13R to evaluate CERP ASR against performance measures developed by the PDT.
- Determine if modifications of the proposed 333 CERP ASR system are needed to meet performance objectives.
- Use a Monte Carlo analysis to evaluate the uncertainty in the predictive scenario results in a probabilistic manner.

## 7.3 Supporting Studies

The following subsections provide an overview of the regional groundwater modeling studies performed in support of CERP ASR. Additional details related to each study can be found at http://www.evergladesplan.org/pm/projects/pdp_32_33_34_44_asr_combined.aspx#groundwater .

### 7.3.1 Existing Groundwater Model Compilation and Summary

A substantial amount of research and modeling had been performed on the FAS prior to the ASR Regional Modeling effort. In 2005, CH2M HILL was contracted by the USACE to compile and review the preliminary hydrogeologic framework and modeling studies developed previously for south Florida up to that point in time (CH2M Hill, 2005). This compilation formed the background for the conceptual model upon which the initial ASR regional models were developed. The conclusions of this study were used to provide specific recommendations for future model development.

The models compiled and summarized in this study included:

1. Peninsular Model (Sepúlveda, 2002)
2. Southern District Model (Beach and Chan, 2003)
3. Eastern Tampa Bay Model (Barcelo and Basso, 1993)
4. HydroGeoLogic Model (HydroGeoLogic, 2002)
5. SWFWMD District Wide Regulatory Model (ESI, 2004)
6. Lee County Model (Bower et al., 1990)
7. Lower East Coast Floridan Aquifer Model (SFWMD, 1999)
8. East-Central Floridan Aquifer Model (McGurk and Presley, 2002)

Based on the data reviewed, CH2M HILL (2005) recommended construction of a 12- to 14-layer model to be run using finite-element groundwater modeling software. This layering scheme included six semi-confining/confining units and six permeable units. The permeable units consisted of the Surficial Aquifer System (SAS), Intermediate Aquifer System (IAS) , Upper Floridan Aquifer (UFA), Middle Floridan Aquifer (MFA, later defined as the Avon Park Permeable Zone or APPZ), Lower Floridan Aquifer (LF1), and the Boulder Zone (BZ). Preliminary recommendations were also provided for model grid or mesh spacing. These model layering recommendations and information from the compiled models guided ASR Regional Model development. Additional details related to this study can be found in CH2M HILL (2005).

### 7.3.2 Bench Scale Study

Subsequent to completion of the PMP, advances in model software made the use of a density-dependent groundwater modeling codes more feasible. However, concerns related to model run time, schedule constraints, and resource availability called into question the feasibility of using a fully density-dependent groundwater model of the scale needed to evaluate CERP ASR. In order to balance the needs of the project with the technical capabilities of software and hardware available at the time, the model development team recommended the development of a bench scale model to evaluate various model codes and approaches. The primary objectives of the bench scale modeling effort were:

- Provide an improved estimate of model run times for long term simulations.
- Provide a preliminary understanding of model development issues relating to resolution requirements, boundary types, and starting conditions.
- Uncover model limitations and short comings.

Bench testing of several model codes provided a solid basis for model code selection. The four codes selected for the bench scale study were: WASH123D; MODFLOW/MT3DMS; SEAWAT; and SWI. WASH123D (Yeh et al., 1998) is a finite-element numerical model designed to simulate variably saturated, variable-density water flow and reactive chemical and sediment transport in watershed systems. MODFLOW (Harbaugh et al., 2000) is a groundwater modeling code that numerically solves the three-dimensional groundwater flow equation for a porous medium using a finite-difference method. MT3DMS (Zheng and Wang, 1999) is a computer program for modeling multispecies solute transport in three-dimensional groundwater systems using multiple solution techniques, including the finite-difference method, the method of characteristics (MOC), and the total-variation-diminishing (TVD) method. For the bench scale study, the MODFLOW and MT3DMS codes were run in a coupled manner to simulate both flow and transport; however, these coupled MODFLOW/MT3DMS simulations did not simulate the variable density of the fluid in the model domain. The SEAWAT program (Guo and Langevin, 2002) is a combination of MODFLOW and MT3DMS designed to simulate three-dimensional, variable-density, groundwater flow and solute-transport. The Sea Water Intrusion (SWI) package (Bakker and Schaars, 2002) is intended for the modeling of regional seawater intrusion with MODFLOW 2000. Other codes such as SUTRA (Voss and Provost, 2002) and FEFLOW (DHI-WASY, 2014) were also considered but rejected. SUTRA has been used for past ASR simulation studies so that some of its advantages and disadvantages were already known. FEFLOW is a proprietary code from Europe that would have been difficult to procure for U.S. Government work efforts.

A 40-mile by 40-mile box model was developed using each modeling code. This model extended vertically from the ground surface through the Floridan Aquifer System (FAS) to the base of the Boulder Zone (BZ). **Figure 7-1** and **Figure 7-2** show the vertical resolution used in the finite element and finite difference bench scale models, respectively.

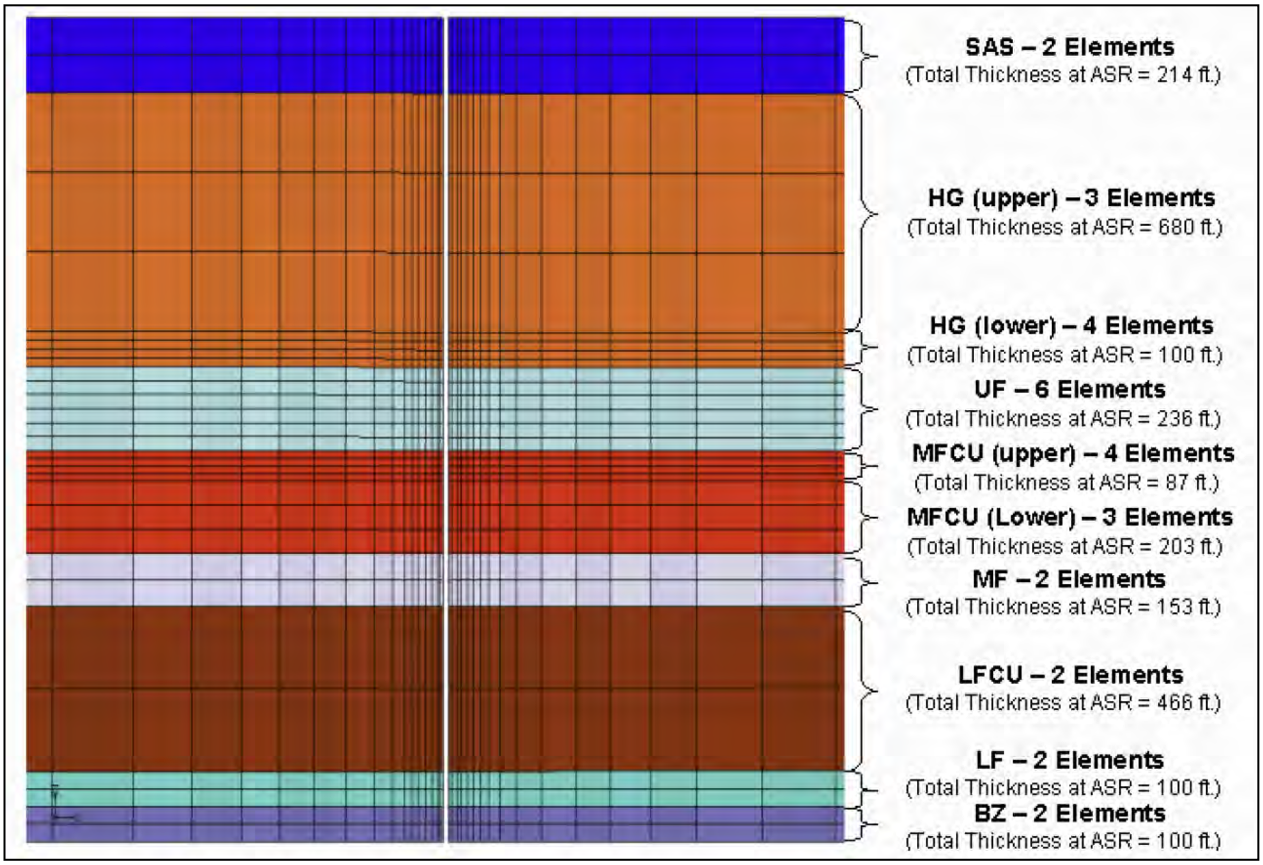


**Figure 7-1 -- Vertical mesh resolution (finite element).**

Although the vertical resolution varied due to the inherent differences between finite element and finite difference solutions, the geologic layering used for each model remained the same to facilitate comparison. Identical hydrogeologic properties, boundary conditions and initial salinity distributions were used for each model. Five separate cases were selected to evaluate relevant ASR modeling issues including mixing, hydrodynamic dispersion, density stratification, upconing, and changes in salinity distribution as a result of ASR recharge and/or recovery. The numerical results and model run times for each code were evaluated and used to determine the best path forward for the regional scale modeling.

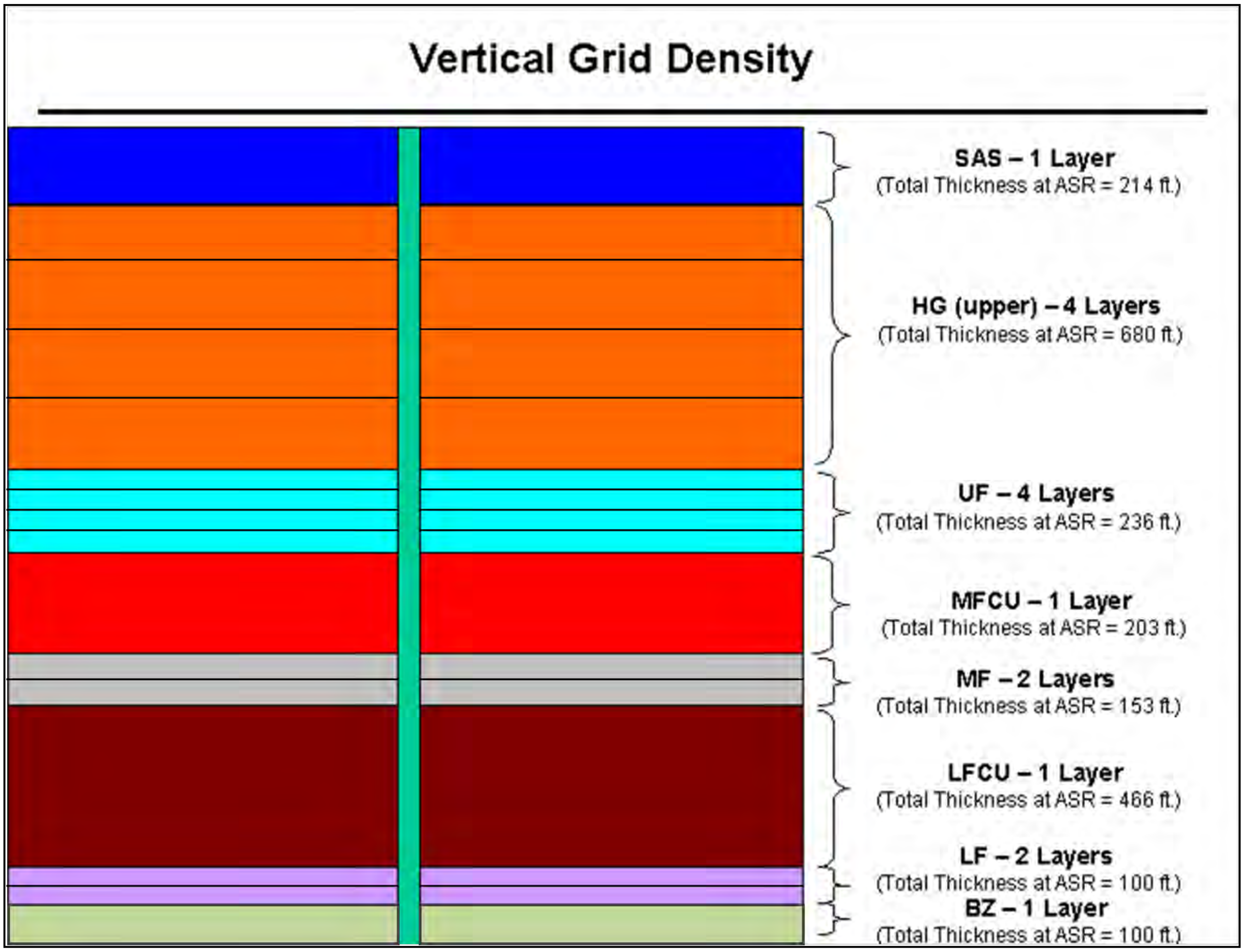


**Figure 7-2 -- Vertical grid resolution (finite difference).**

This bench scale study was useful for comparison of four different model codes under consideration for use in development of a regional ASR model. Each code exhibited both strengths and weaknesses. As shown in **Table 7-1**, all of the codes provide much of the model functionality desired for the ASR Regional Study, with the SEAWAT and WASH123 codes providing the best overall functionality.

**Table 7-1 -- Bench Scale Model Summary**

| Modeling Code | 3-D Simulations | Density Dependent | Stability Assessment | Run Times | Computing Requirements |
|---|---|---|---|---|---|
| MODFLOW/MT3D | Yes | No | Stable with minor oscillations | Acceptable | Workstation |
| SEAWAT | Yes | Yes | Stable with minor oscillations | Acceptable | Workstation |
| WASH123D | Yes | Yes | No stability issues | Acceptable | Workstation |
| SWI | No | Yes | Minor Oscillations | Acceptable | Personal Computer |

None of the codes proved unacceptably difficult to use and all codes (with the exception of SWI) probably require workstation class computers to efficiently develop and calibrate a large regional model. Effective pre- and post-processors can be utilized directly by all model codes with the exception of SWI. Weighing all of the factors and considering improvements that could be made to the model grid or mesh for future models, SEAWAT and the WASH123 groundwater modeling codes were selected as appropriate for the ASR Regional Study modeling. Both codes generated reasonable solutions in comparison to published density-dependent case studies, were capable of 3-D simulations, and solved the requisite flow and transport equations with reasonable run times.

Additional details related to the modeling codes tested, simulations performed, and analysis of the simulations can be found in the “ASR Regional Study – Bench Scale Modeling Final Report” (Brown et al., 2006). This report was reviewed by the Interagency Modeling Center (IMC), which is responsible for the oversight and review of all CERP modeling projects. The IMC is an equal partnership between SAJ and SFWMD, with participation from other Federal and state agencies. All comments provided by the IMC were addressed and incorporated into the final report.

### 7.3.3 Phase I Regional Study

Based on the findings of the bench scale study, the regional model calibration effort was divided into two phases. The intent of the Phase I Study effort was ***not*** to develop a calibrated model to be used for predictive simulations. Rather, the goal of Phase I was to develop coarse resolution, simplified regional models as test beds to evaluate the effect of model parameters, boundaries and other assumptions on simulation results. The development of these simplified models provided a path to move the project forward before the completion of data collection tasks and was a valuable tool for early analysis of an extremely complex groundwater system. By adopting this phased approach, modeling issues were identified early using the computationally faster Phase I model while developing a better understanding of the regional flow and transport patterns. Both WASH123D and SEAWAT models were used for Phase I. Lessons learned from this Phase I modeling were later used to guide field data collection efforts (see **Chapter 3**) and develop the higher resolution Phase II Calibration models that would be used for calibration and analysis of various ASR configurations. The specific goals of the Phase I modeling were:

- Identify model boundaries and test model boundary parameters.
- Identify regional flow and salt migration pathways.
- Identify the timing of salt water intrusion.
- Evaluate model run times and model sensitivity to time step sizes.
- Test hydraulic and transport parameter sensitivity.
- Compare WASH123D and SEAWAT results.

At the time of the Phase I model construction, only limited data were available. In order to address the Phase I goals, several simplifications were made, including:

- Model domains (vertical and horizontal) were kept consistent to the maximum extent possible
- Large, uniform mesh/grid elements were used to reduce model run times
- Since accurate pumping data were not yet available, no pumping was included in the models
- Boundary conditions remained constant over time

The results of similar simulations in both WASH123D and SEAWAT models were compared to evaluate the numerical schemes and determine if either model reacted differently to boundary condition changes. The model simulations were also compared to “pre-development” heads in the FAS based on contour maps generated by the USGS (Bush and Johnston, 1988). Although this approach is greatly simplified, it was necessary to move the modeling forward and was useful in defining improvements needed for Phase II. Based on this Phase 1 effort, the need for additional and more accurate boundary data as well as finer mesh/grid resolution in the Phase II model became apparent.

The following is a summary of the models developed and analyzed for the Phase I effort.

#### 7.3.3.1 Model Extent and Spatial Discretization

The grid/mesh boundary used for the Phase I models was selected with the 3D nature of the study area in mind. Horizontally, the ideal model boundary alignment would be around the Florida peninsula boundary, where all the geologic units outcrop to the ocean. This would ensure that boundary effects in the interior of the model would be limited because boundary condition assignments would be greatly simplified: all of the boundary heads in each geologic unit would be equal to sea level and all of the boundary salinity concentrations would be that of salt water. However, since the Florida peninsula extends 150 miles westward into the Gulf of Mexico, modeling the entire peninsula was not feasible within the scope of this study. The model boundary chosen for the Phase I model generally follows a path just north of Polk County and extends around the peninsula approximately 20 miles seaward from the coast. The distance of 20 miles was selected to balance the competing requirements of the model. The boundaries must be far enough away to eliminate boundary effects on the area of interest. At the same time, if the model is too large, run times become unreasonable. If the boundaries are too far from known head data, selection of a boundary condition becomes more difficult. The northern boundary was chosen to ensure that the entire recharge area, a major driving force in the model, was incorporated. The model boundary for the Phase I models is shown in **Figure 7-3**. Both the WASH123D and SEAWAT models used a horizontal element resolution of approximately 25,000 ft for each element/cell and encompassed an area of approximately 39,000 square miles.

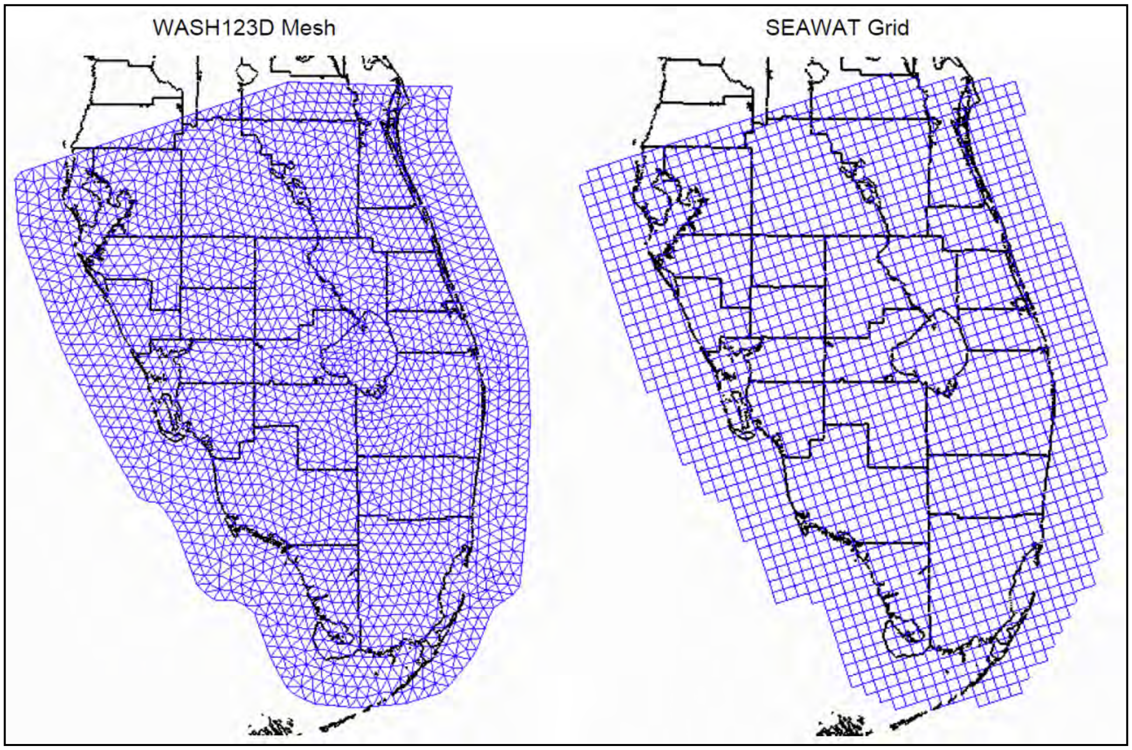
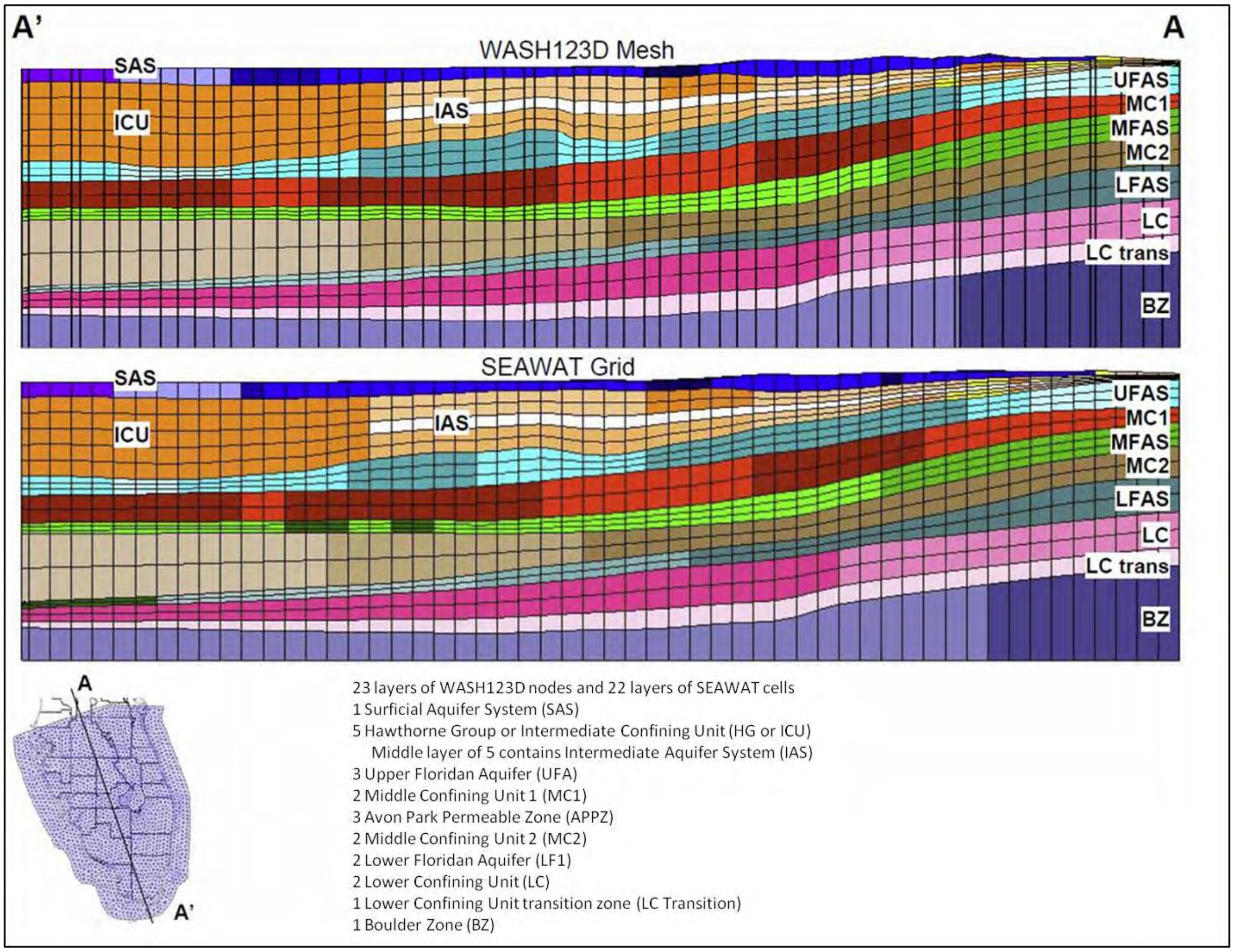


**Figure 7-3 -- Phase I regional model extents.**

Vertically, the mesh/grid was based on the geologic interpretations discussed in the preliminary hydrogeologic framework **(section 3.1**). The 3D mesh/grid represents geology between the water table and the Sub-Floridan Confining Unit. The top of the model is the low water table rather than the land surface. The low water table was generated by selecting the lowest value from the transient data set of SAS monitoring well heads in online databases and interpolating over the model area. Low water table was chosen for the top of model to eliminate computations in the unsaturated zone. These computations are not needed to reach the model goals and would slow model run times. From the low water table, the model extends down to a constant elevation of approximately -3250 ft NGVD. **Figure 7-4** shows a cross section of the geologic units as classified in the 3D mesh and grid. The cross section shows the distribution of the model's 23 layers of nodes for the WASH123D model and 22 layers of cells for the SEAWAT model.



23 layers of WASH123D nodes and 22 layers of SEAWAT cells
1 Surficial Aquifer System (SAS)
5 Hawthorne Group or Intermediate Confining Unit (HG or ICU)
Middle layer of 5 contains Intermediate Aquifer System (IAS)
3 Upper Floridan Aquifer (UFA)
2 Middle Confining Unit 1 (MC1)
3 Avon Park Permeable Zone (APPZ)
2 Middle Confining Unit 2 (MC2)
2 Lower Floridan Aquifer (LF1)
2 Lower Confining Unit (LC)
1 Lower Confining Unit transition zone (LC Transition)
1 Boulder Zone (BZ)

**Figure 7-4 -- Phase I vertical model extents.**

### 7.3.3.2 Model Time Discretization

Groundwater age data indicates that the groundwater in the southern portions of the FAS is up to 25,000 years old (Morrisey et al., 2010). For the Phase I model, a total simulation time of 35,000 years was selected to provide enough time for groundwater to move completely through the system. The computed head and salinity distributions of the SEAWAT and WASH123D model were compared at the end of each simulation to evaluate differences between the codes and the effect of model parameter variations.

Several time step sizes were evaluated to determine the largest time step (i.e. shortest run time) that provides similar results. These time-step sizes included 0.1 year, 1 year, 5 years, 10 years and 100 years. Plots for both the WASH123D and SEAWAT models were created depicting the head and concentration variation over time at wells in the model domain. An example of this sensitivity analysis is shown in **Figure 7-5**.

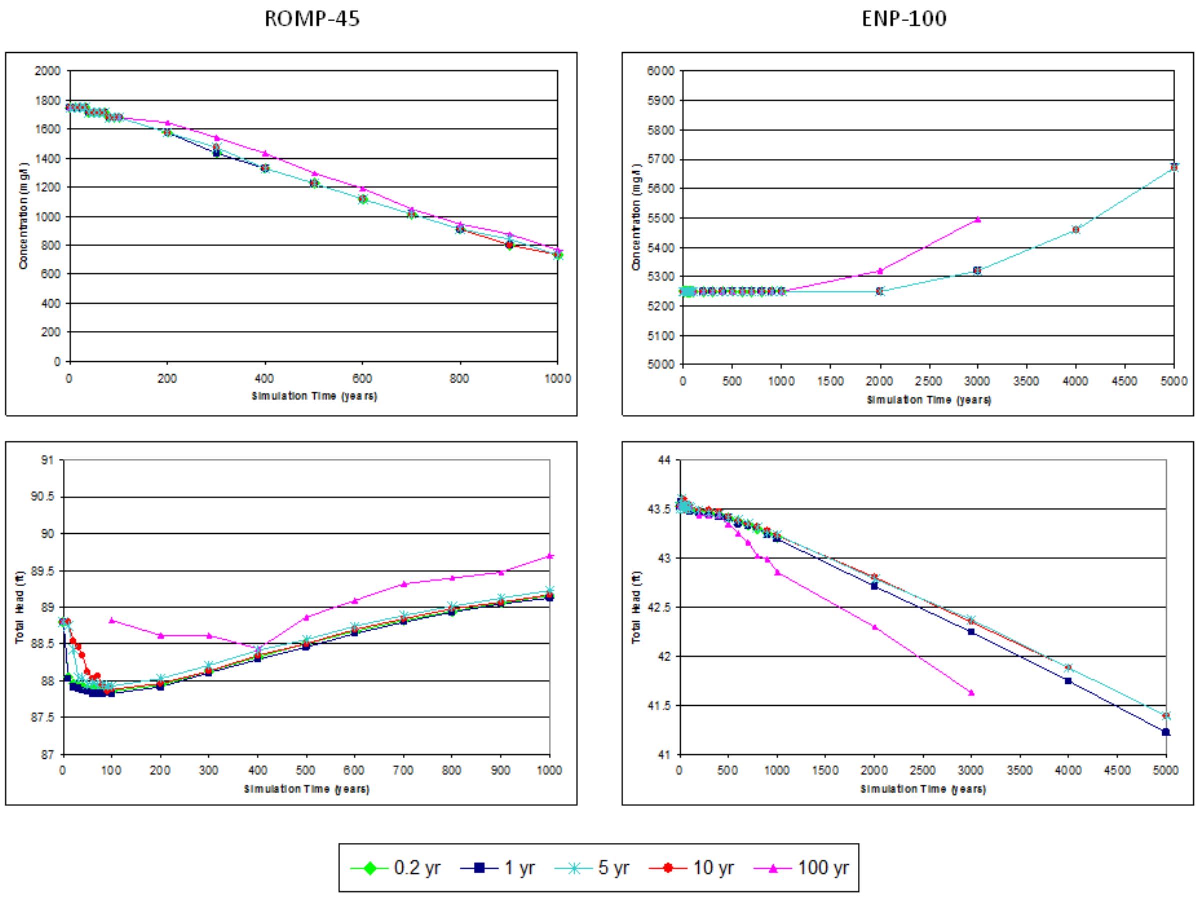


**Figure 7-5 -- Phase I time-step sensitivity at selected wells.**

Based on the results of this sensitivity, the 10-year time step was selected as the most computationally efficient time step size. Simulations using this time step are completed in the shortest run time, but yield results that are very similar to those produced by the smallest time steps.

### 7.3.3.3 Conceptual Model

**Geology.** The conceptual geology for the Phase I models was based predominantly on the findings documented in the Preliminary Hydrogeologic Framework (Reese and Richardson, 2004; 2008). A summary of this report is presented in **Section 3.1**, which correlates major aquifers and confining units in key wells across the study area. Hydrostratigraphic surfaces shown in **Figure 7-6** were based on these correlations and used to identify the depth and thickness of the geologic units.

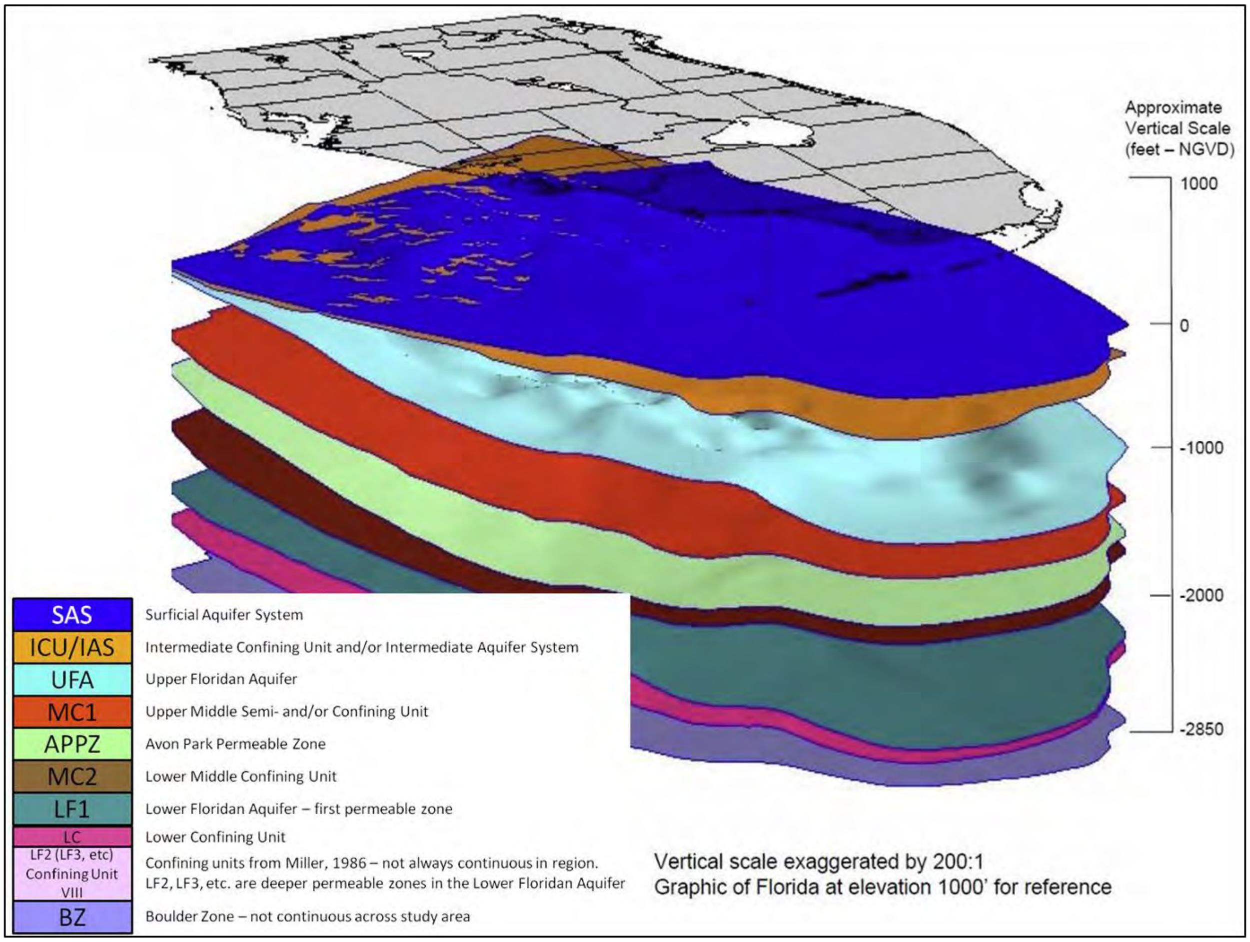


**Figure 7-6 -- Hydrostratigraphic surfaces used in the groundwater flow model.**

As discussed in **Section 3.1**, the major geologic units in the FAS include the Upper Floridan (UFA), Avon Park Permeable Zone (APPZ), Lower Floridan (LF1), Upper Middle Confining Unit (MC1), Lower Middle Confining Unit (MC2), and the Lower Confining Unit (LC). In addition to these FAS units, simplified representations of the Surficial Aquifer System (SAS), the Intermediate Confining Unit/Intermediate Aquifer System (ICU/IAS), and Boulder Zone (BZ) were incorporated into the models. These units essentially follow the recommendations of CH2M Hill (2005), with the exception that the three zones of the UFA were composited into one hydraulic unit and the Middle Floridan (MF) is defined as the APPZ to be consistent with the Final Hydrogeologic Framework described in **Section 3.2** of this report.

**Hydrogeologic Properties.** For the Phase I modeling, hydraulic properties such as hydraulic conductivity and storage terms were based on the preliminary hydrogeologic framework (Reese and Richardson, 2004) and other available data sources. For the aquifers, it was assumed that the vertical hydraulic conductivity was one-tenth of the published horizontal hydraulic conductivity. For the confining units and the ICU/IAS, it was assumed that the horizontal hydraulic conductivity was 2 times the published vertical hydraulic conductivity values.

Any element in the ocean was assigned with an ocean material type and a high hydraulic conductivity of 10,000 ft/d. Where the ocean abuts a confining unit hydraulic conductivity, a buffer hydraulic conductivity of 100 ft/d was defined to make the simulation computations more stable.

**Boundary Conditions.** Constant head boundary conditions were specified along the entire model perimeter for each aquifer. The observed groundwater level in wells was used to help define the model heads. Along the northern model boundary, the water level data are numerous for the SAS and UFA; however assumptions were required for the APPZ, LF1, and BZ head boundaries. For the remaining boundaries (east, south, west), the head for the SAS boundary was equal to sea level, but the heads for the UFA, APPZ, LF1 and BZ were estimated. These estimates were based on the limited water level data available at the time of Phase I model construction. For model simplicity, the APPZ water level was assumed to be equal to the UFA, while the water levels in the BZ and at ocean outcrops were assumed to be at elevation 0.0 ft. Since no pumping was incorporated into the Phase I models and these models were used to evaluate long term variations in regional flow and salinity trends, the boundary heads were assumed to be predevelopment in nature. Estimated predevelopment head contours maps of the UFA (Bush and Johnston, 1988; Meyer, 1989) were used to guide boundary condition assignment. Boundary heads in deeper layers were estimated based on a combination of observed water level data and predevelopment head trends in the UFA.

Boundary conditions for salinity were assigned around the entire model perimeter using a variable concentration condition. A variable concentration is equal to the concentration specified if the direction of flow is into the model. If the direction of flow is out of the model, the concentration on the boundary is computed by the model. For this study, reported measurements of total dissolved solids (TDS) are used as proxy for salinity. The terms 'TDS' and 'salinity' are used interchangeably in this chapter. For both WASH123D and SEAWAT codes, salinity values along the SAS perimeter boundary were specified as fresh water along the land boundary in the north and salt water (35,000 mg/L TDS) along the ocean boundary. Boundary concentrations for the FAS aquifers and confining units were based on observed concentration data. For elements in the ocean, a 100 percent salinity value of 35,000mg/L was assigned. Because of limited salinity data along the western and southern coasts, the 35,000 mg/L salinity value also was used for the FAS aquifers and confining units. The BZ boundaries were assumed to be 35,000 mg/L except for a small area along the northern boundary, which is less than 10,000 mg/L based on observed data.

**Initial Conditions.** The initial condition potentiometric heads were specified at every computational point in the Phase I models. The initial condition was used as a starting point in the iterative solution process. A constant total head was specified at the top of layer 1 for the steady state model simulation. The resulting heads from the steady state simulation were used to begin the transient simulation. Initial head assumptions had no impact on final results because the convergence criteria used for the steady state results was very small.

The initial salinity concentrations were specified at every computational point in the models based on an interpolation of the available water quality data. Salinities were consistent with the boundary condition assignment.

#### 7.3.3.4 Phase I Model Simulations

Since the observed groundwater elevations in the FAS across the study area are impacted by on-going groundwater pumping and no pumping was included in the Phase I model, the results of the WASH123D and SEAWAT simulations could not be compared to measured water levels. Instead, the model results were roughly compared to estimated pre-development head contour maps published by USGS (Bush and Johnston, 1988). The results of this comparison for the steady state WASH123D model are shown in **Figure 7-7**.

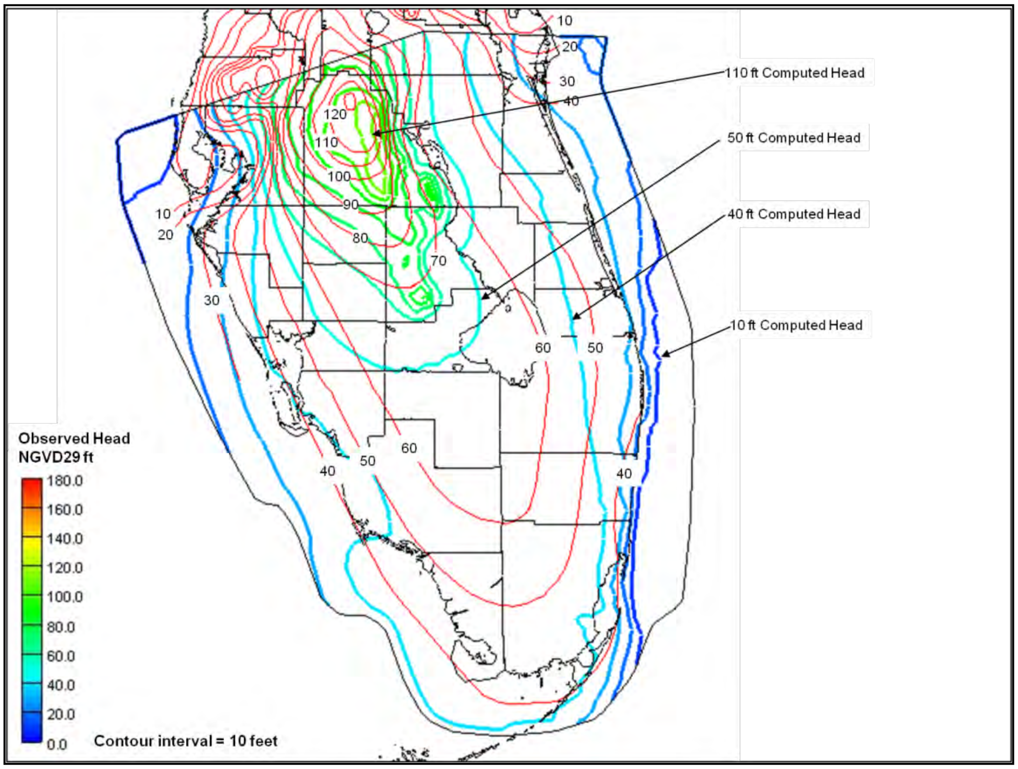


**Figure 7-7 -- Pre-development groundwater heads in the UFA.**

In both the steady state and transient (35,000 year) simulations, the computed heads in the north of the model generally agree with the pre-development head patterns, but are generally too low in the south. The salinity levels in the upper portions of the FAS south of Lake Okeechobee also increased more than expected at the end of the 35,000 year simulations. Several potential reasons for this model behavior were identified, including:

1. Possible regional anisotropy that allows freshwater entering the FAS in the north to preferentially move to the south.

2. Initial salinity condition assumptions, which were based on the limited data available at the time of model construction.
3. Uncertainty in the boundary conditions due to the location of the selected model boundary.
4. Variations in boundary heads and salinity over time due to sea level change.
5. Need for better spatial distribution of hydrogeologic parameters.
6. Need for finer mesh/grid resolution.

Although the computed heads were slightly low in comparison to estimated pre-development heads, the model was useful to address the Phase I goals and guide the Phase II modeling. The Phase I modeling indicated that the models were sensitive to the boundary conditions used to set the heads and concentrations on the exterior faces. Based on these findings, a thorough analysis of the existing water level and water quality data were needed for Phase II (see Appendix C of the Phase II Calibration report, provided in Appendix E of this report). Due to the uncertainty and model instability along the western boundary, it was determined that a more defensible model boundary was needed in this area in the Phase II model (see Section 2.3 of the Phase II Calibration report, provided in Appendix E of this report). The Phase I model results also indicated that the model resolution needed to be increased for the Phase II model in order to improve stability and to include regional and ASR pumping (see Section 2.3 of the Phase II Calibration report, provided in Appendix E of this report). Sensitivity analyses for flow, transport, and time-step parameters conducted during Phase I provided some insight for how varying model parameters would affect Phase II model results. Because these parameters are very dependent on model resolution, these sensitivities served mainly as a broad guidance for Phase II parameter variation.

From a regional perspective, the flow patterns computed in the Phase I models generally reflect the conceptual understanding of groundwater flow in the FAS. Water entering the model in the Polk County recharge area moves downward to provide a source of fresh water to the underlying aquifers. The highest heads and lowest salt concentrations occur in the recharge area in all the aquifers. From Polk County, water moves in a radial pattern. As the water moves south, there is a point in the vicinity of Lake Okeechobee where the gradient across the confining units becomes upward. Saltier water from the units below the UFA and the ocean outcrop along the eastern model boundary intrude into the FAS, which results in increasing salinity in the FAS over geologic time.

In addition to identifying several areas for future improvement, the Phase I models were useful for comparison of the WASH123D and SEAWAT modeling codes. Although the FAS a complex flow and transport system, the two codes produced similar results. **Figures 7-8** and **7-9** compare the computed groundwater heads in the UFA from both models under steady state and transient conditions, respectively.

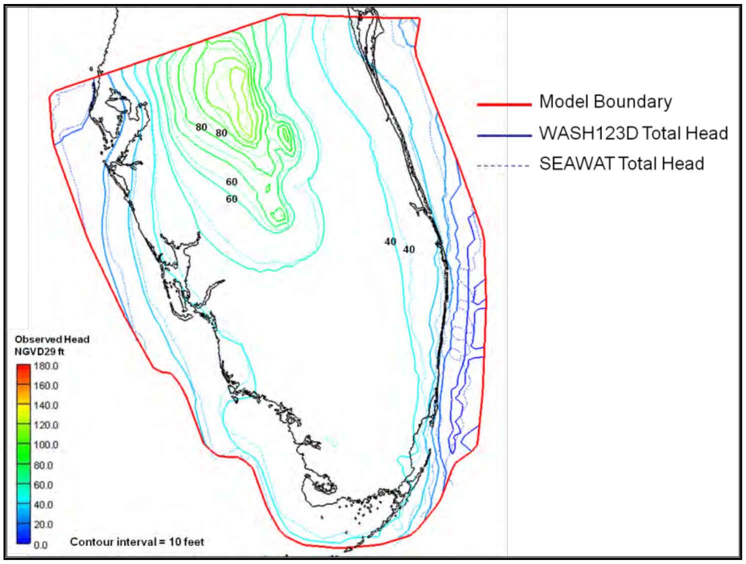


**Figure 7-8 -- Comparison of computed steady state groundwater heads in the UFA.**

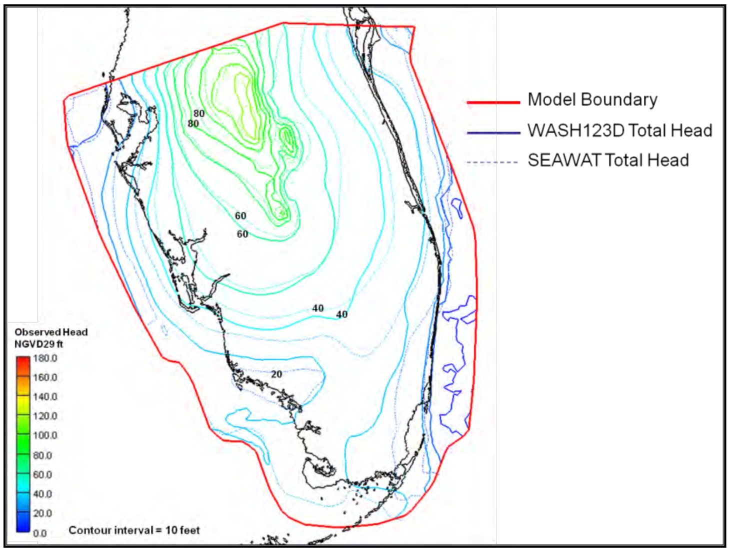


**Figure 7-9 -- Comparison of computed transient (35,000 years) groundwater heads in the UFA.**

The minor differences between the results were attributed to variations in boundary condition assignment and computational schemes resulting from differences in the numerical approaches of the models. Although these differences in computational methodologies and treatment of hydraulic parameters have a minor impact on the computed groundwater flow fields, both codes were determined to be reasonable for future CERP ASR modeling.

In moving forward into Phase II, the recommendation was made to use both WASH123D and SEAWAT. Since the two codes use different numerical schemes to compute the flow and transport fields, the results of the two codes could be compared to determine if problems encountered with calibration resulted from limitations in the conceptual model or were a function of the numerical solvers within the codes.

### 7.3.4 Phase II Regional Study (RASRSM)

The primary objective of the Phase II ASR modeling effort was to quantitatively evaluate the impacts of the proposed CERP ASR wells on the hydrogeologic conditions in the FAS. This evaluation was performed by using both regional and local scale models and incorporating the recommendations of the Phase I modeling. Each scale of model was used to address different project objectives. The initial work on the Phase II Regional ASR Study Model (RASRSM), which is described briefly in this section and in detail in **Appendix E**, involved the development and calibration of the regional scale models, which provided planning level information to address large-scale issues, such as the regional effect of the ASR well clusters on water levels, groundwater flow patterns, and the potential for rock fracturing. This scale of modeling is *not* appropriate for evaluating local issues, such as well-to-well interaction within an ASR well cluster, ASR well recovery efficiency, salt water intrusion, or upconing. These issues were addressed with local scale models that have significantly finer mesh/grid resolution and are discussed in USACE and SFWMD (2013).

The RASRSM was developed simultaneously using the USGS modeling code SEAWAT and the USACE code, WASH123D. Eventually, the WASH123D model was eliminated in favor of the SEAWAT model, which had a shorter run time. The local scale models were built using only SEAWAT. Although details of the WASH123D model are provided in **Appendix E**, only the SEAWAT model will be described here.

#### 7.3.4.1 Model Extent and Spatial Discretization

The Phase II RASRSM model boundaries were established based on conclusions from the bench scale and Phase I modeling efforts (Brown, et al. 2006; USACE, 2006). The side boundaries of the model were generally established along geologic outcrops to the ocean or aligned near observation wells using available data during the calibration and validation periods. The eastern boundary of the top model layer is located along the coast of the Atlantic Ocean. Subterranean geologic units extend eastward to their outcrop on the ocean floor, resulting in an additional 7,000 square miles of the model located offshore beneath the Atlantic Ocean. Ideally, the west and south boundaries would also extend out to the locations of the outcrops for each geologic layer in the Gulf of Mexico and be based on tide gauge data similar to the eastern boundary. However, these outcrops occur nearly 150 miles from the Florida coastline. Extension of the model boundary to these outcrops would add significantly to the model size, computational requirements, and the time required to reach a convergent solution. This would also add a large area to the model that has not been extensively studied, and for which there is no significant data regarding heads, water quality, or aquifer characteristics. Additional testing confirmed that the boundary effects on ASR performance measures were insignificant at the ASR locations. This analysis is presented in Appendix A of the D13R Report **(Appendix E)**.

**Figure 7-10** shows the horizontal extent of the deepest layer of the model domain, which covers just over 23,000 square miles of the Floridan peninsula. The northern model boundary for all geologic units cuts across the Florida peninsula through Orlando. The western model boundary closely follows the Gulf coast of Florida, beginning at the model's northwest corner, just west of Tampa. South of Sanibel Island, the model boundary moves inland, crossing the Everglades to intersect the eastern boundary at the south end of Biscayne Bay (Locations are labeled on Figure 1.1 of the Phase II report; USACE, 2011 and **Appendix E)**.

The computational grid/mesh resolution was selected to balance the purpose of the model with the constraints of time and computer resources. Higher resolution on the grid or mesh can provide greater accuracy and detail, but can also tax project budgets and computer resources due to the additional time required to compute the solution. This resolution was selected based in part on the recommendations of the Phase I modeling.

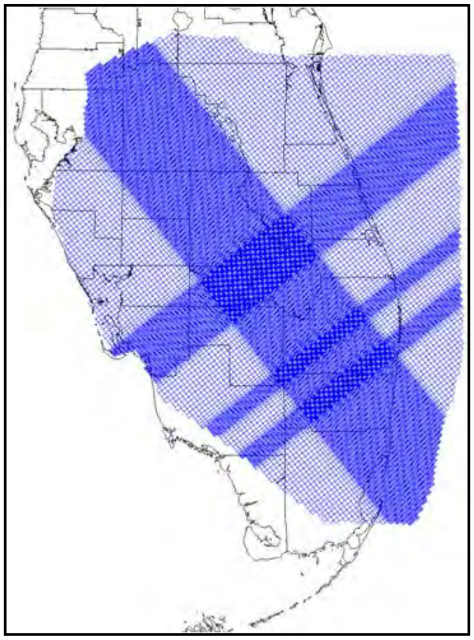


**Figure 7-10 -- Phase II regional model extents.**

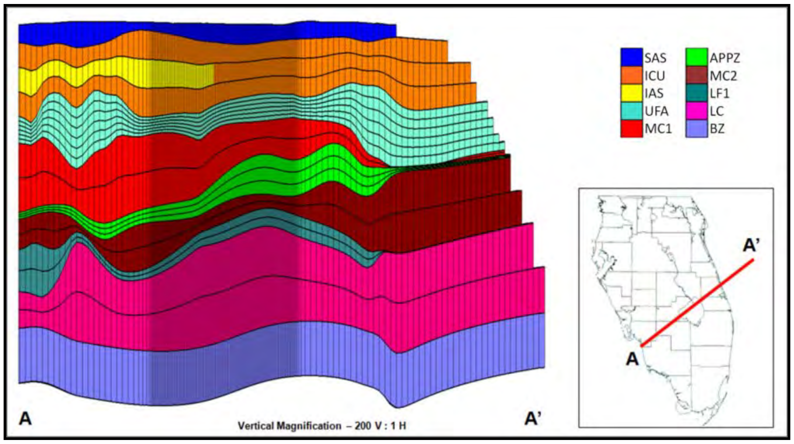


**Figure 7-11 -- Vertical cross-section of SEAWAT model.**

**Figure 7-10** shows the horizontal resolution of the SEAWAT computational grid. The smallest resolution (2,000 ft) is found at the proposed ASR well cluster locations where greater accuracy and detail are necessary. The size of the grid cells increases to 10,000 ft along the model boundary.

Vertically, the models extend from the ground surface to the bottom of the confined Boulder Zone (BZ) member of the Lower Floridan (LF1) aquifer (**Figure 7-11; Table 7-2**). Although the top layer of the SEAWAT grid is set to coincide with the Surficial Aquifer System (SAS), no calculations were made in this layer. While the layer elevations of the model vary, the topographic high is near elevation 250-ft NGVD29 and the deepest point in the model is about -3,600 ft NGVD29.

Table 7-2 -- Assignment of Model Layers to Hydrogeologic Units

| Model Grid Layer | Hydrogeologic Unit |
|---|---|
| 1 | Surficial Aquifer System (SAS) |
| 2 | Intermediate Confining Unit (ICU) |
| 3 | Intermediate Aquifer (IA) /<br>Intermediate Confining Unit (ICU) |
| 4 | Intermediate Confining Unit (ICU) |
| 5-10 | Upper Floridan Aquifer (UFA) |
| 11-12 | Upper Middle Confining Unit (MC1) |
| 13-15 | Avon Park Permeable Zone (APPZ) |
| 16-17 | Lower Middle Confining Unit (MC2) |
| 18-19 | Lower Floridan Aquifer (LF1) |
| 20-21 | Lower Confining Unit (LC) |
| 22 | Boulder Zone (BZ) |

As shown in **Figure 7-11**, the models include five confined aquifers and four confining units (note that the ICU confines both the IA and the UFA, see **Figure 7-6**). The layering matches the results of the Hydrogeologic Framework, pictured in **Figure 3-1**. Heterogeneity within the model layers was incorporated using zonal modifications to hydrogeologic properties of each geologic unit, or pilot point interpolation of hydrogeologic properties to individual cells of the model. Model grid layers are assigned to hydrogeologic units as shown in **Table 7-2.**

#### 7.3.4.2 Model Time Discretization

The calibration period selected for the transient calibration of the regional model was October 31, 2003 through December 31, 2004. The calibration model was set up with 15 stress periods – one for each month of the period. Most boundary conditions and source/sink options in SEAWAT require constant values during each stress period. Thus, for head data, the average measured head during each month was applied as a boundary condition for the entire month. For pumping data, the total pumped volume was divided by the number of days in the month and applied as a constant flux during the entire month. This simplification can result in some differences between observed and calculated data, but was necessary due to the paucity of reliable pumping data available at many locations in the model domain.

The validation period of August 1993 through July 1994 was originally selected to be consistent with the calibration period of the USGS model by Sepúlveda (2002). Analysis of the head data indicated that October 1993 was a better starting point for the model since the heads were reasonably constant during the period leading up to October 1993. The validation period was, therefore, shortened to October 1993 through July 1994. The same process of assigning month-long stress periods to the model period was followed as explained above. Head results at the observation points are available at each time step (approximately every 5 days). Head results on the grid as a whole were generally output every 10 days to save on file sizes.

### 7.3.4.3 Conceptual Model

**Geology.** A wealth of geologic and hydrogeologic data is available for the regional model domain. Geologic interpretations were based primarily on Reese and Richardson (2008) and a draft report developed by Reese and Richardson (2004), which are summarized in **Chapter 3** of this report. Additional details on the application of the hydrogeologic information to the Phase II model are available in **Appendix E**.

**Hydrogeologic Properties.** Hydrogeologic properties such as hydraulic conductivity and specific storage were estimated for each model layer based on the available data. Then, during the calibration process, the property values were adjusted until an adequate calibration to available data was achieved. During calibration, the parameter values were required to remain within reasonable ranges as defined in the Reese and Richardson (2008), and incorporating data from aquifer pump tests (APT), packer tests and core permeability measurements provided by SFWMD (**Section 3.5**). Additional hydrogeologic data were collected from other sources and online databases including the SFWMD DBHYDRO, the USGS South Florida Information Access (SOFIA), the National Park Service South Florida Natural Resources Center (SFNRC), CH2M Hill (2005), and a number of published reports and papers.

On a regional scale, the hydraulic conductivity used in the model varies both vertically and horizontally. Over the model domain the flow zone hydraulic conductivities generally vary from 1.0 ft/day to 10,000 ft/day, while the confining unit hydraulic conductivities generally vary from 0.000005 ft/day to 0.5 ft/day. The spatial distribution of the hydraulic conductivity used in each geologic unit in the Phase II model is presented on Figures 4.31 to 4.40 of the Phase II Calibration Report.

Transmissivity was not explicitly determined in the Phase II Calibration Report. However, a recent compilation and regional extrapolation of transmissivity data was presented for the UFA (Kuniansky et al., 2012). Here, transmissivity values in the confined UFA of south Florida range between approximately 5,000 $ft^2$/day and 50,000 $ft^2$/day. Additional properties such as porosity, dispersivity, and molecular diffusion coefficient, were found to have little effect on the calibration of the model. Sensitivity analyses of these parameters are presented in Section 5.2 and 5.3 of **Appendix E**.

**Regional Anisotropy.** During the Phase I modeling, the SEAWAT grid angle was set at 18 degrees west of north to align with the axis of the Floridan peninsula. Bittner et al. (2008) analyzed a number of options for improving the agreement between the initial model results and the estimates of pre-development heads in the UFA from Meyer (1989) and Bush and Johnston (1988). They concluded that both the inclusion of anisotropy in the aquifers and the inclusion of temperature effects on density could improve the calibration of the model.

A lineament study (USACE, 2004) and preliminary results from some image log fracture analyses at SFWMD indicated that the dominant fracture orientation was NW to SE at an angle of approximately 38 degrees west of north. For this reason, the regional grid for Phase II modeling was designed with a 38 degree angle, in place of the 18 degree angle used in Phase I. However, after the grid was developed, additional analysis by SFWMD indicated that the NW to SE orientation was based on a lumped view of all the UFA fractures from all the wells. When the data were split out to look at the dominant orientations from individual wells, it became clear that the dominant orientations varied geographically. The lumped view gave additional weight to a large volume of fractures in the UFA at the Kissimmee River ASR pilot location. This led to the conclusion that there currently is no conclusive evidence of regionally dominant orientation for fractures in the UFA. The anisotropy option was, therefore, not used in this Phase II regional model (although the grid angle of 38 degrees remained). These studies and their conclusions are summarized in **Sections 3.6.2** and **3.6.3**.

**Boundary Conditions.** The time-variant specified head boundary (CHD) was used for the top of the model and for the sides of aquifer layers. The heads assigned to the top boundary were set by interpolating available SAS head data. This method simulates recharge by allowing the model to compute flux in and out of the model to match assigned heads. The heads assigned to the eastern Atlantic Ocean boundary were based on the monthly mean sea level measured at two NOAA tide gauges. Note that with the coarse time discretization, this model does not attempt to reproduce daily tidal cycles. The heads assigned to the north, west and south boundaries were based on interpolations of average heads measured at monitoring wells near the model boundaries.

A no-flow boundary was used as the base of the model because of the much lower conductivity of the Sub-Floridan confining unit that underlies the Boulder Zone. Preferential flow in the Boulder Zone is expected to be horizontal with only insignificant flows in or out of the bottom of the model.

No-flow boundaries were used at cells along the side boundaries of the confining units, except where they outcropped to the ocean. The sensitivity analysis showed that horizontal flow through the model boundary in these confining units was an insignificant source or sink when compared to flow through the aquifers.

SEAWAT requires the user to define the water quality of the flows entering the model at any boundary condition. The SSM package (Source & Sink Mixing) was used to assign the TDS and temperature to each cell with a CHD boundary condition and all wells. For the boundary cells, the water quality of the incoming water was set based on the initial conditions at that location. For recharge wells, the TDS values were assigned using available data. Recharge water temperature values were assumed to be consistent with the temperature initial conditions for the SAS.

**Initial Conditions.** The initial conditions applied to the model included initial head, salinity and temperature. The initial head condition was based on early test runs of the model. For the transient model, the first stress period was solved in steady state mode to give the starting head condition for the subsequent transient simulation. It is important to note that while the initial head condition affects the speed at which the steady state solution is reached, it has no effect on the model results.

The model requires that initial salinity concentrations and temperatures be specified at every computational point in the model domain. In order to meet this requirement, an extensive data collection effort was undertaken to identify representative water quality data from the SAS to the BZ. The collected data were interpolated to each active cell of the model.

In general, fresher zones in the deeper geologic units are observed in the northern portion of the model beneath the Polk County recharge area and south of Orlando. The TDS concentration increases to the south and near the geologic outcrops at the ocean. Additional details concerning the procedure used to develop the TDS data sets and initial conditions are presented in an appendix of the Phase II report (USACE, 2011), which is found in **Appendix E** of this report.

The starting temperature also was interpolated from available data and increases with depth on the western side of the peninsula but decreases with depth on the eastern ocean boundary. This trend creates a very large temperature variation, from 5$^{o}$C to 44$^{o}$C, in the BZ where temperature effects on density have the largest impacts on model results. The warmer west coast temperatures also extend through the mid-section of the state toward Lake Okeechobee in most of the geologic units.

**Sources and Sinks.** In addition to the model boundaries, pumping wells constitute a significant source/sink for groundwater in South Florida. This pumping includes withdrawal wells (irrigation and water supply, for example), existing ASR wells, and Class I injection wells. An extensive data collection effort was performed to compile and evaluate detailed data sets of the pumping distribution within the model domain. Over 30,000 wells were identified as active during the calibration/validation periods within the model domain. However, many of the wells were missing specific location information such as horizontal coordinates or open interval depths. Also, monthly transient pumping rate records for many wells were either unavailable or incomplete. As part of the data collection effort, estimates were made to fill these data gaps.

Additional effort was required to appropriately assign the pumping to the grid and mesh. The depths of the top and bottom of the open interval for each pump were converted to elevations based on the approximate ground surface elevation at the point. These elevations were compared to the model-simplified geology to determine the aquifer (or aquifers) impacted by each well. The pumping elevations were adjusted to prevent the model from pumping in confining units. Pump rates for wells covering more than one aquifer were prorated based on the length of open interval and the estimated hydraulic conductivity of each aquifer. Because SEAWAT requires all pumping to be applied to the center of a cell, all wells were automatically moved to the center of the cell containing them and the monthly pump rates were added to the pump rates of any other wells located in the same cell.

#### 7.3.4.4 Calibration/Validation

Model calibration is the process of varying model input parameters within a reasonable range until the model output matches observed conditions within some acceptable error criteria. For the Phase II RASRSM, a steady state calibration was first performed to the October 2003 and February 2004 observed water level data sets. Once the steady state model was calibrated, a transient calibration was performed for the 15 month period from October 2003 to December 2004. Finally, a transient validation simulation was performed for a 10-month transient period from October 1993 to July 1994. Observation wells for calibration were selected from the monitoring well database (see **Section 3.3**).

**Steady State Calibration.** A steady state calibration was performed for October 2003 and February 2004 by varying the input parameters (principally hydraulic conductivity) until the model output (heads) matched the measured heads at non-pumping monitoring wells with data for either month. The model for each month was provided with a separate set of specified heads around the edges of the aquifers and at the surface, simulating different hydrologic conditions as reflected in the available data. The pumping data also were different for each month and based on the available reported pump rates and estimates. Starting conditions (salinity and temperature), hydraulic conductivity, and all other input parameters were identical for the two steady state calibration models.

The quality of the steady state calibration was evaluated in several different ways, including error statistics, calibration target figures, gradient analysis of well clusters, and comparison to other published information, such as estimates of recharge to the UFA and pre-development heads. More details on the criteria for selection of the calibration is provided in USACE (2011) and **Appendix E**.

During the course of the steady state calibration, it was found that the best calibration method was a combination of "trial and error" calibration with automated calibration using PEST, an open source calibration code developed by Watermark Numerical Computing (2004). The process also included numerous discussions with scientists from SFWMD to "truth-check" the calibration parameters against their superior local hydrogeologic knowledge and experience.

The main parameters varied for the steady state calibration were horizontal and vertical hydraulic conductivity for layers 2 through 22 (IAS through BZ). The conductivities were assigned smooth conductivity fields developed using the "pilot point method" (Doherty, 2003). Each aquifer or confining unit was given a set of "pilot points" placed somewhat randomly, but with a greater density in areas of expected heterogeneity. A hydraulic conductivity value was assigned to each point and a kriging algorithm (distributed with PEST for use with MODFLOW) was used to assign a unique hydraulic conductivity value to each grid cell. Details on the final calibrated hydraulic conductivity fields and comparisons of observed and calculated heads are provided in the Calibration section of the Phase II RASRSM report (USACE, 2011) found in **Appendix E**.

**Transient Calibration/Validation.** In order to model the successive recharge, storage, and recovery periods for the ASR wells, it was necessary that the ASR regional model be calibrated in transient mode. The addition of the time term necessitates a substantial increase in the number of parameters which can be varied during calibration. The hydraulic conductivity values had been tentatively set during the steady state calibration, though some iteration between the steady state and transient models occurred. Most of the transport parameters (porosity, dispersivity, and molecular diffusion coefficient) proved to be relatively insensitive on a regional scale due to minimal solute and heat transport occurring on the brief duration of the model calibration and validation periods (15 months or less). Specific storage was found to be the most sensitive parameter during the transient calibration.

The transient SEAWAT calibration advanced in a manner similar to the steady state SEAWAT calibration. The pilot point method was again implemented to create smoothed fields of specific storage. Calibration advanced as a combination of “trial and error” calibration and automated calibration. PEST was again used as the code for automated calibration.

Because of the time discretization (constant boundary conditions and pumping for each month) it is impossible for the model to correctly calculate the head every single day. The goal of the calibration effort was to match gross seasonal variations in head, including the average head during the driest period (usually during the month of June 2004) and the average head during the wettest period (usually late fall 2004).

See the Phase II RASRSM report (USACE, 2011) in **Appendix E** for specific details on the final calibrated storage coefficients and the comparison of measured and model-calculated heads. The same report also shows the results of the validation runs and the sensitivity analyses.

## 7.4 Groundwater Flow Patterns in South Florida

### 7.4.1 Concept of Equivalent Freshwater Head

Because of the large variability in salinity and temperature in the Floridan Aquifer System, the density of groundwater can vary substantially. These density variations can affect the direction and rate of groundwater movement. Both WASH123D and SEAWAT require the user to enter head boundary conditions and initial conditions as observed head based on local density, or the water level measured in a well. The models then use the temperature and salinity to calculate the *equivalent freshwater head*, which takes into account TDS, temperature, and pressure to determine the potential energy at a given location. The flow equations are solved based on equivalent freshwater heads with a pressure adjustment and then the solutions are converted back to observed heads for viewing and analysis.

Because model results are reported as heads, the solutions sometimes appear to show unusual flow patterns. When there are significant differences in salinity, groundr flow may appear to be moving upgradient. If the salinity is markedly different between two points, high heads may not correspond to high equivalent freshwater heads. More details on the relationship between observed head and equivalent freshwater head are given in Section 2.1 of the Phase II RASRSM report (USACE, 2011 and **Appendix E**).

### 7.4.2 UFA/APPZ Aquifer Flow

The model computed heads in the UFA and APPZ from the October 2004 steady state run are shown in **Figure 7-12** and **Figure 7-13**, respectively. The head contours have been overlain with flow directions at a number of locations to show the general direction of groundwater movement.

In general, water flows from the recharge area in northern Polk County towards exit points at the west and northeast boundaries. There is also a potentiometric high in the UFA and APPZ heads in the southern part of the model, from which groundwater flows in all directions. The source of this higher head water is the underlying geologic units (see the following section).

The APPZ groundwater flow pattern (**Figure 7-13**) is similar to those of the UFA. Flow directions are from the recharge area in Polk County towards exit points in Hillsborough, Manatee and Brevard Counties. Another groundwater high is found in the southern part of the model where groundwater flows radially in all directions from that high point.

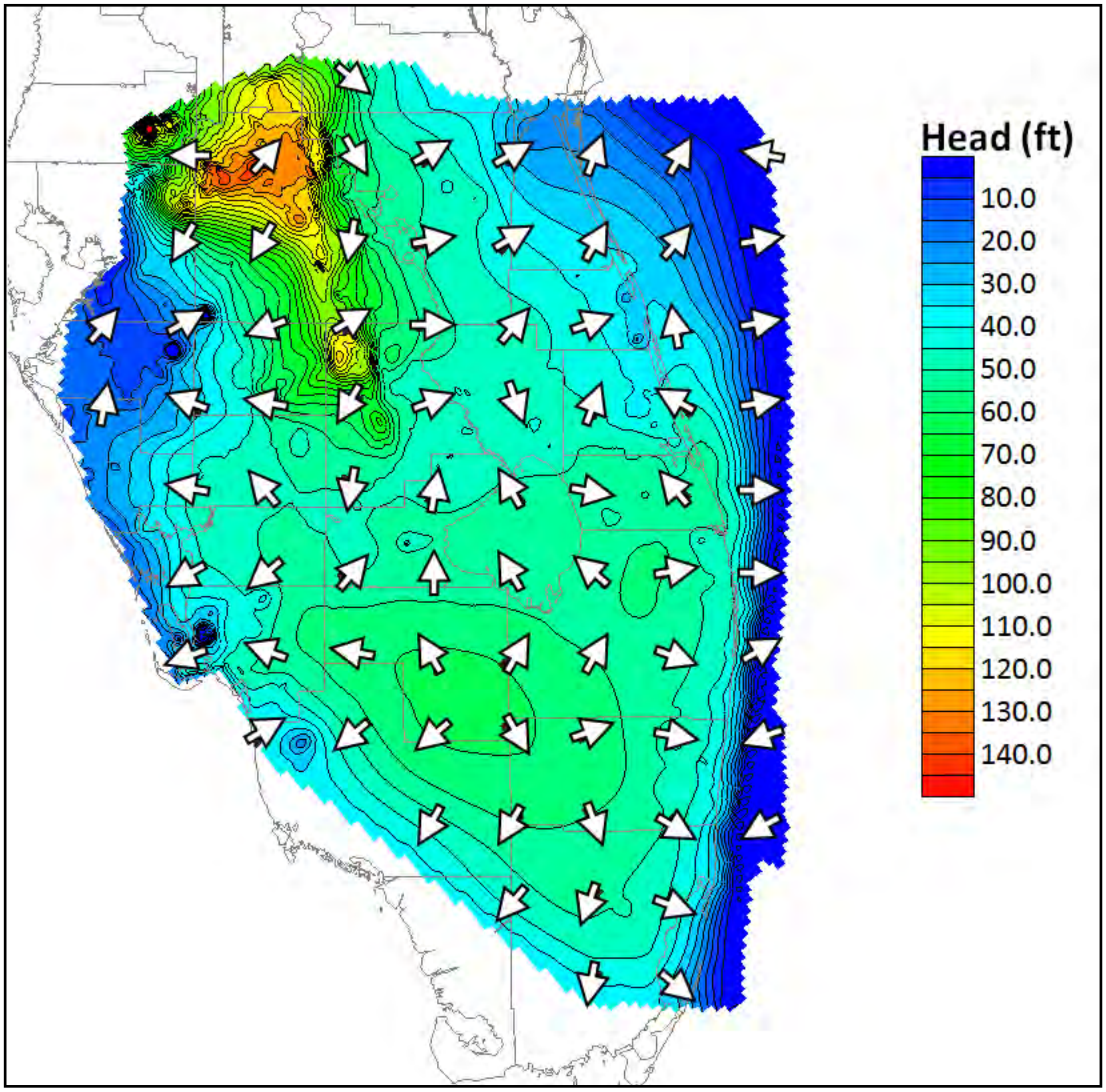


**Figure 7-12 -- Model output heads and horizontal component of flow for UFA (February 2004 model solution).**

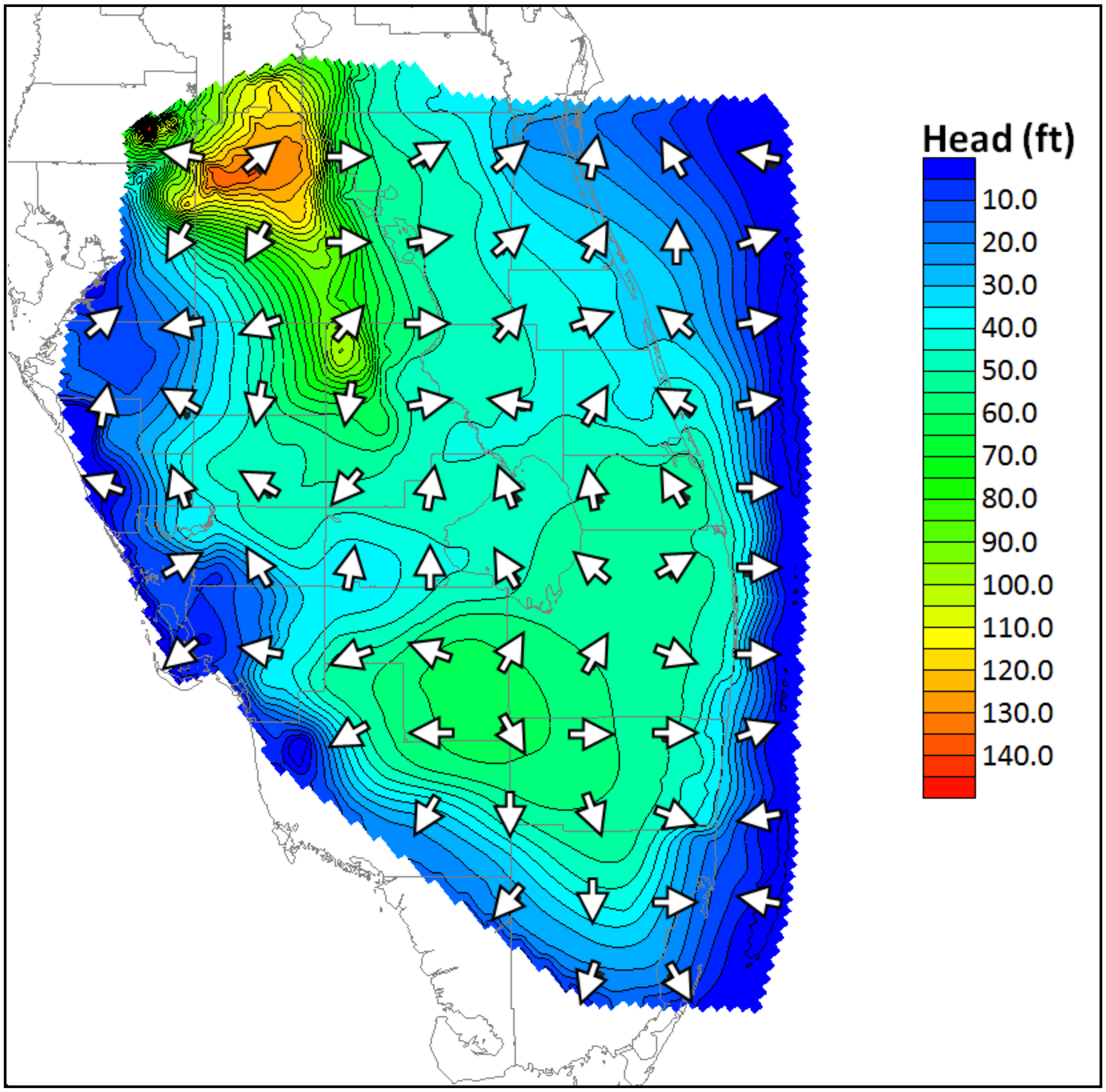


**Figure 7-13 -- Model output heads and horizontal component of flow for APPZ (February 2004 model solution).**

### 7.4.3 LF1 and BZ Aquifer Flow

Model output for the LF1 and BZ layers are shown in **Figure 7-14** and **Figure 7-15**. The head contours have been overlain with flow directions at a number of locations to show the general direction of groundwater movement. Where large salinity differences exist, these flow paths may not be perpendicular to head contours. Note that in these layers, the density has a great impact on flow direction. In the LF1, the Polk County recharge area is still visible. Flow in the south of the model is much more difficult to summarize because of a number of slight groundwater highs and lows.

The analysis of the BZ flows helps explain many of the anomalies seen in the shallower layers. As with the upper layers, the Polk County recharge area is visible. The flow in the south shows a strong inward flow component from the lower east coast. This component of flow explains the groundwater highs noted in the UFA and APPZ southwest of Lake Okeechobee.

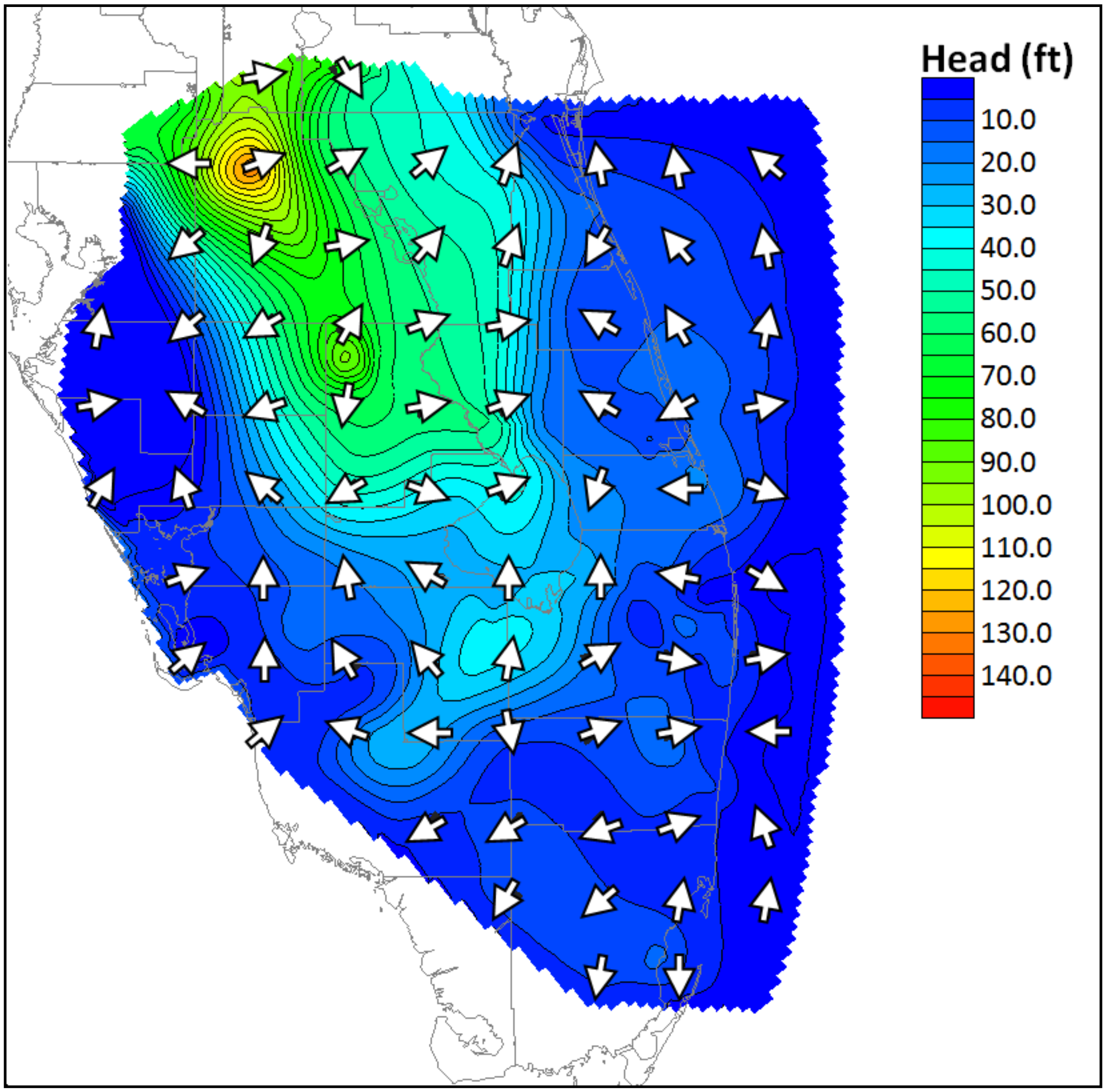


**Figure 7-14 -- Model output heads and horizontal component of flow for LF1 (February 2004 model solution).**

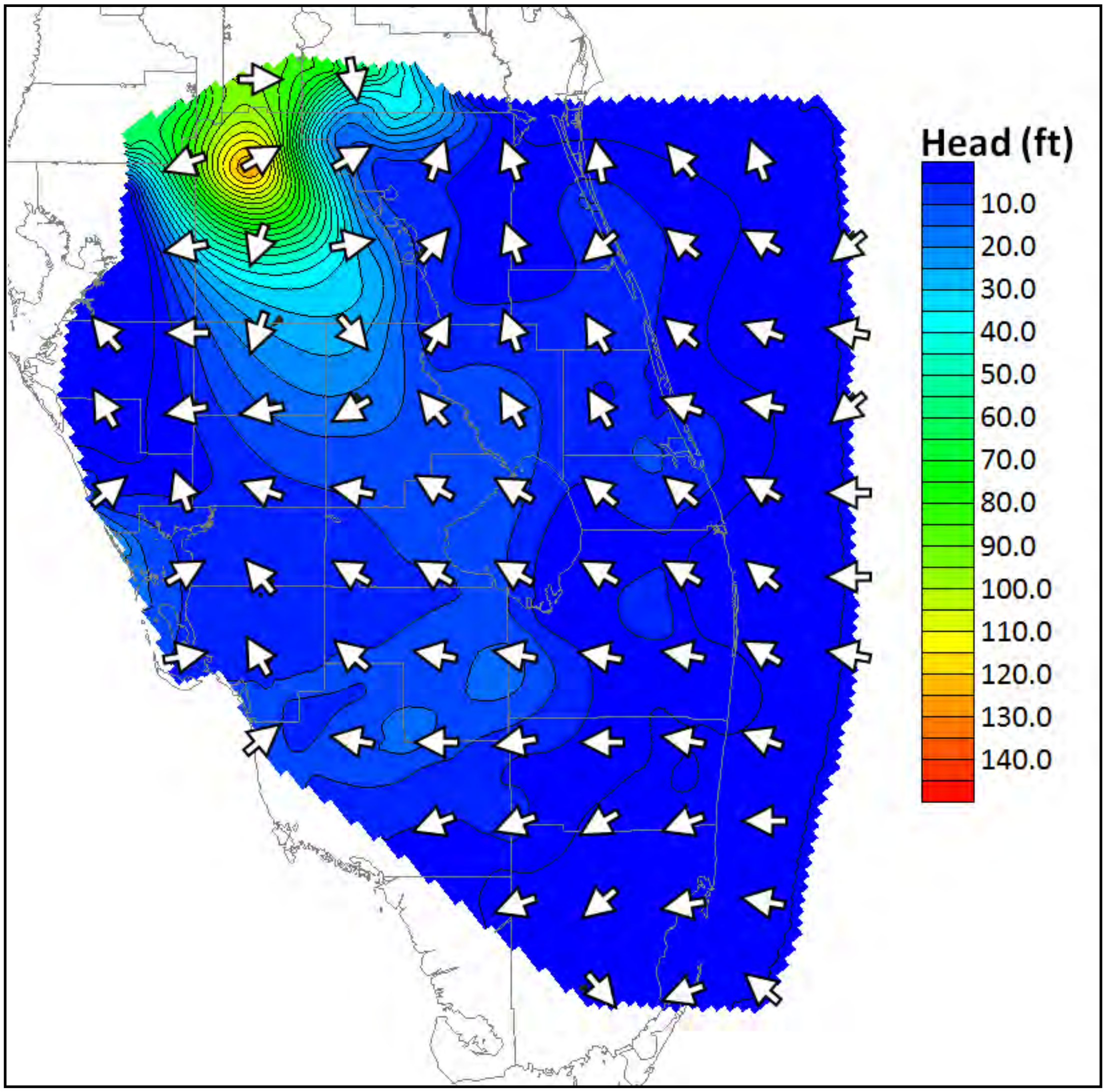


**Figure 7-15 -- Model output heads and horizontal component of flow for BZ (February 2004 model solution).**

### 7.4.4 Recharge Areas

**Figure 7-16** shows the discharge and recharge for the top of the UFA as calculated from the October 2003 model solution. Blue areas are discharge areas (upward flow direction) and green, yellow or red areas are recharge areas (downward flow direction). Note that the recharge area covers the northwest portion of the model with the rest of the model discharging water through the UFA towards the surface. The area near the northwest boundary with variegated red and blue colors is caused by large cells in an area of great topographic variability. This area is not of concern for the validity of the model since it is far from the proposed ASR sites.

The upward flow noted in the remaining three quarters of the model is caused by the inflow of high salinity water from the ocean at the BZ level. Due to the high salinity and extreme depth of the BZ, the ocean exerts great pressure on the BZ groundwater causing rising potential energy in the center of the model for all layers.

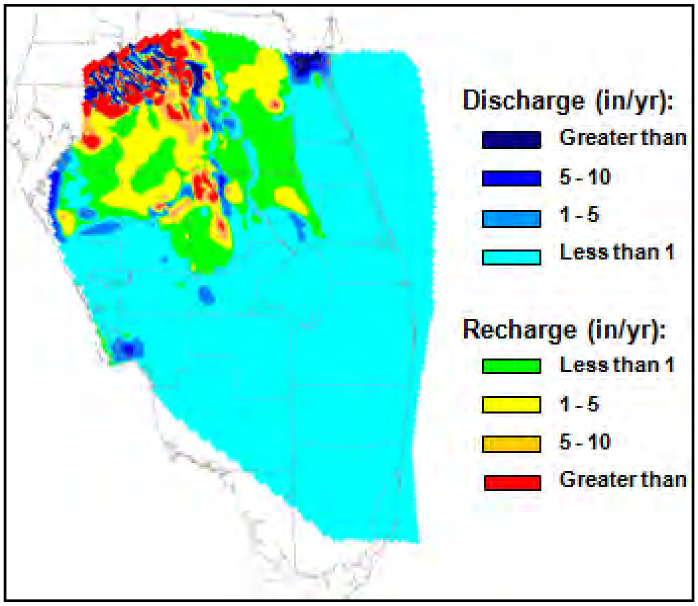


**Figure 7-16 -- Recharge and discharge from the top of the UFA (October 2003 model solution).**

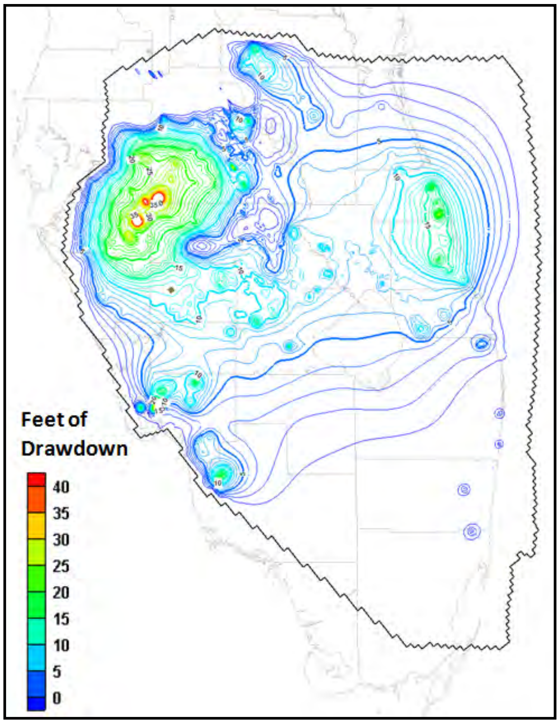


**Figure 7-17 -- UFA drawdown caused by pumping. (February 2004 model solution).**

### 7.4.5 Regional Pumping

Regional extraction pumping has a substantial impact on the groundwater system in south Florida. **Figure 7-17** shows the impact of pumping on the model. The drawdown in this figure was calculated by subtracting the heads from a model run with no wells from the heads calculated in the calibration model run. Note that zero drawdowns at the north and west boundaries are not necessarily accurate. Regional pumping affects the heads in observation wells that were used to set the boundary conditions. When the pumping was removed from the model for this analysis, there was no way to remove the impact of pumping at the boundaries.

The majority of the pumping occurs in the northern part of the model. Drawdowns can be significant, exceeding 35-ft in Manatee and Polk Counties. Other areas of significant pumping occur along both coasts and in the section between Lake Okeechobee and the Polk County recharge area.

### 7.4.6 General Flow Observations

The Phase II RASRSM results provide several general insights about groundwater flow in south Florida. Additional details are available in **Appendix E**. General flow observations are summarized below:

- Flow is mostly horizontal in the aquifers and vertical in the confining units.
- The two major sources of groundwater are the BZ along the southern and eastern boundaries and precipitation recharge in the highlands of Polk County.
- Pumping is a major sink to groundwater in the Floridan peninsula.
- Recharge in Polk County causes downward flow of fresh water all the way to the BZ.
- Inward flow of high salinity water in the BZ along the lower east coast is a significant source of water pressure and high groundwater heads throughout southern Florida.
- Most flow is vertically upward in the southern half of the model (south of Lake Okeechobee)

## 7.5 Phase II RASRSM D13R Predictive Simulations

The regional impact of the proposed CERP ASR system was evaluated by applying the storage and recovery rates from the November 1998 D13R simulation on the South Florida Water Management Model [SFWMM] (USACE and SFWMD, 1999) to the RASRSM described in **Section 7.3.4**. The November 1998 D13R simulation on the SFWMM is the "official" simulation recognized by the IMC and constituted the correction of a few errors found in the CERP Yellow Book document (personal communication, Dan Crawford, SAJ).

After first running the RASRSM with the CERP ASR design, simulated ASR wells were removed until limits on the performance measures were met. (See **Section 7.5.2** for a description of the performance measures developed by the PDT.) During the process, simulated ASR wells were added to other aquifers (APPZ, BZ) based on requests from and discussions with the PDT.

The SFWMM is a regional scale, physically based model that combines hydrology and water management practices in southern Florida. Model development began at SFWMD in the 1970s and several major revisions were completed during the last 4 decades. Although the SFWMM includes a groundwater component, it considers only surficial, unconfined flows and addresses them as 2D, vertically averaged flow. ASR wells are incorporated as reservoirs without the evapotranspiration losses. The model simply keeps track of the volumes of injected water (removed from the modeled system), applies a 70 percent recovery efficiency and tracks the volume of the net accumulation of excess water recharged during ASR. Recovered water is limited to the recharged volume. The SFWMM is only able to quantify the impacts of the ASR system on the water demands in the surface system. ASR wells are included as an additional management option for removal of excess water or supplementation during periods of water deficiency (SFWMD, 2005). The SFWMM is not able to consider regional-scale hydrogeologic impacts of the ASR wells in the FAS. The RASRSM was developed to investigate these hydrogeologic impacts which the SFWMM was not able to quantify.

The SFWMM-D13R included CERP and non-CERP projects and determined the volumes of water that would need to be removed or restored by ASR wells in six different basins. The maximum required rate for the ASR wells turned out to be 1.65 billion gallons per day. Assuming that all wells are sized to be able to pump 5 MGD, 333 ASR wells would be required to meet that maximum rate.

Although the SFWMM-D13R designated a certain number of ASR wells for each basin, the PDT for the ASR Regional Study selected a number of property sites near water sources and divided the ASR wells in each basin among the selected sites. The RASRSM-D13R adds the ASR wells to the selected sites and then investigates the regional hydrogeologic impacts of these wells. The 'calibration model' referenced in this section is the RASRSM before the addition of the ASR wells, when it was calibrated to field data from 2003 and 2004 as described in **Section 7.3.4**.

The following sections give an overview of the RASRSM-D13R modeling approach, the selection of a final scenario and the Monte Carlo analysis. Further details are available in the Regional Model Production Scenario Report (USACE, 2014) which is attached as **Appendix E** to this report.

### 7.5.1 Approach

The RASRSM-D13R model was built using the same computational grid and geologic layering as the calibration (RASRSM) model described in **Section 7.3.4**. This analysis made use of the results of all calibration efforts previously described. Changes to the model included the addition of the ASR wells, change of the model time period (which required adjustments to boundary conditions and source/sink terms), and shortened stress periods.

#### 7.5.1.1 Introduction of ASR Wells

USACE provided the daily volumes of recharge and recovery at ASR wells from the SFWMM-D13R scenario for each of 6 basins: Lake Okeechobee, Caloosahatchee River, L-8, C-51, Central Palm Beach, and Hillsboro. The number of wells required in each basin was determined by dividing the maximum flow rate by the expected individual well capacity of 5 MGD. See **Figure 7-18** for the general locations of these basins and **Table 7-3** for the numbers of required wells. Based on discussions with the ASR Regional Study PDT, a total of 16 sites were selected for the simulation of ASR wells. Note that the selection of these sites was based on current state ownership of the land. Other sites may be considered in the future based on future ownership or leases of land. The L-8, C-51, Central Palm Beach and Hillsboro basins each have only one possible site for ASR wells. The Caloosahatchee River Basin has three sites and the Lake Okeechobee Basin has nine.

**Table 7-3 -- CERP ASR Well Counts**

| **Basin** | **Number of CERP D13R Planned ASR Wells (5 MGD each)** |
|---|---|
| Caloosahatchee River | 44 |
| Lake Okeechobee | 200 |
| L-8 | 10 |
| C-51 | 34 |
| Central Palm Beach | 15 |
| Hillsboro | 30 |
| **Total** | **333** |

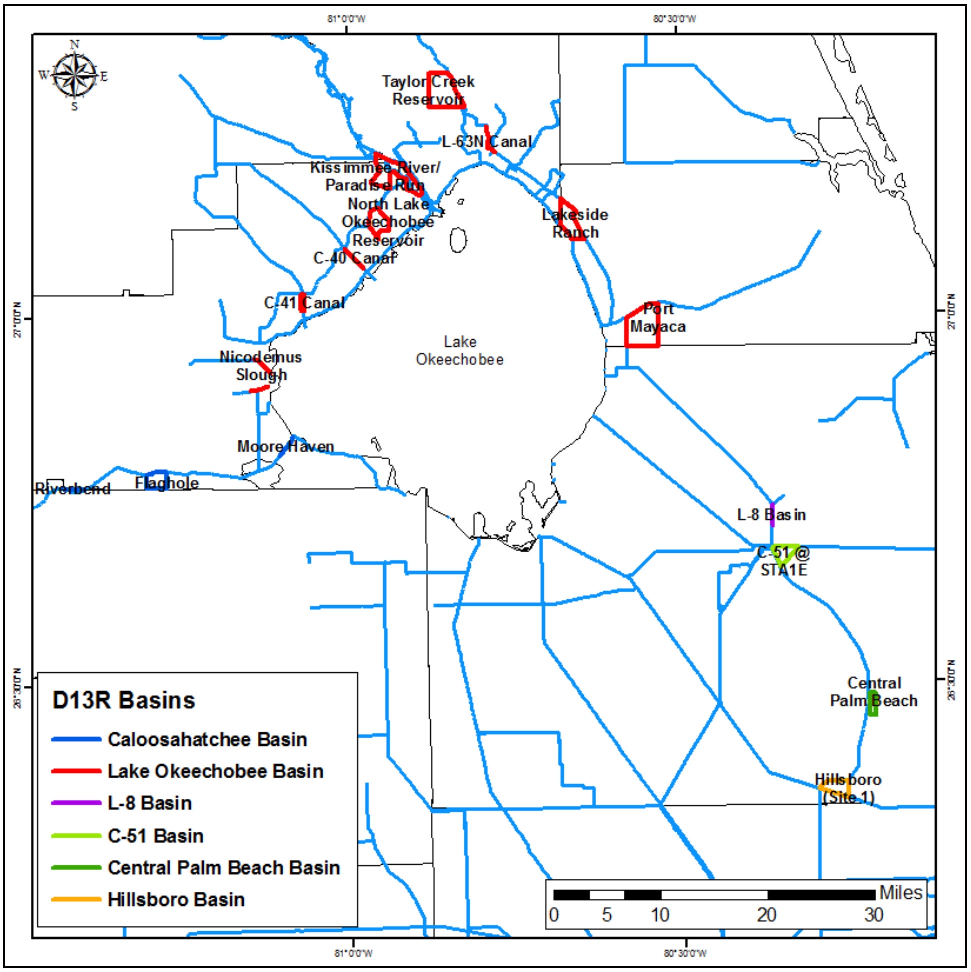


**Figure 7-18 -- Proposed ASR Locations in D13R Basins.**

The wells in each basin were divided among the available sites based roughly on the perimeter length of the sites. As will be described in **Section 7.5.3**, as additional scenarios were developed, the numbers of wells at each site changed from the original design.

### 7.5.1.2 Modeled Time Period

The SFWMM-D13R scenario covered the 30-year period from 1965 to 1995. File size limitations and run times make it difficult to run the RASRSM for such a long period of time. The input and output files for a single 30-year RASRSM-D13R run required nearly 52 GB of storage space and the run-time was between 18 and 30 hours. In addition, some of the input files were too large for the allocation of memory for the file buffer. In order to address the problems of run-times and space requirements, additional computer resources were acquired and the decision was made to run a shorter section of the D13R period.

**Figure 7-19** shows the recharge and recovery rates and available aquifer storage at each basin. Available aquifer storage is a running calculation made by adding 70 percent of recharged water (to account for recovery efficiency) and subtracting recovered water. The year 1965 was selected as the start time for the regional model run so that the starting condition would not be impacted by previous recharge periods. The year 1977 was selected as the end time for the regional model run to include periods covered by SAJ Lake Okeechobee models and to incorporate the entire first cycle of the Lake Okeechobee basin wells (which return to zero stored volume in 1977). An analysis of precipitation data and SFWMM ASR pump rates indicated that this shortened period covers a wide variety of hydrologic conditions similar to what would have been seen with the full 30-year time period.

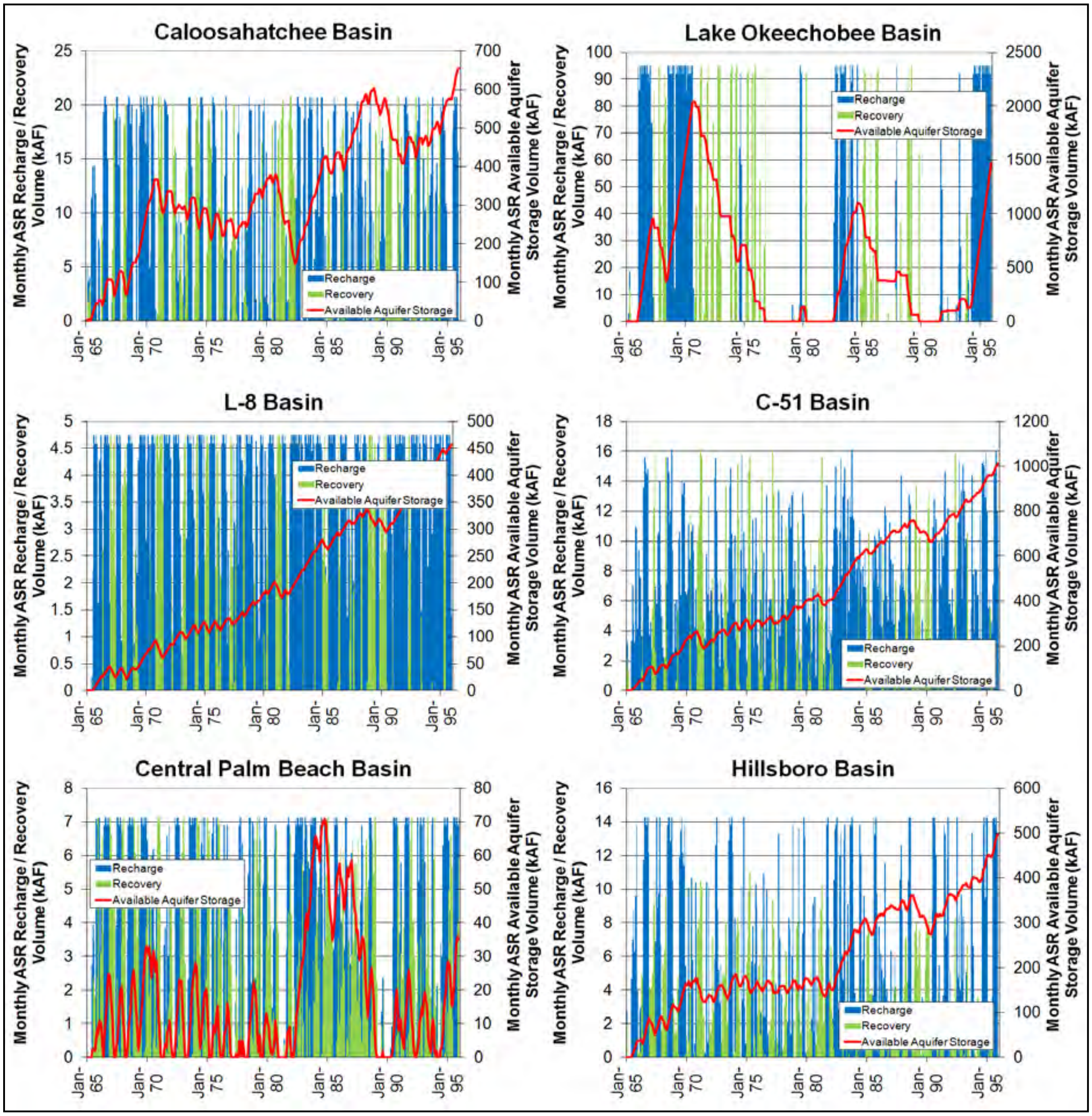


**Figure 7-19 -- Monthly D13R recharge and recovery volumes with running storage volume.**

The adjustment of the modeled time period required the adjustment of both boundary conditions and sources/sinks (regional pumping) to reflect the conditions for the period 1965-1977 (as opposed to the

2003/2004 period used in the calibration model). The boundary conditions and the regional pumping for the D13R period were estimated using trend analyses of some available data and applying the results to the boundary conditions and pumping rates from the calibration model. Greater detail on the methodology is presented in the Regional Model Production Scenario Report (USACE, 2014) which is attached as **Appendix E** to this report. The resulting model was run without ASR wells and compared to some data from the era and found to match reasonably well.

#### 7.5.1.3 Shortened Stress Periods

The calibration model was built with month-long stress periods, meaning that all boundary conditions and sources/sinks were averaged over the month and assumed constant for that period. Time-step sizes (calculation times) were approximately 5 days in length. This provided reasonable precision on the results for comparison to field data and calibration of material parameters.

The month-long stress period was found to be too coarse for the D13R scenarios due to the rapid changes in ASR pumping that often occurred in the SFWMM-D13R output. Pumping often changed significantly on a daily basis, even shifting from recharge and recovery and back again within the same month. In order to more precisely reproduce the ASR pumping schedule, stress periods were set to 10 days, with 5-day time steps. These shorter stress periods resulted in larger output files, but provided a better simulation of D13R pumping scenarios.

### 7.5.2 Performance Measures

The PDT developed a set of performance measures which were used to assess the impacts of the ASR wells to the hydrogeologic system. Several of these performance measures were used to eliminate unrealistic D13R pumping scenarios and are called “specific” performance measures. Other performance measures were simply used to provide decision-making information and are called “informative” performance measures.

#### 7.5.2.1 Specific Performance Measure: Rock Fracturing

One of the initial concerns, expressed early in the regional ASR study process, was that large volume, high pressure recharge into the aquifers would fracture rock that includes the UFA or overlying confining units. Rock fracturing could result in significant, permanent changes to the subsurface hydrogeologic conditions of south Florida and vertical leakage between permeable zones. The PDT turned to Nick Geibel of USACE Omaha District to analyze the strength of the rock and the pressures that would cause rock fracturing (Geibel and Brown, 2012).

This analysis resulted in a calculation of the maximum allowable head at each point in each aquifer. An example result is shown for the UFA in **Figure 7-20**. A similar analysis was made for the APPZ and can be found in USACE (2014), also in Appendix E. In the UFA, the maximum allowable total head in the areas of the proposed ASR sites ranged from 300-ft to 600-ft. In the APPZ, maximum allowable total heads were even higher. Because these limits were so high, other performance measures became limiting factors and the D13R scenario results were not compared to these rock fracturing limits.

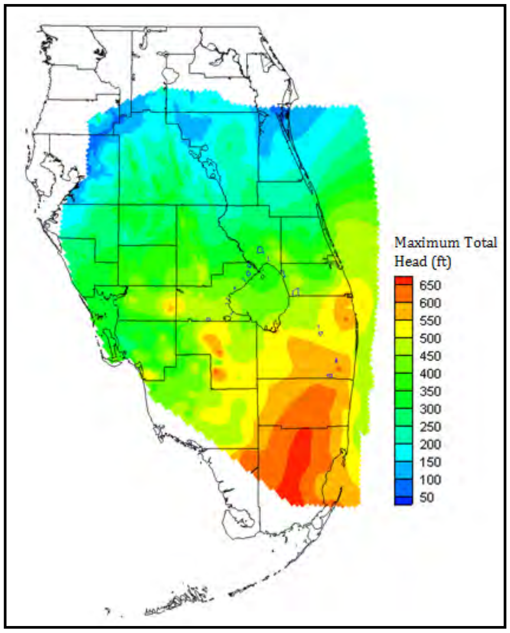


**Figure 7-20 -- Maximum total head estimated to preclude rock fracturing (UFA).**

### 7.5.2.2 Specific Performance Measure: Pump Pressure

As the PDT discussed the ramifications of early model results, it became clear that a limit should be set on the pressure the ASR pumps were required to overcome. The well package in SEAWAT forces the user-defined fluxes into the model without regard to the size of the pump that would be required to achieve this flux rate. The PDT determined that it would be unlikely that an ASR pump would be able to overcome more than 100 psi of head. This is also the pressure at which most FAS wells are tested and the pressure at which both the KRASR and HASR system ASR wells were tested. This performance measure was used in the first few RASRSM-D13R scenarios to eliminate ASR wells from sites where this pressure would be exceeded.

The source of the recharge water was assumed to be a surface water body located near the ASR site. Thus, the head to overcome is approximately equal to the difference between the model-calculated aquifer head and the ground surface elevation at the well, if head losses and pump efficiency are ignored. This head difference can be converted to pressure using the density of water. Greater detail on this calculation is provided in USACE (2014) and **Appendix E**.

### 7.5.2.3 Specific Performance Measure: Artesian Pressure Protection Area (APPA)

Another performance measure requested by the PDT was the evaluation of the impact of ASR on the artesian pressure in the UFA and APPZ aquifers in St. Lucie and Martin Counties. Water users in that area depend on the artesian heads for water withdrawal. Permits for ASR systems in the APPA will require that the flow from artesian aquifers not be reduced by more than 10 percent as a result of the project.

Merritt (1997) presents an equation to estimate the flow from an artesian aquifer. When added to a percent reduction equation and simplified, the remaining parameters include only the ground surface elevation and the aquifer head estimated with and without the ASR wells. This calculation was made for each cell in St. Lucie and Martin Counties at each output time step for the UFA and APPZ. The result was reported with maps of the UFA and APPZ layers with the cells colored by the maximum percent flow reduction across the time period. Additional details are available in the Phase II RASRSM report (USACE, 2014; **Appendix E** of this report).

#### 7.5.2.4 Informative Performance Measure: Head Impacts

Another matter of importance when analyzing the regional effects of the CERP ASR program is the drawdown which might be experienced by neighboring water users due to the extraction cycles on the ASR wells. For permitting purposes, it is important to know the extent of the 1-ft and 5-ft drawdown contours. Since CERP ASR wells in each basin have different pumping schedules and varying rates, it is not reasonable to select a specific time period during the 13-year model run at which maximum drawdown would be expected for the entire model. Instead, the drawdown was calculated for each cell of the model at each output time step by subtracting the head in a model run with no ASR wells from that in the ASR simulation. Then, at each cell, the maximum drawdown was extracted and combined with the maximums in other cells into a single dataset representing the maximum drawdown over the model run period (1965-1977). Note that the maximum drawdown may not occur at the same time in each cell of the model. The 1-foot contour and the 5-foot contour were delineated for each aquifer and these contours are plotted in output figures (see USACE, 2014; **Appendix E** of this report).

Although neighboring users may, at some periods, experience reductions in water levels due to ASR recovery, they will also, at other periods, experience increases in water levels due to ASR recharge (mounding). Similar to the drawdown analysis, the maximum mounding in each cell was combined into a single dataset and the 1-foot and 5-foot mounding contours for each aquifer are presented on maps (USACE, 2014). Note again that the maximum mounding may not occur at the same time in each cell of the model.

The maximum drawdown and mounding figures give a good picture of the worst-case scenario for head impacts. However, this worst case may be a rare occurrence over the 13-year simulation. In addition, the mounding is generally greater and longer lasting than the drawdown. These details are not evident in the previously described maximum drawdown and mounding map figures. To give an idea of the temporal component of head impacts to neighboring users, additional figures are provided for each scenario that show time plots of drawdown and mounding at numerous locations near the ASR sites (USACE, 2014 and Appendix E). These locations are positioned at distances of 5, 15, and 25 miles from the proposed ASR well sites and have been chosen in all radial directions.

Although the drawdown/mounding analysis is listed here as a performance measure, the PDT has not selected a drawdown/mounding limit beyond which the ASR scenario would be rejected. Although these results did not impact scenario selection in the same way that the other performance measures did, these results are important for stakeholders and decision-makers and, as such, is termed an informative performance measure.

#### 7.5.2.5 Water Quality Migration and Salt Water Intrusion

Because the ASR wells will recharge fresh water to mostly saline aquifers, and because the recharge volumes will exceed recovery volumes, it is reasonable to expect that the CERP ASR plan will have a beneficial impact on coastal seawater intrusion and overall water quality in the Floridan peninsula. The PDT wished to quantify this impact since it is an advantage of ASR system over some other components of CERP. Other members of the PDT expressed some concern that the ASR systems might push low quality water into the zone of influence of a water supply well and requested that this possible impact be investigated.

Unfortunately, this regional model is not well-suited to answering these questions for at least two reasons. First, the cells are too large to accurately portray solute transport, especially near the wells. Second, impacts to salinity at locations far from the ASR wells are highly dependent on transport parameters such as dispersion, which could not be calibrated due to lack of TDS time series data and the short time period of the calibration models. Investigations of water quality migration are better suited to pilot study cycle testing with associated local-scale models (USACE and SFWMD, 2013). This performance measure was not evaluated with the regional model.

#### 7.5.2.6 Informative Performance Measure: Ability to Provide Storage/Recovery Designated in SFWMM-D13R

SFWMM-D13R was developed to be able to meet urban, agricultural, and ecological water supply requirements. It also provides storage for excess water that may be required later. Many of the scenarios tested in the RASRSM-D13R involved a reduction in the number of ASR wells from the SFWMM-D13R design, or a reduction in the volume pumped. The volume of stored and recovered water that can be provided by each scenario will be important for decision-makers.

Like the drawdown performance measure, the PDT defined no limit beyond which the scenario would be rejected based on storage and recovery rates, so this is designated as an informative performance measure. Plots are provided showing the total annual injected and extracted volumes for each scenario compared to the volumes defined by SFWMM-D13R. This allows decision makers to quickly analyze the water volumes that would need to be made up using other components of CERP.

### 7.5.3 Development of Scenarios

After the calibrated RASRSM model had been adjusted to reflect the 1965-1977 period as described previously, the model was first set up to run the entire suite of 333 ASR wells as designated in SFWMM-D13R. The locations of these wells are shown on **Figure 7-14.** The results were compared to the full suite of performance measures and then the PDT designed a number of follow-up simulations, which were also analyzed against the performance measures. The following scenarios were run using the regional model and are discussed below:

**Scenario 1:** Full D13R design from SFWMM

**Scenario 2:** Scale back Scenario 1 to meet pump pressure requirement by successively removing wells from the model until pump pressures are near or below 100 psi. This is not a unique design – there may be other arrangements of the wells that will meet this requirement, but will have more or fewer wells or a different distribution of the same number of wells.

**Scenario 3:** Add all wells that were removed for Scenario 2 to the APPZ. This simulation allows for full recharge capacity, but because of the assumed lower (30 percent) recovery efficiency in the APPZ, the recovery volumes are often lower than the original SFWMM-D13R design. Recovery efficiency in the APPZ was estimated based on early results from the Hillsboro ASR Pilot Project (USACE and SFWMD, 2013).

**Scenario 4:** Scale back Scenario 3 to meet pump pressure requirement by successively removing wells from the model (APPZ layer) until pump pressures are near or below 100 psi. This is not a unique design – there may be other arrangements of the wells that will meet this requirement, but will have more or fewer wells or a different distribution of the same number of wells.

**Scenario 9:** Add all wells that were removed for Scenario 4 to the BZ. These wells are to have capacities of 10 MGD and 0 percent efficiency. Because of the doubled capacity, the number of wells in the BZ is half what had been removed from Scenario 4. Some well counts in upper layers were adjusted slightly to prevent the inclusion of "half wells."

**Scenario 10:** Scale back Scenario 9 to meet APPA performance measure and to eliminate drawdown greater than one foot at a distance of one mile from each site.

**Scenario 11:** Scale back Scenario 9 to meet APPA performance measure (allow drawdown of any magnitude outside the APPA.)

**Scenario 12:** Remove BZ wells from Scenario 11.

Scenario 5 was similar to Scenario 9 and was removed from this analysis because it added no unique information. Scenarios 6 through 8 investigated the possibility of using gravity drainage to extract water during recovery periods. The application of the RASRSM to these scenarios was questionable and the PDT ultimately decided to eliminate these runs from the analysis.

### 7.5.4 Final Simulation

Scenario 11 was designed to meet all specific performance measures while balancing impacts to the informative performance measures. It was developed by starting with Scenario 10 and gradually increasing extraction volumes until just before the APPA requirement was exceeded. The resulting design is shown in **Table 7-4**. This simulation was selected by the PDT as the scenario best able to achieve the performance objectives and it was used in the Monte Carlo analysis.

**Table 7-4 -- Scenario 11 Design.**

Recovery efficiency is the ratio of available extraction volume to injected water volume; Extraction percentage is an additional reduction of extraction rates to meet the Artesian Pressure Protection Area rules.

| | Proposed ASR System | UFA (5mgd capacity) | | | APPZ (5 MGD capacity) | | | BZ (10 MGD capacity) | | Total No. Wells | Target No. Wells (at 5 mgd) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | # Wells | Recovery Efficiency (percent) | Extraction Percentage (percent) | # Wells | Recovery Efficiency (percent) | Extraction Percentage (percent) | # Wells | Recovery Efficiency (percent) | | |
| **Caloosahatchee Basin** | **Moore Haven** | 4 | 70 | 100 | 0 | | | 6 | 0 | **27** | **44** |
| | **River Bend** | 3 | 70 | 100 | 1 | 30 | 100 | 2 | 0 | | |
| | **Flaghole** | 2 | 70 | 100 | 0 | | | 9 | 0 | | |
| | **Basin Total** | **9** | | | **1** | | | **17** | | | |
| **Lake Okeechobee Basin** | **Nicodemus Slough** | 0 | | | 10 | 30 | 100 | 0 | | **139** | **200** |
| | **C-41 Canal** | 0 | | | 0 | | | 5 | 0 | | |
| | **C-40 Canal** | 2 | 70 | 100 | 0 | | | 4 | 0 | | |
| | **North Lake Okeechobee** | 8 | 70 | 25 | 2 | 30 | 100 | 5 | 0 | | |
| | **Kissimmee R/ Paradise Run** | 15 | 70 | 25 | 0 | | | 30 | 0 | | |
| | **Taylor Creek** | 0 | | | 10 | 30 | 50 | 5 | 0 | | |
| | **L-63N** | 0 | | | 9 | 30 | 50 | 3 | 0 | | |
| | **Lakeside Ranch** | 4 | 70 | 0 | 0 | | | 8 | 0 | | |
| | **Port Mayaca** | 18 | 70 | 0 | 0 | | | 1 | 0 | | |
| | **Basin Total** | **47** | | | **31** | | | **61** | | | |
| **L-8** | | 6 | 70 | 100 | 0 | | | 2 | 0 | **8** | **10** |
| **C-51** | | 12 | 70 | 100 | 2 | 30 | 100 | 10 | 0 | **24** | **34** |
| **Central Palm Beach** | | 10 | 70 | 100 | 3 | 30 | 100 | 1 | 0 | **14** | **15** |
| **Site 1 (Hillsboro)** | | 10 | 40 | 100 | 0 | | | 10 | 0 | **20** | **30** |
| **Total** | | **94** | | | **37** | | | **101** | | **232** | **333** |

#### 7.5.4.1 Scenario 11 Results and Conclusions

The ultimate purpose of this modeling effort was to find a distribution of ASR wells that would meet all of the specific performance measures while maximizing the volumes of water recharged and recovered according to the SFWMM-D13R pumping schedules. More extensive explanation of the results is provided in Appendix E. Here we present a few key findings.

- Specific Performance Measure: Pump Pressure. Most pump pressures remain below 100 psi with a few being slightly over the limit **(Figure 7-21)**. These exceedances are within the error tolerance of the model.

- Specific Performance Measure: Artesian Pressure Protection Area. Artesian pressure reductions in St. Lucie and Martin Counties meet the 10 percent requirement in both the UFA and APPZ. Areas outside these counties see greater loss of artesian pressure during the extraction periods of the ASR pumping schedule **(Figure 7-22)**.
- Informative Performance Measure: Head Impacts to Neighboring Users. Maximum head impacts are extensive across the model domain **(Figure 7-23).** Note that not all areas will experience these impacts at the same time or all the time. Increased heads are as common as decreased heads.
- Informative Performance Measure: Ability to Provide Storage/Recovery Volumes Designated in SFWMM-D13R. This design, which incorporates a large number of BZ wells with no recovery, can provide the full amount of recharge volume envisioned in SFWMM-D13R. However, recovery volumes cannot be met. The amount of recovered water varies by site and by year, but is between 12 percent and 60 percent during the 13 year period across the entire CERP-envisioned system **(Figure 7-24)**. The variability of the percentage is due to a number of factors, including hydraulic conductivity at the site, numbers of wells at the site, numbers of nearby ASR sites, proximity to St. Lucie and Martin Counties, and previous recharge and recovery activities.

As has been mentioned, this scenario is not unique. There may be other distributions of ASR wells which would provide greater recovery volumes without exceeding the specific performance measures. Further, the current locations were based on present state ownership of the land. Future changes in land ownership or leasing arrangements could result in additional ASR sites which would change the results of this scenario. Selection of new ASR sites in areas of greater hydraulic conductivity, farther from St. Lucie and Martin Counties and placement of additional wells in smaller, more isolated clusters will likely improve recovery volumes. However, with the current constraints, it does not seem likely that ASR alone will be able to provide the total recovery volumes designated the SFWMM-D13R.

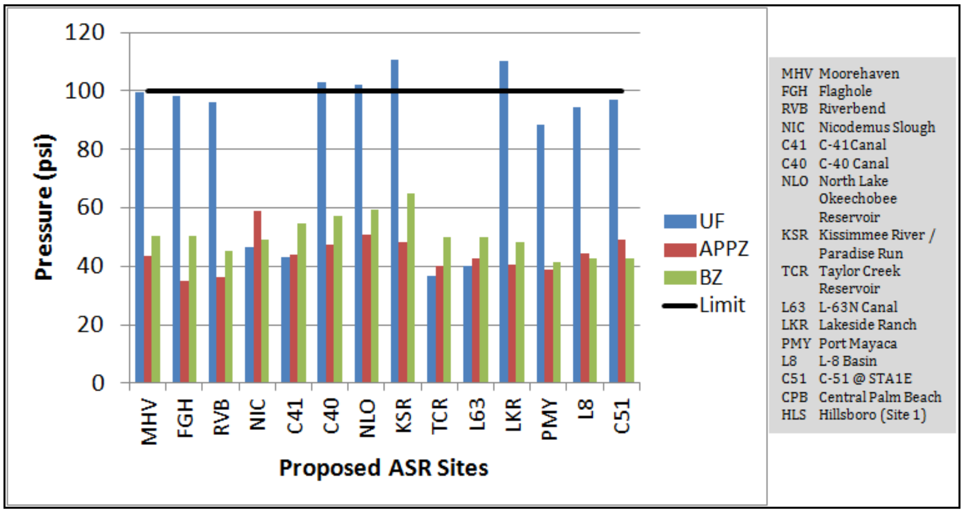


**Figure 7-21 -- Maximum pressure pumps must overcome at each proposed ASR system.**

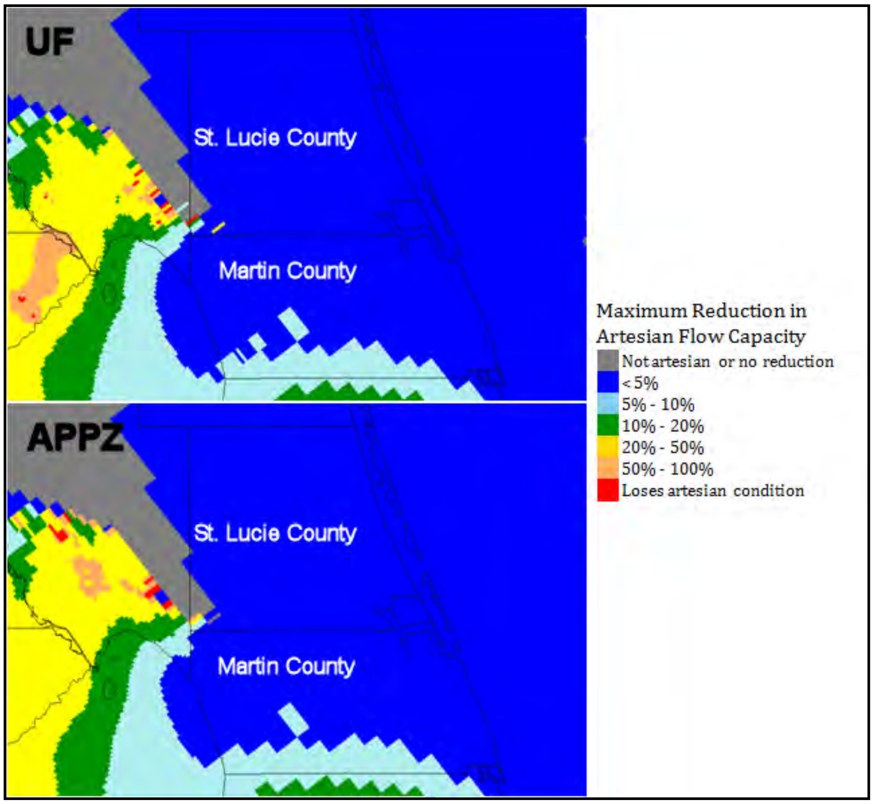


**Figure 7-22 -- Artesian Pressure Protection Area: Maximum percent loss of flow.**

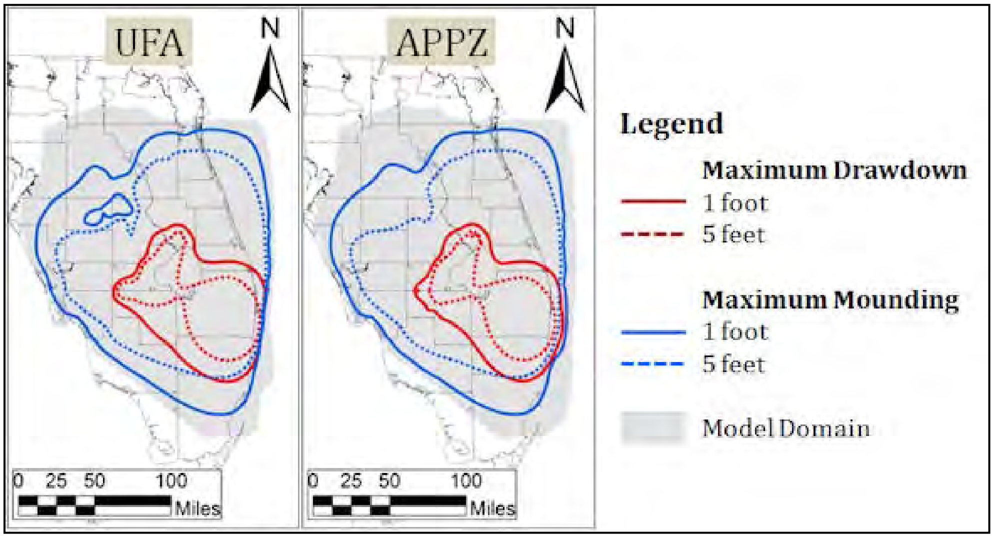


**Figure 7-23 -- Maximum head changes due to CERP ASR pumping in model layers representing the UFA and APPZ.**

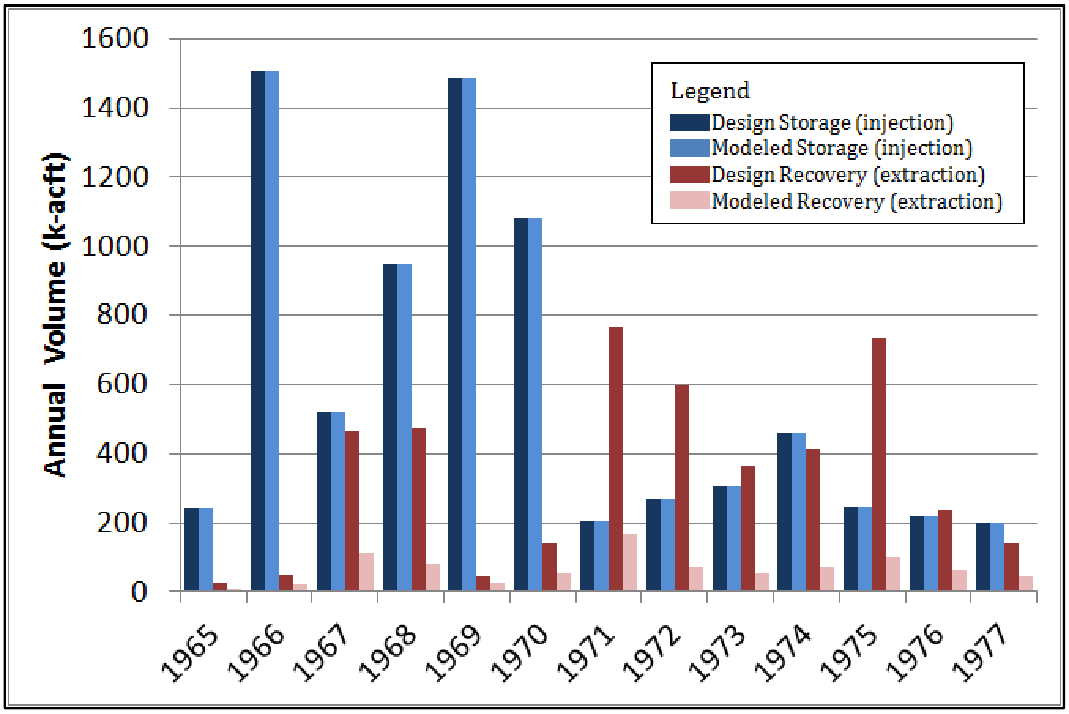


**Figure 7-24 -- Comparison of D13R design to allowable annual volumes.**

#### 7.5.4.2 Supplementary Scenario 12

After the completion of all the production scenario analyses and the Monte Carlo simulation (presented in **Section 7.5.5**), discussions with the PDT and the IMC model reviewers revealed some concerns about the BZ ASR wells from stakeholders not originally involved in the scenario decisions. Concerns included:

- Drilling to BZ depths is quite expensive, perhaps prohibitively so,
- With no recovery cycle, these wells are not truly “ASR wells,”
- Despite the ecological and flood-protection advantages of disposing of excess water through these BZ wells, this water is desperately needed in the Everglades and although there is no current mechanism to transport it there, the idea of disposing of needed water is not palatable to some.

To address these concerns, an additional scenario (Scenario 12) was added which was identical to Scenario 11, except it did not include any BZ wells. See Appendix E for the full results of this and all other scenarios.

### 7.5.5 Monte Carlo Analysis

Often, numerical groundwater modeling is treated in a deterministic way – i.e. the modeler inputs his best guess for all parameters and treats the result as the “correct answer.” In reality, there is uncertainty in all models. Model uncertainty can stem from uncertainty in the input parameters, simplifications made to force the system to fit a mathematical model, error caused by spatial and temporal discretization, etc. It is often more advisable to approach groundwater modeling from a probabilistic standpoint and use the uncertainty in the input parameters to estimate the uncertainly in the output. In a probabilistic model, there is not just one "correct answer;" instead there are a range of possible answers. The decision makers can then provide for a range of possible results in their planning.

A Monte Carlo sensitivity analysis is one way to quantify the uncertainty in the output. In this type of analysis, the input parameters are given probability distributions instead of discrete values. The range and distribution of the values should be an indication of the uncertainty in the parameter. Parameters that are well known or have been measured at the site might be given a narrower range of values than parameters that are unknown or obtained from the literature. The model is then run multiple times with different sets of randomized parameter values selected from those distributions. Assuming that the input distributions are valid, this methodology results in a number of equally probable model results. Instead of reporting a single answer, modelers can report the range and distribution of the model results and planners can design for contingencies based on the output distributions. Also, if the results of the Monte Carlo analysis indicate a wide variability in output, it can signal the need to collect more data to reduce the uncertainty and tighten the variability of the model output.

During the Monte Carlo analysis of the RASRSM, the input parameters for Scenario 11 were randomized and model was run with and without ASR wells using each randomized set of parameters. The results were then analyzed in comparison to the performance measures. The entire process was automated so that the computer could run a large number of randomized scenarios and provide statistics on output without user intervention.

#### 7.5.5.1 Monte Carlo Setup

The input parameters that were varied for this Monte Carlo analysis were porosity, dispersivity, molecular diffusion, hydraulic conductivity, specific storage, starting TDS, starting temperature, the thickness of the BZ and horizontal anisotropy. Their probability distributions varied based on the parameter type and included log-normal distributions and uniform distributions with a few variations. Ranges of acceptable values were set based on estimated uncertainty in the parameter value. In each case, efforts were made to achieve useful levels of variability without straying too far from the calibrated, accepted values.

The process of verifying each randomized simulation is pictured in **Figure 7-25**. Once the distributions were set up, each iteration began by selecting a randomized value for each parameter and running the steady state calibration model. The results were compared to the calibration field data and if the run did not meet a pre-determined error limit, the iteration was abandoned and a new set of randomized parameters was selected. Once the steady state calibration was met, the transient calibration model was run with the same randomized parameters. Again, the results were compared to the calibration field data and those runs not meeting a predetermined error limit were eliminated from consideration.

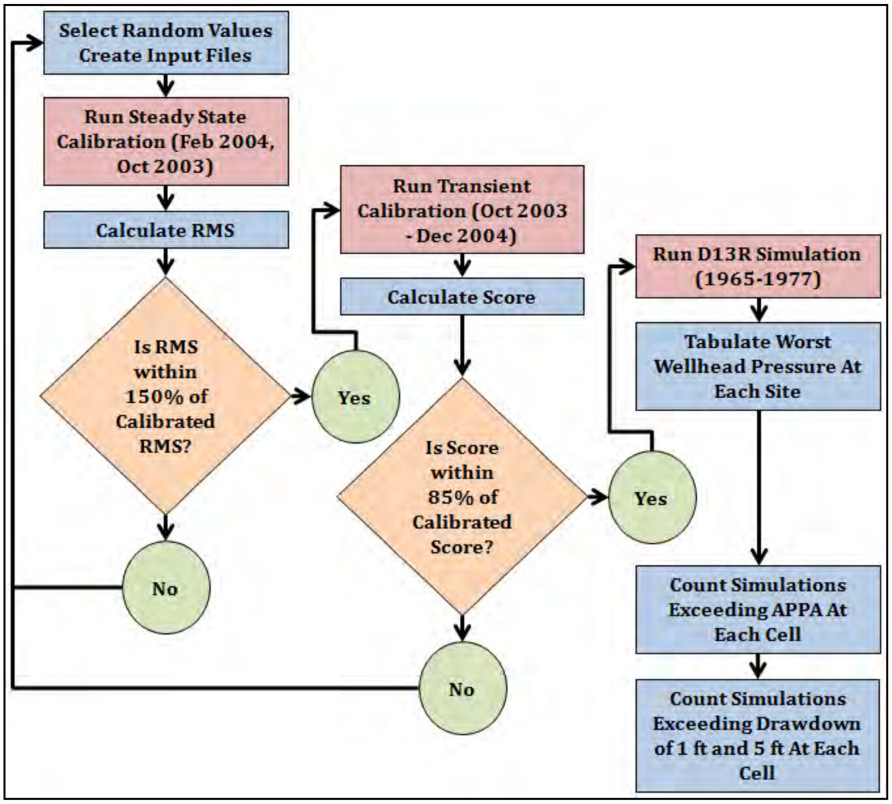


**Figure 7-25 -- Monte Carlo setup.**

Once a randomized model scenario had met both the steady state and transient calibration criteria, the D13R Scenario 11 ASR wells were added to the model and it was run for the 1965-1977 period. A similar model was run without the ASR wells for comparison. The results were then analyzed for compliance with the performance measures. To save computer storage space, the actual solution files could not be saved. Instead, running counts of simulations exceeding performance measures were stored as the simulations finished. The result was a distribution on the performance measure results, which helped quantify the impact of uncertainty of input parameters on the output performance measures. In total, 825 scenarios were run to completion and their results were used in the analysis.

#### 7.5.5.2 Monte Carlo Results

The final result of the Monte Carlo simulation included:

- A grid dataset showing the number of Monte Carlo simulations with a loss of more than 10 percent of the artesian pressure at each cell,
- A grid dataset showing the number of Monte Carlo simulations with more than 1 foot of maximum drawdown at each cell,
- A grid dataset showing the number of Monte Carlo simulations with more than 5 feet of maximum drawdown at each cell, and

- A list of the maximum pump pressures encountered at each proposed ASR site for each Monte Carlo iteration.

These results are shown in **Figure 7-26** through **Figure 7-28**.

**Pump Pressure.** For all of the UFA sites, the majority of the Monte Carlo runs met the pressure requirements. The percentages and the spread of the results vary significantly, however. Some results of the Monte Carlo pump pressure calculations are shown in **Figure 7-26**. More detailed results are shown in USACE (2014) and Appendix E. Note that all Monte Carlo simulations met the pump pressure requirement at all sites in the APPZ and BZ.

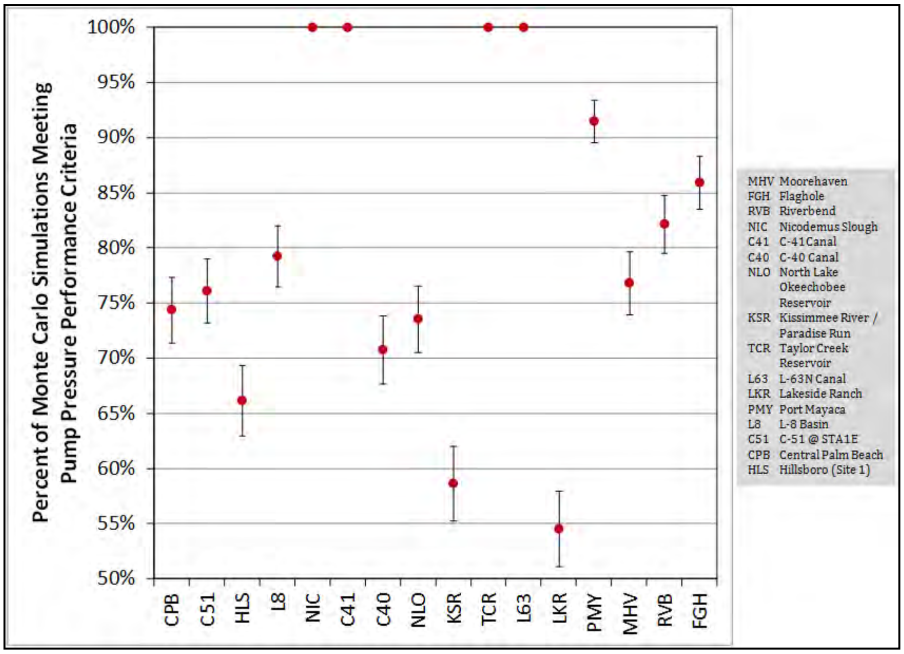


**Figure 7-26 -- Monte Carlo Results. Percent of random scenarios meeting pump pressure performance criteria.** Vertical bars indicate 95 percent confidence interval.

Only four sites passed the criteria for every Monte Carlo run, but these are the four sites that have no ASR wells assigned to the UFA in Scenario 11. All other sites failed the criteria at least part of the time, so there is a possibility that the number of ASR wells would need to be reduced at some or all of the sites. The most critical sites are Kissimmee River and Lakeside Ranch, both of which slightly exceeded the 100 psi requirement in Scenario 11. Hillsboro is the third most critical site, although it was below the limit in Scenario 11.

**Artesian Pressure Protection Area.** One of the performance criteria was that not more than 10 percent of artesian well flow be lost in the APPA, in St. Lucie and Martin Counties. As the Monte Carlo simulations finished, each cell was investigated and the loss of artesian pressure was calculated. The number of simulations where more than 10 percent of the artesian pressure was lost was summed up for each cell in the model. **Figure 7-27** shows the percentage of Monte Carlo runs where more than 10 percent was lost at any time during the 13-year simulation. These results show that the distribution of ASR wells in Scenario 11 is very likely to be able to meet this performance measure. More extensive results are presented in USACE (2014) and Appendix E.

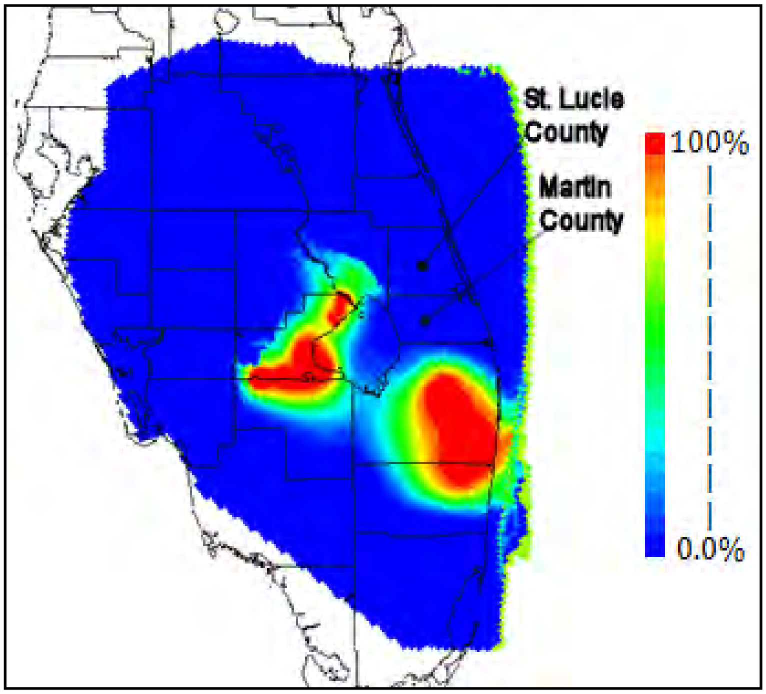


**Figure 7-27 -- Monte Carlo Results. Percent of random runs which exceeded 10 percent artesian flow loss at any time during the 13-year simulation (UFA).**

**Drawdown.** Drawdown was not a specific performance measure, since there was no specific limit on how much drawdown would be allowable or the distance at which impacts could be felt. However, the drawdown impacts to the neighboring areas were investigated and incorporated into the Monte Carlo simulation. After each Monte Carlo run, the maximum drawdown was computed for each cell of the grid. It is important to note that this magnitude of drawdown is a worst-case condition and would not be found during most of the run period. In fact, the figures in USACE (2014) show that the water table actually rises during much of the period. As the Monte Carlo analysis progressed, the scenarios with greater than 1 foot drawdown, and greater than 5 feet drawdown, were counted for each cell.

**Figure 7-28** shows the percentage of Monte Carlo scenarios that had a maximum drawdown in the UFA greater than 5 feet sometime during the 13-year simulation. More extensive results are provided in USACE (2014) and Appendix E. Impacts to the head surrounding the ASR sites are significant. Red areas, indicating nearly all Monte Carlo simulations exceeded 5-feet drawdown, are large. It is likely that maximum drawdown across Glades County, Palm Beach County, Broward County and Lake Okeechobee will exceed 5 feet at times.

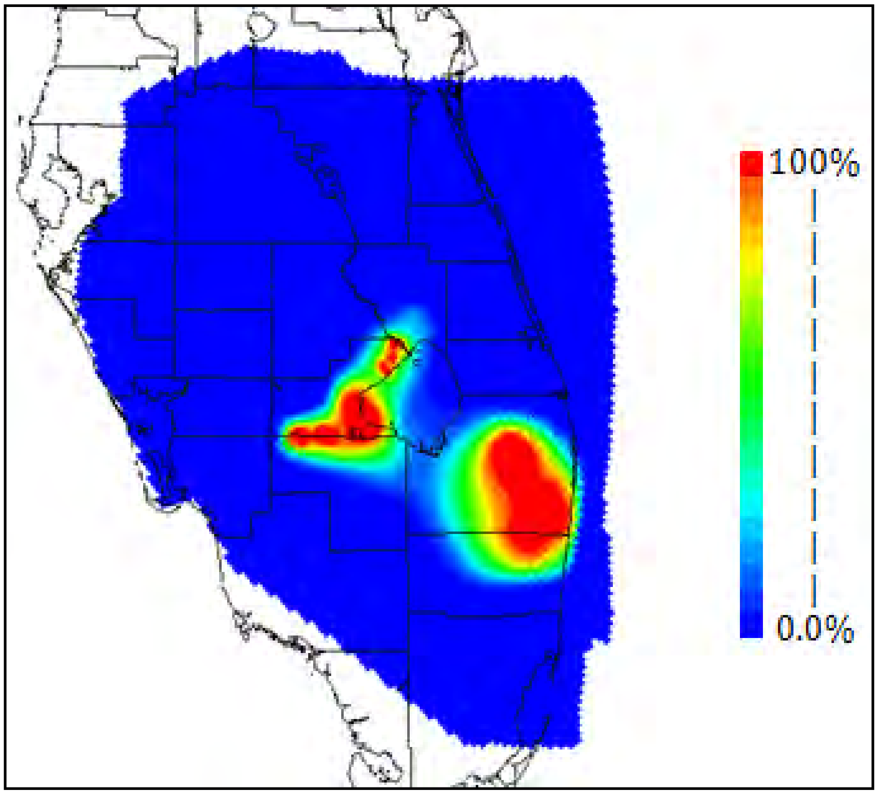


**Figure 7-28 -- Monte Carlo Results. Percent of random runs which exceeded 5 ft drawdown at any time during 13-year simulation (UFA).**

## 7.6 Summary and Conclusions

The models described in this chapter were developed in support of CERP to look at regional hydrogeologic impacts of the proposed 333 ASR wells in southern Florida. The modeling project was developed in stages to provide opportunities for testing hypotheses and methods before application to the final model. Each stage was reviewed independently by the PDT and the IMC. Comments were incorporated into final documents. The documents are available as **Appendix E** attached to this document.

The project began with a search of available models and literature **(Section 7.7.3.1**). This provided valuable information and background and offered recommendations on implementation details. The bench scale study **(Section 7.7.3.2)** evaluated several modeling codes and recommended the use of SEAWAT and WASH123D.

The Phase I Study models **(Section 7.7.3.3**) were coarsely refined and did not include all of the data used in later versions. Most notably, the pumping data were not yet available at the time of Phase I model development. This model provided information on where best to set boundaries and what types of parameter values might be most useful. This model had difficulty reproducing both the salinity and heads in the southern part of the model and led to additional research and study to determine the cause of this difficulty and to recommend options for improvement in the Phase II model.

The Phase II Calibration models **(Section 7.3.4**) were much more finely gridded and included all of the available data, including regional pumping. These models were very closely calibrated to all of the available head data. Extensive sensitivity analyses looked at possible variability in the results. This model was subjected to the greatest degree of review and scrutiny both during the modeling process and after completion of the report. This review process was meant to ensure that the result was as accurate and defensible as possible, given the available data.

The calibration model was broadened to include the D13R scenario with ASR pumping rates and schedules drawn from SFWMM-D13R **(Section 7.7.5**). Changes to the design were made to meet PDT-developed performance measures, including the pressure that well pumps would be required to overcome and the effect of the ASR system on the APPA in St. Lucie and Martin Counties. The suggested arrangement of these wells (Scenario 11) is indicated in **Table 7-4**. Although full recharge potential will be available, a significant reduction in the available water for recovery will limit the effectiveness of the system. The model also indicates that this arrangement of wells will result in significant head impacts over a large area of the Floridan peninsula.

Due to the depth and poor water quality in the BZ, it is unlikely that so many BZ wells could be built. Scenario 12 was developed to simulate a more likely scenario including only the UFA and APPZ wells. The comparison of these results to the performance measures is only slightly different from Scenario 11 but it involves a significant reduction in storage capacity for the system.

A Monte Carlo analysis (**Section 7.7.5.5**) of the results of Scenario 11 showed that some additional reduction in the number of wells or the extraction rates may be necessary at a few sites due to pump pressure limitations. The sites most likely to require a small reduction in ASR wells are Lakeside Ranch, Kissimmee River/Paradise Run and Hillsboro (Site 1). It is unlikely that any further reduction will be necessary in protection of artesian conditions in St. Lucie or Martin Counties, though the design for Scenario 11 already includes significant reductions in extraction volumes for several sites around the northeast shore of Lake Okeechobee.

The RASRSM-D13R run makes assumptions about the conditions of the aquifer, the seasonal variations during the 1960s and 1970s and the recovery efficiencies expected from the aquifers. All of these assumptions will need to be closely analyzed through pilot studies at the proposed ASR sites with local scale models to predict the local effects of the ASR well system.

The final results show that it is unlikely that the aquifer will sustain the pumping requirements of 333 UFA ASR wells as defined in the CERP plan. The modeling process showed that pump pressure requirements and protection of the APPA can be met with approximately 94 ASR wells in the UFA, 37 ASR wells in the APPZ and 101 ASR wells in the BZ if the extraction at sites near the APPA is significantly reduced.

# 8 Ecological Risk Assessment: Effects of ASR on the Lake Okeechobee and Greater Everglades

## 8.1 Introduction

In response to concerns expressed by the South Florida Ecosystem Restoration Working Group (SFERWG) and the National Academy of Sciences Committee on the Restoration of the Greater Everglades Ecosystem (CROGEE), the Jacksonville District of the Army Corps of Engineers (USACE) and the SFWMD conducted ecological, toxicological, and modeling studies to quantify the risks and benefits of implementing CERP ASR. These studies culminated in an Environmental Risk Assessment (ERA) Report that is included in this document as **Appendix F**. A summary of the major study efforts (ecotoxicology, hydrologic /water quality modeling, and mercury methylation) are provided followed by the conclusions from the ERA.

## 8.2 Ecotoxicology

This section describes the measured effects of ASR recovered water on a broad set of aquatic organisms. These data were developed through the use of laboratory toxicological tests, onsite studies, and field assessments. In order to evaluate the intensity of the effects, a series of laboratory, onsite and in-situ studies were developed and conducted during cycle tests 1 and 2 at KRASR. Acute and chronic studies were conducted with algae, invertebrates, fish and frogs. The effects included mortality, growth, reproduction, and bioaccumulation potential. Toxicological data was developed by exposing test organisms to control water and increasing dilutions of recovered waters (up to full strength recovered water). In situ studies included periphytometers, bioaccumulation studies and stream condition index measurements.

### 8.2.1 Acute and Chronic Toxicology

An ecotoxicology research program was conducted to identify a set of aquatic tests to evaluate the ecotoxicity and bioconcentration potential of ASR recovered waters discharged to aquatic ecosystems (Johnson, 2005; Johnson et al., 2007). All toxicity tests conducted at KRASR are summarized in **Table 8-1** for all cycles. Over 80 acute and chronic toxicity tests were conducted as part of this effects characterization at KRASR. Most likely this is the largest development of acute and chronic toxicity dataset for an ASR system. An effect on reproduction of *C. dubia* was observed during cycle test 1 in two of the tests using recovered water. The March 10, 2009 test showed a statistically significant difference between the 12.5 percent recovered water and the controls. This data point is considered a test anomaly since no effects on reproduction were observed at higher recovered water concentrations up to 100 percent. The March 24, 2009 sample of recovered water showed an **$IC_{25}$ of 95.52 percent**, indicating a minor but measurable reduction in reproduction of the water flea in 95.52 percent recovered water. Cycle test 2 showed an effect on reproduction on two tests. The November sample showed a decrease in reproduction in **100 percent** recovered water and the last sample near the completion of the cycle showed an **$IC_{25}$ of 76.4 percent.** Cycle test 3 had one sampling event (May 2011) that showed effects on the survival (96-hour LC50 of 83.92 percent) and reduced reproduction (**$IC_{25}$ of 7.2 percent**), also near the end of the cycle. Two of the mid-cycle samples during cycle test 4 also showed chronic effects on *C. dubia* reproduction with **$IC_{25}$** of **83.9** and **76.2** percent. But the following three monthly tests did not show this effect.

There appears to be a change in recovered water quality that occurs during the mid- to late-period in the recovery cycles that results in a slight reduction in reproduction of this sensitive invertebrate species. Except for the May 2011 test, all other chronic test results show a minor, but measurable, reduction in reproduction. These chronic tests also show that a recovered water dilution greater than 50 percent would not be expected to elicit this effect on reproduction. The May 2011 showed the highest effect ($IC_{25}$ of 7.2 percent) and these results appear to be valid. A separate acute test also showed acute toxicity to *C. dubia* with that sample. This effect observed on this sample during cycle test 3 was not apparent in the subsequent samples taken in May 2011. Similar results were observed during cycle test 4, slight chronic toxicity in the second and third month, but no further toxicity later in the recovery cycle. Frog Embryo Teratogenesis Assay – *Xenopus* (FETAX) tests were conducted three times during cycle test 1 and three times during cycle test 2 using recovered water. These tests did not show a quantifiable effect of the recovered water on the survival, malformations, or growth.

Overall, the recovered water from KRASR did not show quantifiable acute or chronic effects on any species tested with the exception of the sensitive cladoceran *C. dubia*. The effect observed was on reproduction of this sensitive cladoceran species, showing that at times during mid- to late cycle the recovered water at concentrations greater than 50 percent had an inhibitory effect on the reproduction of this species. The cause for this chronic effect is not known. Toxicological testing at HASR did not identify any chronic or acute toxicity associated with recovered ASR water.

### 8.2.2 Bioconcentration

Bioconcentration studies were conducted at the KRASR during the recharge and recovery periods of cycle test 1 (mobile laboratory exposures of fish and mussels) and the recovery period of cycle test 2 (field exposures using caged mussels). During cycle test 4 field collected mussels were evaluated for metal concentration in their tissues. During the mobile laboratory bioconcentration studies, the metals analyzed in the recharge/recovered waters and animal tissues were mercury (total and methyl mercury), arsenic, molybdenum, antimony, aluminum, cadmium, chromium, nickel, selenium, and zinc. Radium-226 and -228 radionuclides were also analyzed in freshwater mussels. The recovered water bioconcentration study was conducted using a laboratory control and three treatments as follows:

- Laboratory control water prepared using reverse osmosis water
- RCV: Recovered ASR water, 100 percent unaltered
- BSW: Background surface water (receiving water), 100 percent unaltered
- MIX: 50/50 mixture of receiving water and recovered ASR water

The objectives of these bioconcentration tests were to evaluate the potential accumulation of selected metals and radium in the tissues of the test organisms exposed to surface water and recovered water. Statistical comparisons were made to determine if there was a difference in metal concentrations in treatment types and tissue concentrations. During cycle test 1, arsenic, nickel and mercury increased in

**Table 8-1 -- Summary of Acute and Chronic Toxicity Test Results for all KRASR Cycle Tests**

| Cycle | Phase | Test Initiation Date | *Selenastrum capricornutum* 96-hr Chronic (Green Algae) | *Ceriodaphnia dubia* 7-day Chronic (Water Flea) | | *Pimephales promelas* 7-day Chronic (Fathead Minnow) | *Daphnia magna* 21-day Chronic (Water Flea) | | FETAX Frog Embryo Toxicity Assay (Frog – *Xenopus*) | | | *C. dubia* 96-hr Acute (Water Flea) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 96-hr growth test (NOEC) | Percent Survival test (NOEC) | Reproduction test (NOEC/$IC_{25}$) | Embryo-larval survival and teratogenesis test (NOEC) | Chronic survival test (NOEC) | Chronic reproduction test (NOEC/ $IC_{25}$) | Mortality significantly different from control? | Malformation significantly different from control? | Growth significantly different from control? | Acute survival test ($LC_{50}$) |
| Cycle 1 | RCG[1] | Jan 13-15, 2009 | 100 percent | 100 | 100 percent/ >100 percent | >100 percent | 100 percent | 100 percent/ >100 percent | No | No | No | >100 percent |
| | | Feb 2-3, 2009 | 25 percent | 100 percent | 100 percent/ >100 percent | >100 percent | | | No | No | No | |
| | Recovered water (RCV) | Mar 10-12, 2009 | 100 percent | 100 percent | >100 percent | | 100 percent | 100 percent/ >100 percent | No | No | No | >100 percent |
| | | Mar 16-20, 2009 | 100 percent | 100 percent | 100 percent/ >100 percent | | | | No | No | No | >100 percent |
| | | Mar 23-26, 2009 | 100 percent | 100 percent | 100 percent/ **$IC_{25}$95.5 percent** | >100 percent | | | No | No | No | |
| | | Mar 31–Apr 2, 2009 | 100 percent | 100 percent | 100 percent/ >100 percent | >100 percent | | | | | | >100 percent |
| | | Apr 7, 2009 | | | | >100 percent | | | | | | |
| | | Apr 17, 2009 | | | | | | | | | | >100 percent |
| Cycle 2 | RCV | Oct 28-29, 2009 | 100 percent | 100 percent | 100 percent/ >100 percent | >100 percent | | | No | No | No | >100 percent |
| | | Nov 17-19, 2009 | 100 percent | 100 percent | 50 percent / >100 percent | >100 percent | | | | | | >100 percent |
| | | Dec 7-10, 2009 | 100 percent | 100 percent | 100 percent/ >100 percent | >100 percent | | | No | No | No | |
| | | Dec 22, 2009 | | | 50 percent / **$IC_{25}$ 76.4 percent** | | | | | | | >100 percent |
| | | 31-Dec 31, 2009 | | | | >100 percent | | | | | | |
| | | Jan 2-4, 2010 | | | | | | | No | No | No | >100 percent |

**Table 8-1 -- Summary of Acute and Chronic Toxicity Test Results for All KRASR Cycle Tests, *continued.***

| Cycle | Phase | Test Initiation Date | ***Selenastrum capricornutum*** **96-hr Chronic (Green Algae)** | ***Ceriodaphnia dubia*** **7-day Chronic (Water Flea)** | | ***Pimephales promelas*** **7-day Chronic (Fathead Minnow)** | ***Daphnia magna*** **21-day Chronic (Water Flea)** | | **FETAX Frog Embryo Toxicity Assay (Frog – *Xenopus*)** | | | ***C. dubia*** **96-hr Acute (Water Flea)** | ***C. leedsi*** **96-hr Acute (Bannerfin shiner)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 96-hr growth test (NOEC) | Percent Survival test (NOEC) | Reproduction test (NOEC/IC$_{25}$) | Embryo-larval survival and teratogenesis test (NOEC) | Chronic survival test (NOEC) | Chronic reproduction test (NOEC/IC$_{25}$) | Mortality significantly different from control? | Malformation significantly different from control? | Growth significantly different from control? | Acute survival test (LC$_{50}$) | 96-hr growth test (NOEC) |
| **Cycle 3** | **RCV** | January 2011 | | | 100 percent / >100 percent | >100 percent | | | | | | >100 percent | >100 percent |
| | | February 2011 | | | No test | No test | | | | | | >100 percent | >100 percent |
| | | March 2011 | | | No test | No test | | | | | | >100 percent | >100 percent |
| | | May 2011 | | | **IC$_{25}$ 7.2 percent** | >100 percent | | | | | | **83.92 percent** | >100 percent |
| | | June 2011 | | | >100 percent/ 100 percent | >100 percent | | | | | | >100 percent | >100 percent |
| **Cycle 4** | **RCV** | January 2013 | | | >100 percent/ 100 percent | >100 percent | | | | | | >100 percent | >100 percent |
| | | February 2013 | | | >100 percent<br>**IC$_{25}$ 83.9** | >100 percent | | | | | | | |
| | | March 2013 | | | >100 percent /<br>**IC$_{25}$ 76.2** | >100 percent | | | | | | >100 percent | >100 percent |
| | | April 2013 | | >100 percent | >100 percent/ >100 percent | >100 percent | | | | | | >100 percent | >100 percent |
| | | May 2013 | | >100 percent | >100 percent/ >100 percent | >100 percent | | | | | | >100 percent | >100 percent |
| | | June 2013 | | >100 percent | >100 percent/ >100 percent | >100 percent | | | | | | >100 percent | >100 percent |

NOTES: RCG = Recharge water (source water) , RCV = Recovered water mussel tissue exposed to the BSW and the MIX samples. In fish tissue, molybdenum increased in the MIX sample.

The objective of the bioconcentration *in situ* exposures of caged mussels was to evaluate the potential uptake of metals and radium from recovered water, and its natural dilution in the receiving water body during the recovery period. This study was conducted using the freshwater mussel *E. buckleyi*, similar to the bioconcentration study conducted during cycle test 1 recovery. Mussels were housed in cages, with individual compartments to maintain equal spacing and thus similar exposure for each mussel **(Figure 8-1)**. Three cages were deployed at each station location.

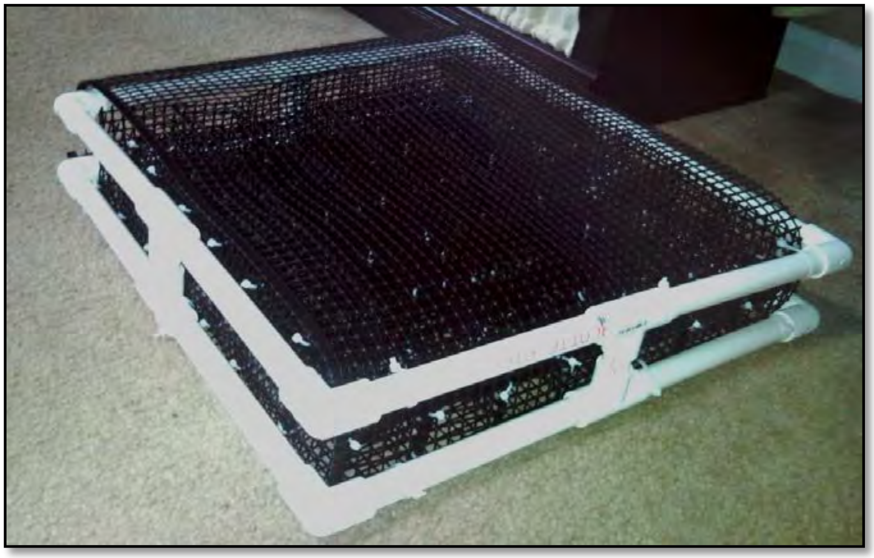


**Figure 8-1 -- Cages for freshwater mussel exposures.**

The exposure locations for the in situ bioconcentration study are shown in **Figure 8-2**. Mercury was found to be significantly higher at the discharge stations than background conditions (p=0.004), while control stations were not significantly different from either background or discharge. Methyl mercury concentrations, however, were found to be significantly lower at the discharge stations than background, and background was significantly lower than control stations (p<0.001). Molybdenum concentrations were higher at the discharge than either the background or control mussels (p<0.001). Treatment was a significant factor (p=0.012) in determining arsenic concentration in mussels with higher concentrations observed at the discharge than control stations. A system-wide effect over time was also observed with significantly higher (p<0.001) concentrations on day 35 than day 0 (background) or day 69.

Native mussels were collected in the vicinity of the KRASR during recharge and near completion of the KRASR cycle test 4 recovery phase. These data appear to show that radiation and mercury tissue concentrations in native river mussels were lower in the Kissimmee River near the end of the recovery period as compared to the recharge period. This is an unexpected result for radiation; however, the lower mercury tissue concentrations are consistent with reduced mercury concentration in the recovered water. There is insufficient data to be sure if these observations are related to the ASR discharges. Manganese and arsenic appear to be slightly higher in mussel tissue during May as compared to December and this could be related to the ASR discharge, but not confirmed through these data. To reduce uncertainty regarding the potential for metals bioaccumulation, additional testing of sessile local fauna is indicated for future ASR testing and operation.

**Figure 8-2 -- Location of *in-situ* exposure of caged mussels, periphytometers, and water quality sondes during the KRASR cycle test 2 recovery period.**

### 8.2.3 Periphyton

Periphyton baseline field studies were included in the ecotoxicology program in order to include plant communities in the assessment of potential risks and/or benefits of ASR implementation. Periphytometers were deployed in the Kissimmee River concurrent with the cycle test 1 KRASR recharge and recovery periods and during cycle test 2 recovery at stations shown in **Figure 8-3.**

Diatom taxa were generally the most abundant and most of the dominant taxa in this data have species that are associated with nutrient-rich environments. Nutrients can influence periphyton abundance and community structure, but other factors (e.g. light availability, amount of colonizable substrate, water temperature, and grazer abundances) can weaken generally positive nutrient-periphyton abundance relationships. Dissolved metals, even at relatively low concentrations, also have been associated with reduced periphyton abundance and shifts in community composition after a few weeks of exposure. While there is no evidence that KRASR recovery water had a significant influence on periphyton communities compared to upstream and downstream sites, low level site repetition and variability in sites used for incubation precludes an in-depth statistical analysis of the periphyton data.

**Figure 8-3 -- Location of stations for periphytometer deployment during KRASR cycle test 1.**

## 8.3 Hydrologic and Water Quality Modeling

Hydrologic, hydrodynamic, hydrogeologic, and water quality simulation models were used to develop plausible ASR implementation scenarios for the Lake Okeechobee Basin and to characterize ASR exposure pathways in terms of timing, intensity and special distribution. **Figure 8-4** shows the modeling scheme that links the SFWMM D13R simulation output to the RASRSM, LOOPs, LOEM, and ELM-Sulfate modeling efforts.

The original CERP plan to construct and operate 200 ASR wells within the Lake Okeechobee Basin was specified in the Central and South Florida Restudy Report (USACE and SFWMD, 1999). The D13R scenario originally prepared for the Restudy Report did not consider possible hydrogeologic or engineering constraints on the number and placement of CERP ASR facilities. Since the placement and operation of CERP ASR wells are key to defining the spatial component of the exposure pathways, additional CERP ASR scenarios were developed to ensure that the RASRSM considered consistent and plausible alternatives.

The additional ASR scenarios were initially developed using a regional groundwater model to determine the hydrogeologic feasibility of well placement and operation scenarios. These scenarios as defined by the number of wells, aquifer placement, and assumed recovery efficiency, were input into the LOOPS model to determine the timing and duration components of the exposure pathway. The output from the LOOPS model was used to define the timing and duration of ASR exposure for each alternative scenario as well as to provide ASR flow boundary conditions (recharge and recovery event timing and duration) for the Lake Okeechobee Environmental Model (LOEM).

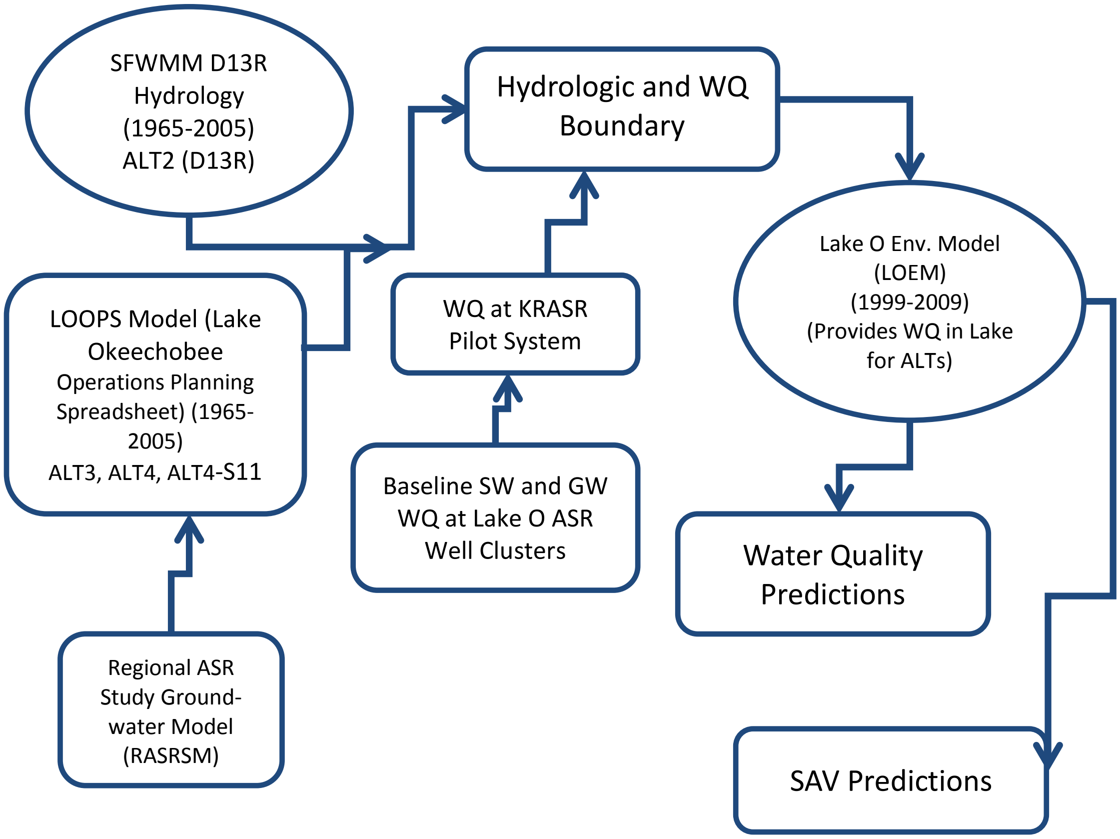


**Figure 8-4 -- Modeling scheme used to evaluate water quality impacts of ASR scenarios in Lake Okeechobee**

The LOEM is a hydrodynamic and water quality model of Lake Okeechobee. It was used to simulate the water quality and SAV impacts due to changes to the lake operation schedule. The water quality assumptions for ASR exposure were developed from available surface and groundwater quality data as well as water quality data collected from the Kissimmee ASR Pilot site.

**Figure 8-5** shows the locations of potential ASR well clusters within the Lake Okeechobee Basin. Model simulation outputs for the Lake Okeechobee Basin were the basis for estimating the exposures to the near-field, mid-field, far-field, and far-far field receiving water bodies for the ASR scenarios evaluated in the ERA. The scenarios considered were the following:

- **Alternative 1 -** ALT1 is the no-action alternative. Under this alternative, no ASR facilities or wells would be constructed or operated.

- **Alternative 2 -** ALT2 includes 200 wells within the Lake Okeechobee Basin. This scenario matches the original D13R scenario from the CERP report in terms of the number of wells in the basin, their placement in the UFAZ, and their assumed recovery efficiency of 70 percent. The regional hydrogeologic modeling determined that this implementation scenario posed unacceptable groundwater stage conditions during recharge and recovery and thus was not considered feasible.
- **Alternative 3 -** ALT3 includes 100 wells within the Lake Okeechobee Basin. This scenario is essentially half the size of ALT2 and it also has the wells placed in the UFAZ.
- **Alternative 4 -** ALT4 includes 200 wells within the Lake Okeechobee Basin; however, some of these wells are placed in the APPZ and BZ portions of the Floridan Aquifer in order to ensure that they don't result in excessive recharge pressures during recharge or groundwater stage drawdown during recovery.
- **Alternative 4-S11 -** Alternative 4-Scenario 11 (ALT4-S11) has the same number of wells and placement as ALT4. This scenario was developed by the hydrogeologic team to further refine the operating scheme of ALT4 to reduce recovery volumes so that ASR operations would not exceed Martin and St. Lucie Counties groundwater protection rules that require the maintenance of artesian conditions in the Floridan Aquifer.

Each of the simulation models used in the ERA was configured to simulate the ASR implementation scenarios. A short description of each modeling effort along with key output is provided.

**Figure 8-5 -- Proposed well cluster locations within Lake Okeechobee basin.**

### 8.3.1 SFWMM D13R Simulation

The location, frequency, magnitude, and duration of CERP ASR recharge and discharge events are provided by the D13R version of the South Florida Water Management Model (SFWMM) 2x2 regional surface hydrology model. The ASR D13R output was used to drive the operation of the ASR wells in the

ASR Regional Groundwater models (see below) as well as to define critical exposure conditions for surface waters exposed to ASR discharges. Additional SFWMM 2x2 modeling was not done to develop other CERP ASR implementation scenarios for the Regional ASR study due to the cost and time involved. The Lake Okeechobee Operations Planning Spreadsheet (LOOPS) model, described below, was used to the develop Lake Okeechobee basin ASR implementation hydrology other than that defined by the D13R assumptions.

### 8.3.2 Regional Groundwater Model for CERP ASR

The regional groundwater model was used to determine the hydrogeological impact (pressure, drawdown, etc.) of operating CERP ASR facilities. The findings of this modeling effort, described in **Chapter 7**, was used to bound the ecological and water quality impacts expected from CERP ASR under realistic hydrogeological scenarios.

### 8.3.3 Lake Okeechobee Operations Planning Spreadsheet (LOOPS)

The Lake Okeechobee Operations Planning Spreadsheet (LOOPS) (Niedrauer et. al, 2006) simulates the effect of lake operations schedules on Lake Okeechobee stages. This tool is set up to simulate the 1965 to 2005 period of record with boundary conditions for surface water inflows to the lake and rainfall and evapotranspiration for this period. For this study, the LOOPS model was modified to include ASR operations for CERP ASR within the Lake Okeechobee Basin. Its specific use in the ERA was as a means to predict the timing and volume of ASR recharge and recovery in the Lake Okeechobee basin under ASR implementation scenarios other than D13R. **Figures 8-6** and **8-7** show the timing of ASR recharge and recovery over the 36 year simulation period (1965-2000) for the ASR implementation alternatives considered in the ERA. These hydrographs provide a general indication of the duration and timing of recharge, recovery, and idle time which are important factors in assessing exposure to ASR flows. These hydrographs show that different ASR implementation scenarios generally will not significantly influence the timing of recharge or recovery events and that approximately one-third of the time the facilities are likely to be idle. The LOOPS was used to develop the ASR exposure scenarios for the Kissimmee River Basin to compare recharge and recovery volumes to historic S-65E flows.

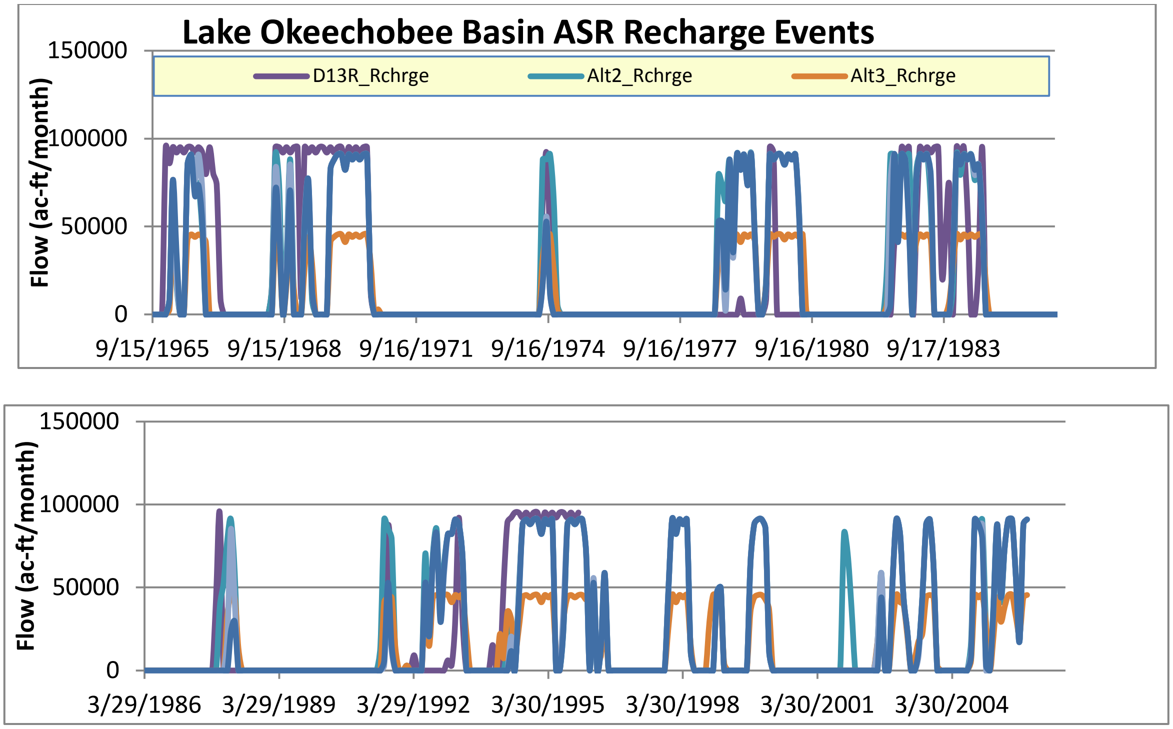


**Figure 8-6 -- Lake Okeechobee basin recharge events as predicted using SFWMM (D13R) and LOOPS.**

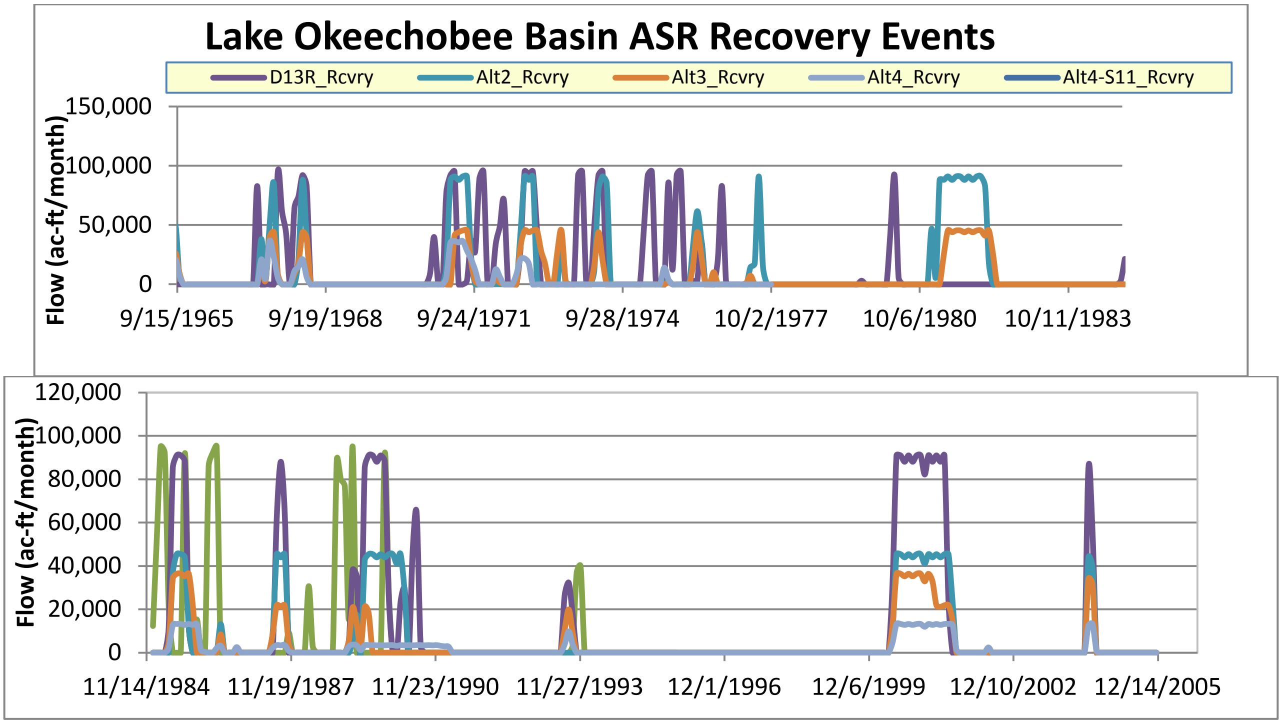


**Figure 8-7 -- Lake Okeechobee basin recovery events as predicted using SFWMM (D13R) and LOOPS.**

### 8.3.4 Lake Okeechobee Environmental Model (LOEM)

The LOEM (Lake Okeechobee Environmental Model) is a 3-D finite element water quality simulation model that is based on the Environmental Fluid Dynamics Code (EFDC) package (Hamrick and Wu, 1997). The model simulates hydrodynamic and water quality conditions (nutrients, temperature, and toxics) on a 1 square kilometer basis. For the ecological risk assessment, the existing LOEM model was modified to include an enhanced submerged aquatic vegetation (SAV) model and boundary conditions were developed to simulate the 1999 to 2009 period with and without ASR operations (AEE, 2012; Jin and Ji, 2012). The model was configured to simulate the WQ impact to Lake Okeechobee of several critical ASR discharge events as predicted for the ASR implementation scenarios developed by the groundwater modeling team. LOEM model boundary conditions were developed using a spreadsheet that incorporated LOOPS output and KRASR recovered water quality data to generate time-varying water quality boundary conditions for ASR inflows and outflows to the lake for ALT2, ALT3, and ALT4.

The concentrations of water quality constituents in the recovered water generally are bounded by the surface water quality and the groundwater quality compositional end-members. At the start of a recovery event, the quality of the recovered water is similar to the surface water quality. As a recovery event proceeds, the concentrations typically become closer in composition to groundwater quality. Given the uncertainty in the quality of the recovered water, two conditions were modeled for each ASR scenario. One set of model runs were designated with a “C” as in constant water quality as set by the baseline groundwater quality concentrations (ALT2C, ALT3C, ALT4C). The other set of model runs were designated with a “V” to denote variable water quality that trends from surface water quality concentrations to groundwater quality concentrations as a recovery event proceeds (ALT2V, ALT3V, ALT4V).

**Figure 8-8** shows the LOEM model grid and water quality sampling locations used to calibrate the LOEM model and review model predictions. Concentrations of dissolved solids in Lake Okeechobee surface water are generally inversely related to lake stage and volume since years with above average rainfall conditions tend to result in reduced dissolved solids concentrations. The modeled results indicate that for the nutrients (nitrogen and phosphorus species) the ASR scenarios would not significantly increase or decrease average Lake concentrations. For instance, though the recovered water total phosphorus (TP) concentration for the ALT2C model run is 0.01 mg/L which is significantly lower than the recharge water TP concentration of 0.10 mg/L, there is no change in Lake TP concentration. Based on these results, it appears that the ability to sequester phosphorus load in the aquifer through ASR operations will not result in a measurable change to water column concentration of phosphorus in the Lake. This may be due to internal cycling of legacy phosphorus between the water column and the sediment bed. However, the average annual reduction in TP load from ASR implementation varies from around 30 mTONS/yr for ALT2, ALT4, and ALT-4S11 to around 20 mTons/yr for ALT3. All of the alternatives discharge less than 2 mTONS/yr. This load removal will contribute to efforts to meet the TMDL for phosphorus in the Lake.

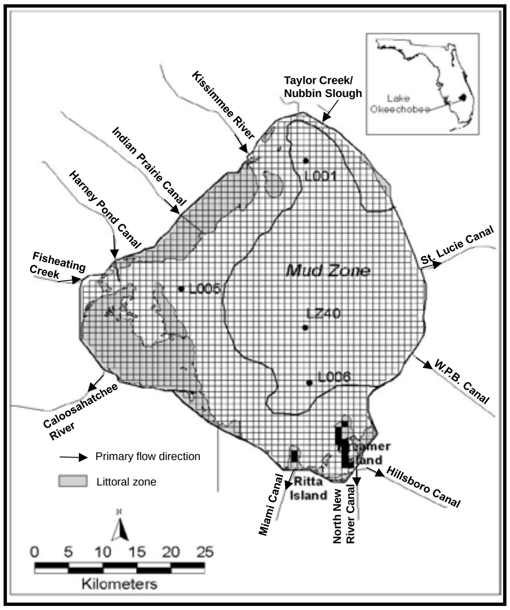


**Figure 8-8 -- LOEM model grid and water quality monitoring stations in Lake Okeechobee.**

Sulfate and chloride concentrations appear to be significantly impacted by the ASR scenarios that have the most wells discharging to the lake. Graphs of the water quality modeling results for several parameters at monitoring station L001 are presented in **Figures 8-9** through **8-12.** The L001 station is located in the northern portion of Lake Okeechobee and the predicted results at this station are representative of the predicted changes in water quality for most of the Lake.

**Figure 8-9** shows the predicted sulfate concentration at L001. Periods of high sulfate concentration in this figure are coincident with low lake stage since sulfate concentrations are inversely correlated to lake stage. Relative to other alternatives, the sulfate concentration at LOO1 for ALT2C results in the largest increase in sulfate concentrations over baseline conditions. This is due to two factors: ALT2C has the maximum number of ASR wells discharging to the Lake, and the recovered water quality concentrations are assumed to match the baseline groundwater concentration during the entire recovery period. The assumption that recovered water quality matches groundwater baseline conditions is not realistic as demonstrated by water quality data collected during recovery events at the KRASR pilot site as well as at other ASR facilities throughout Florida. For this reason, ALT2C is considered to be a conservative estimate of the potential for CERP ASR to alter Lake Okeechobee water quality. As discussed earlier in this report, the number and placement of the 200 wells in ALT2 has been shown to cause unacceptable changes to groundwater stage conditions during both recharge and recovery. For this reason, the ALT2 scenario is not considered feasible. ALT3C with half of the wells as ALT2C increases the maximum sulfate concentration from around 60 mg/L to nearly 80 mg/L. Since ALT3C assumes that recovered water concentrations match the baseline GW concentrations for the entire recovery period, the estimates of peak sulfate concentration shown here are likely high and also conservative for this 100 well scenario. ALT2V provides a more realistic prediction of the impact of 200 Upper Floridan ASR wells on Lake Okeechobee sulfate concentrations. For ALT2V, the maximum sulfate concentration in the Lake appears to increase from around 60 mg/L to 75 mg/L during periods when ASR water is recovered and discharged to the Lake.

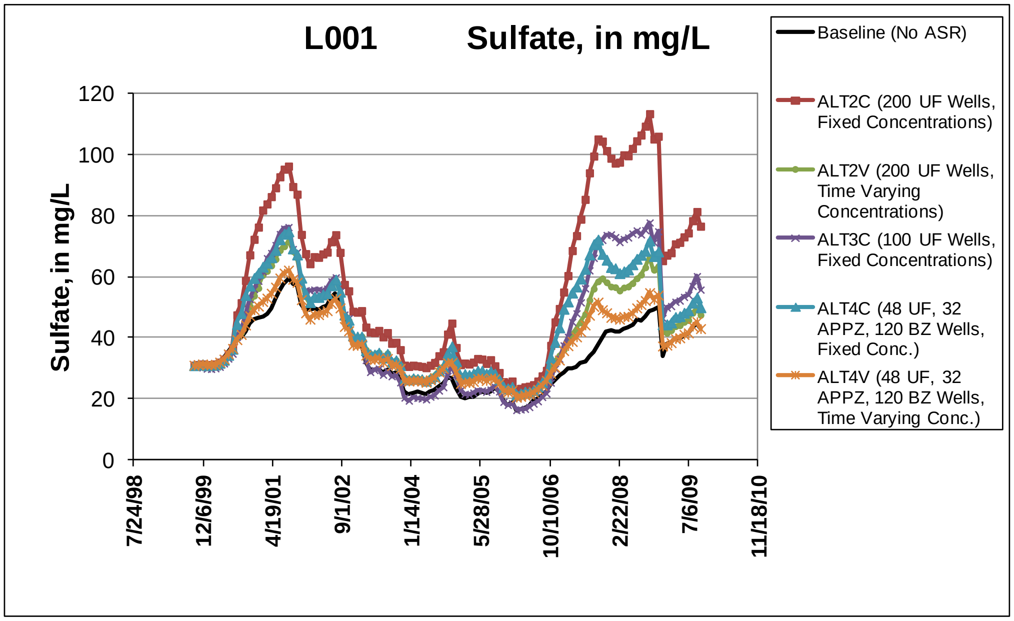


**Figure 8-9 -- Predicted sulfate at L001 (northern Lake Okeechobee).**

Maximum sulfate concentrations for ALT4V increase only moderately at L001 from around 60 mg/L to a peak of approximately 62 mg/L. The maximum increase at any one time of sulfate for ALT4V appears to be approximately 20 mg/L which occurs in 2007. ALT4-S11 was not simulated using the LOEM model since this alternative was created after the LOEM modeling project was completed. However, since ALT4-S11 has approximately 50 percent of the recovered water in comparison to ALT4, it is likely that the maximum increase in sulfate concentration for ALT4-S11 is on the order of 10 mg/L. This is due to the combined effect of reduced ASR discharges in ALT4S-11 with a recovery rate of only 1.25 MGD for the wells located in the high efficiency UF aquifer zone and the 2.5 MGD recovery rate for the APPZ wells.

These modeled results show that several ASR scenarios could cause increased sulfate concentrations in Lake Okeechobee during and immediately after ASR recovery events; however, shortly after the recovery events end, the sulfate concentrations return almost to the baseline (no-ASR) concentration. The strong inverse correlation between Lake stage and sulfate concentrations effectively limits the duration of ASR related exposure to elevated sulfate concentrations since increased Lake stages that result from rainfall runoff naturally dilute sulfate concentrations. Also, the initiation of rainfall and higher lake stages can trigger the end of ASR discharge events that contribute sulfate to the lake.

**Figure 8-10** shows the impact of ASR scenarios on Lake chloride concentrations. Like sulfate, the ALT2C alternative results in the greatest increase in lake chloride from a maximum near 100 mg/L to nearly 200 mg/L. For the more realistic ALT2V and ALT4V, the maximum chloride concentration is around 120 mg/L. Similar to sulfate, chloride concentrations return to near the baseline concentration conditions for all of the alternatives shortly after recovery ceases.

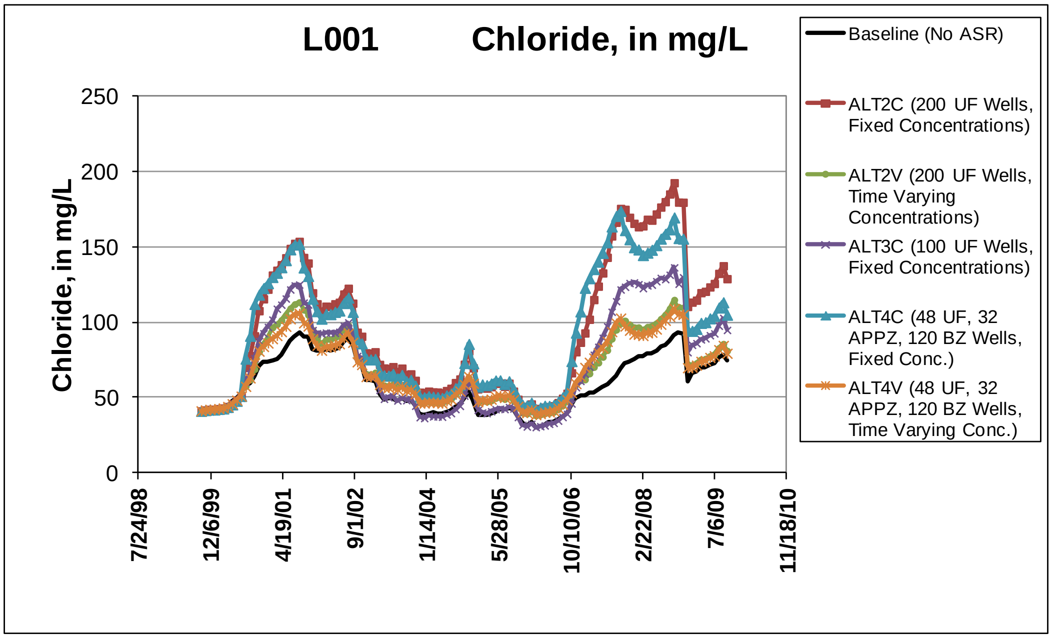


**Figure 8-10 -- Predicted chloride at L001 (northern Lake Okeechobee).**

**Figure 8-11** shows that there is little to no impact from ASR on lake temperature at L001. This is likely due to the fact that the recovered water from ASR wells is near the ambient surface water temperature and this ASR water relatively quickly reaches thermal equilibrium with the lake water. However, there may be areas in close proximity to ASR discharge locations where there is some impact to ambient Lake water temperature. However due to mixing from wind and other environmental drivers such as solar input, the main portion of the Lake (at L001 for instance) is not exposed to thermal impacts from ASR discharges.

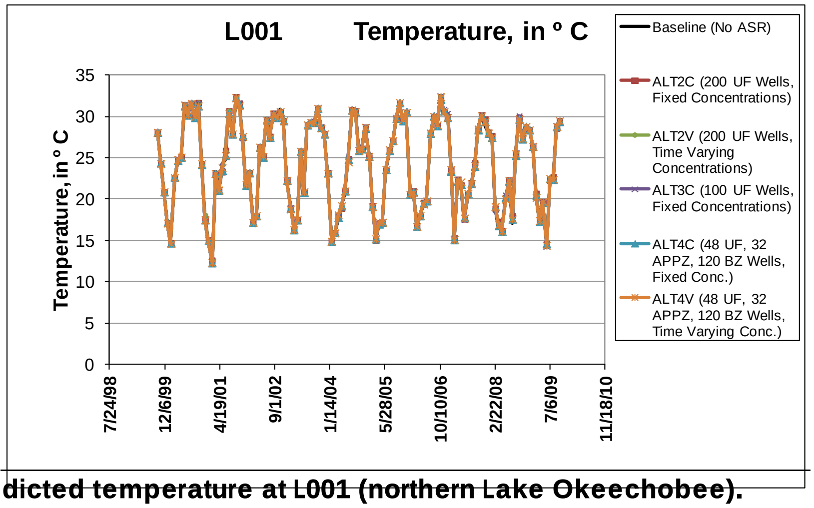


**Figure 8-11 -- Predicted temperature at L001 (northern Lake Okeechobee).**

**Figure 8-12** shows the impact of the ASR scenarios on DO at LOO1. In general, there are no significant changes to Lake DO concentrations due to the assumption that the recovered water is discharged into the Lake with a concentration at 5 mg/L which is likely very close to the ambient Lake DO concentration.

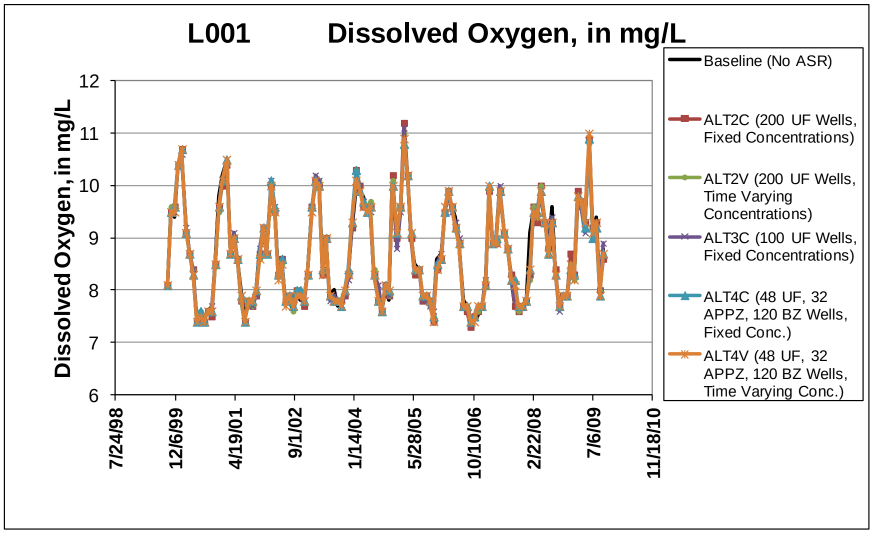


**Figure 8-12 -- Predicted dissolved oxygen at L001 (northern Lake Okeechobee).**

The results for other monitoring locations are similar to those presented here. This is an indication that the Lake is well mixed and that locating ASR well clusters around the perimeter of the Lake rather than at a single location is a good strategy to limit water quality changes associated with ASR discharges. However, given the circulation patterns predicted by the LOEM, it is possible that large volume ASR discharges from Kissimmee River ASR facilities might be pushed into the ecologically significant littoral zone along the southwest shore of the Lake.

**Figure 8-13** shows the LOEM predicted impact of ALT2 hydrology on Lake Okeechobee SAV coverage and biomass for the simulated period of 1999 to 2009. During this period, the lake experienced a significant drought in 2001. Following the drought, the SAV in the lake expanded to more than 50,000 acres which is greatest amount of SAV coverage ever measured. As a result of the 2004 and 2005 hurricanes, the SAV acreage crashed as a result of excessive turbidity which limited light transmittance which is important to SAV. The lake elevation graph at the top of **Figure 8-13** is in meters. The 2.5-meter (m) elevation is equivalent to a lake stage of 17.2-ft NGVD and the 0.5-m elevation is equivalent to a lake stage of 10.6-ft NGVD. In mid-2001, the ALT2 hydrology increases the lake elevation by approximately 0.5-m. This resulted in a predicted increase in SAV acreage of approximately 10,000 acres during a 90-120 day period. Similarly, in 2007 and 2008, the increased lake stage due to ALT2 ASR resulted in two instances where SAV acreage was increased by approximately 10,000 acres. Though ALT2 hydrology appears to increase SAV acreage, SAV biomass does not appear to be substantially impacted by this hydrologic scenario. Note that the ALT2 scenario is not considered feasible for hydrogeologic reasons.

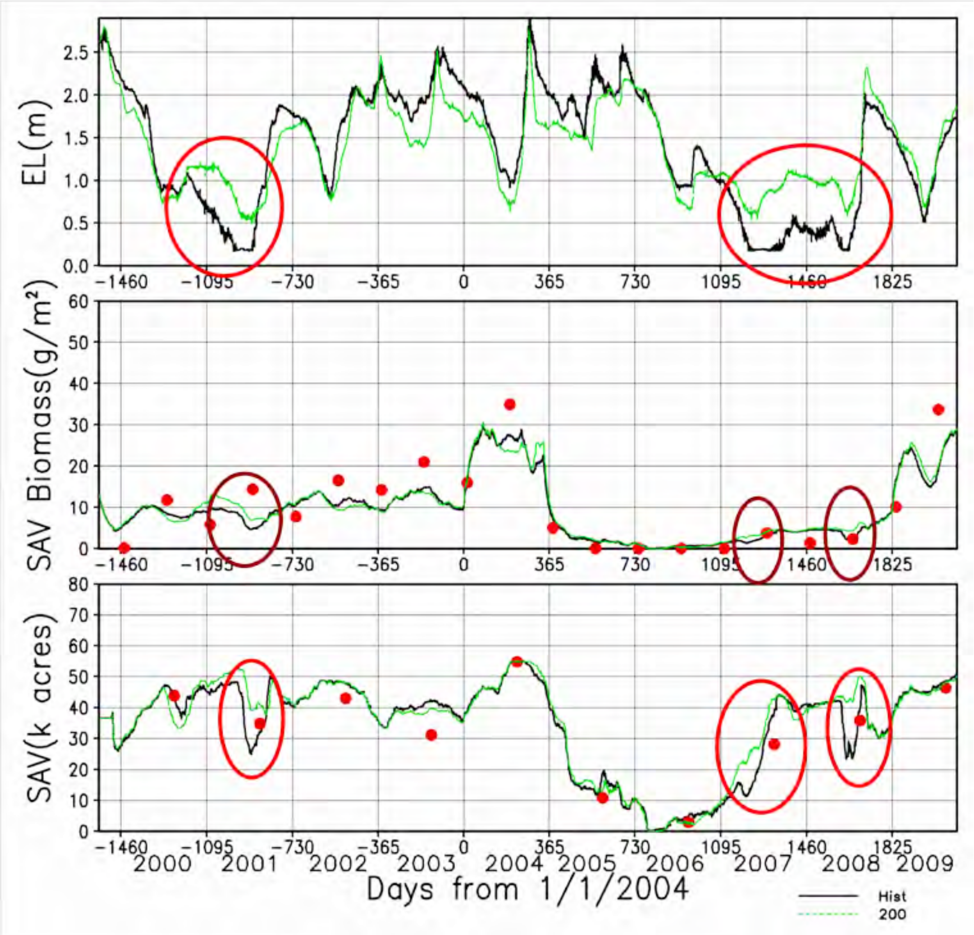


**Figure 8-13 -- SAV predictions for ALT2 scenario.** Red dots represent field data. Base condition represents no-ASR alternative, 200 represents ALT2 scenario.

**Figure 8-14** shows the impact of the ALT4C on SAV biomass and acreage. ALT4 hydrology increases lake stages during 2001 and 2007 by approximately 0.25 meters which is half the increase predicted for ALT2. The LOEM model predicts greater SAV acreage and biomass during 2001 and 2007 for ALT4V relative to the baseline prediction than that predicted for ALT2V. One possible explanation for this is that depth conditions and timing are more favorable for SAV under ALT4 during the 2001 and 2007 critical periods than that for ALT2.

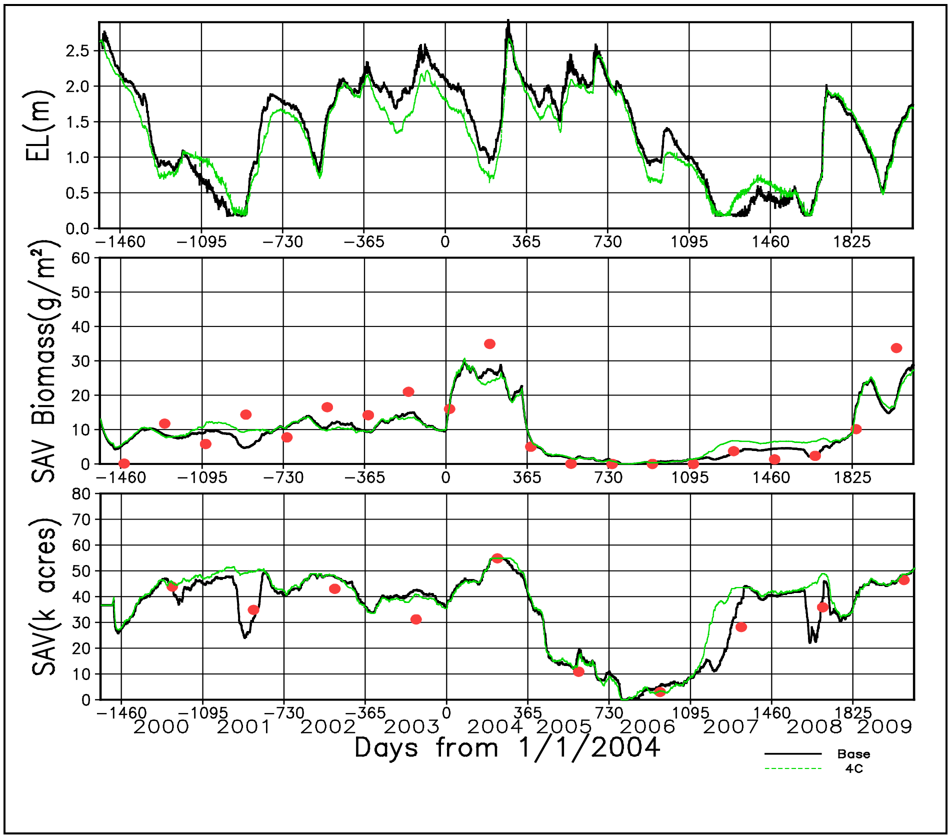


**Figure 8-14 -- SAV predictions for ALT4 scenario.** Red dots represent field data. Base condition represents no-ASR alternative, 4C represents ALT4C scenario).

As discussed earlier, the LOEM model was not used to simulate ALT4-S11 conditions since the LOEM modeling work was completed before this alternative was conceived. Rough projections of impacts to SAV caused by the implementation of ALT4-S11 can be made using SAV output from the ALT4 LOEM model run as a guide and the projected changes in minimum lake stage conditions from the LOOPS simulation output. The maximum ASR related increase in lake stage from ASR is 0.6 ft for ALT4 and 0.1 ft for ALT4-S11. In comparison to the no ASR alternative, the lowest lake stage over the 41 year simulation period increases by 0.3-ft with ALT4 and decreases by 0.1 ft with ALT4-S11. With limited ASR recovery flows, ALT4-S11 performs worse under dry conditions relative to ALT4 and the no ASR alternatives and it is likely that SAV conditions in the lake would either see no improvement with this alternative or a decrease in SAV coverage and biomass. Poor low-lake stage performance for ALT4-S11 is a result of pumping large volumes of Lake water into the APPZ and BZ storage zones and never recovering this water. For instance, in ALT4S-11 the total volume of stored ASR water over the 1965-2005 period is 10 million ac-ft while the predicted recovered volume is less than 900,000 ac-ft. ALT4 has the same recharge volume but its recovery volume of the same period is approximately twice that of ALT4-S11 at 1.75 million ac-ft. Color and turbidity changes to Lake Okeechobee and the Greater Everglades from ASR discharges are considered to be low given the dilution and mixing of recovered ASR water with Lake water so no change to SAV from these water quality effects are anticipated.

### 8.3.5 Everglades Landscape Model for Sulfate

Sulfate dynamics within the Everglades Protective Area (EPA) play a qualitative role in regulating mercury methylation and bioaccumulation by fish. The Everglades Landscape Model (ELM) was originally developed to simulate the landscape vegetation response to changes in hydrology and nutrients within the EPA. ELM version 2.8.6 (Fitz, 2013) was modified for this ERA to include the simulation of ASR related changes to sulfate loads within the EPA. Rather than use the D13R hydrology, the ELM-Sulfate model used the revised CERP0 hydrology since this extended the simulation period from 1995 to 2000. The output from the ELM-Sulfate model was used to evaluate the potential for ASR discharges into the Everglades to change the existing mercury methylation conditions. Output from this modeling effort is discussed in the **Section 8.4**.

## 8.4 Mercury Methylation Potential

Sulfate has been identified by the USGS and other parties as potentially playing a significant role in regulating mercury methylation within Lake Okeechobee and the Greater Everglades. The ERA study team reviewed the ASR well placement scenarios and LOEM modeling output and determined that potential changes to sulfate loads delivered to Lake Okeechobee and the Greater Everglades was the most important exposure to evaluate for this region. ASR-related sulfate loads could potentially alter the location of methyl mercury hotspots and the rate of mercury methylation which could result in increased mercury bioaccumulation in fish. To address ASR-related sulfate loading, the team developed and linked a series of models culminating in the development of the ELM-Sulfate model by Fitz (2013) and the interpretation of this output (Orem et al., in review).

### 8.4.1 Lake Okeechobee Sulfate Simulations

The LOEM model was used to develop the sulfate boundary conditions for the ELM-Sulfate simulations. **Figure 8-15** shows the impact on Lake Okeechobee sulfate concentrations that result from ASR discharges from ALT2C, ALT2V, and ALT4C as predicted by the LOEM model.

LOEM Simulation results indicate that mean Lake sulfate concentrations will increase from the long-term background of 30 mg/L to 50 mg/L, 34 mg/L, and 31 mg/L, for scenarios ALT2C, ALT2V, and ALT4V, respectively. Based on the ALT4V results, no change in the long-term average sulfate concentration would be expected from ALT4-S11 given its reduced recovered water volume discharged to the Lake.

The additional sulfate loading for any of these alternatives is expected to have minimal impacts on methyl mercury production in Lake Okeechobee if the relationship between sulfate and methyl mercury is similar to that observed in the water conservation areas (WCA) and ENP. While no detailed studies of Hg methylation in Lake Okeechobee have been conducted, mercury levels in the muscle of gar and other top predator fish collected from Lake Okeechobee are similar to, or lower than, those generally reported

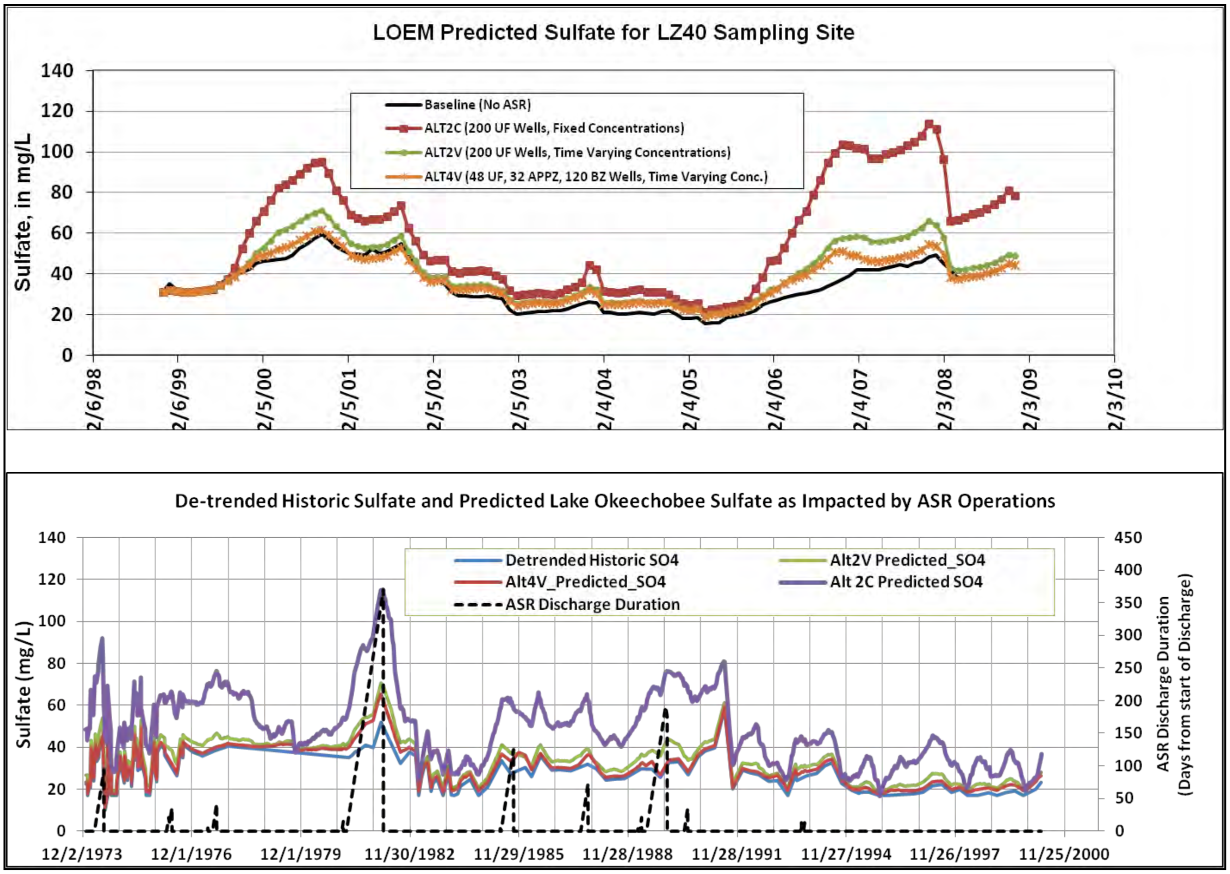


**Figure 8-15 -- Predicted $SO_4$ concentrations in Lake Okeechobee from LOEM for the 1999-2009 period (top graph); and estimated ASR-related $SO_4$ concentrations during the 1974-2000 time period (bottom graph).**

from other areas of the United States. Thus, although the levels of mercury in fish from the Everglades to the south of Lake Okeechobee are sufficiently high to result in human fish consumption advisories, there are no similar advisories for Lake Okeechobee. The reasons for this are not presently known, but there are several likely explanations. First, while there are some areas of mud and peat bottom sediments, most of the lake bottom consists primarily of rubble and sand with relatively low organic carbon content. This type of sediment is not generally associated with sulfate reduction and methyl mercury formation. Second, observed sulfate levels of approximately 30 mg/L in the lake place its condition in the zone of methylation inhibition. Third, several lines of evidence suggest that microbial sulfate reduction is not prevalent in Lake Okeechobee. Sulfur models for Lake Okeechobee indicate that it is more of a reservoir of sulfate within the ecosystem, and there is no source of sulfate and minimal retention of sulfur within the Lake (James and McCormick, 2012). The lack of sulfur retention further suggests that limited sedimentary sulfate reduction is occurring within the Lake. Thus, Lake Okeechobee receives sulfate inflow from rivers to the north, back-pumping from the Everglades Agricultural Area, and small amounts from rainfall, some evapo-concentration of sulfate occurs due to the large surface area of the lake, and the sulfate passes through on its way to the EPA. Fourth, Lake Okeechobee does not commonly stratify with regard to oxygen, which is a condition frequently observed in lakes with elevated methyl mercury (Rask et al., 2010). Last, eutrophic lakes like Lake Okeechobee generally exhibit low methyl mercury levels, likely due to bio-dilution effects (Chen and Folt, 2006). Overall, there appears to be a low risk that any of the ASR alternatives would adversely impact mercury methylation dynamics within most of the Lake; however, there is a moderate level of uncertainty surrounding this risk characterization result since the Lake is very large and there may be locations within the Lake that favor mercury methylation which might be exposed to ASR flows.

### 8.4.2 Greater Everglades Sulfate Simulations

Three spatial performance metrics were developed to evaluate the ELM-Sulfate simulation output. The first performance metric, Sulfate Loss, measures the rate of marsh uptake of sulfate from the water column over the simulation period. This metric provides an integrated perspective of the exposure of additional sulfate load on the landscape; however, since it is a long-term average it tends to mask short-term impulses which may be critical to the mercury methylation and bioaccumulation processes. The second metric is $SO_4$ period of record spatial average concentration. This metric provides a long-term perspective of the areas that are subjected to additional sulfate loading; however, again it does not capture short-term exposure. The third metric is the short-term average water column $SO_4$ concentration mapping. This metric captures short-term increases in sulfate concentrations that potentially could result in changes to methyl mercury dynamics and subsequent bioaccumulation in fish.

**Figure 8-16** shows the water column sulfate concentration in WCA-3A in the vicinity of the L-29 Interceptor canal for a period in 1982 that represents a worst-case scenario. This time period was selected because ASR operations before and after this date would result in the highest Lake sulfate concentrations for the 1974-1999 period as shown in **Figure 8-15**. **Figures 8-17, 8-18,** and **8-19** show the results for the third performance metric for 19 May 1982, which follows an extended ASR recovery event. For ALT2C, **Figure 8-17** shows that there are more than 36,000 hectares (ha) with an increase in water column sulfate of more than 5 mg/L. For ALT2V, **Figure 8-18** shows that there are slightly less than 1,700 ha with an increase in water column sulfate of more than 5 mg/L. **Figure 8-19** shows that for ALT4V there is no area with an increase or decrease of water column sulfate of ± 5 mg/L.

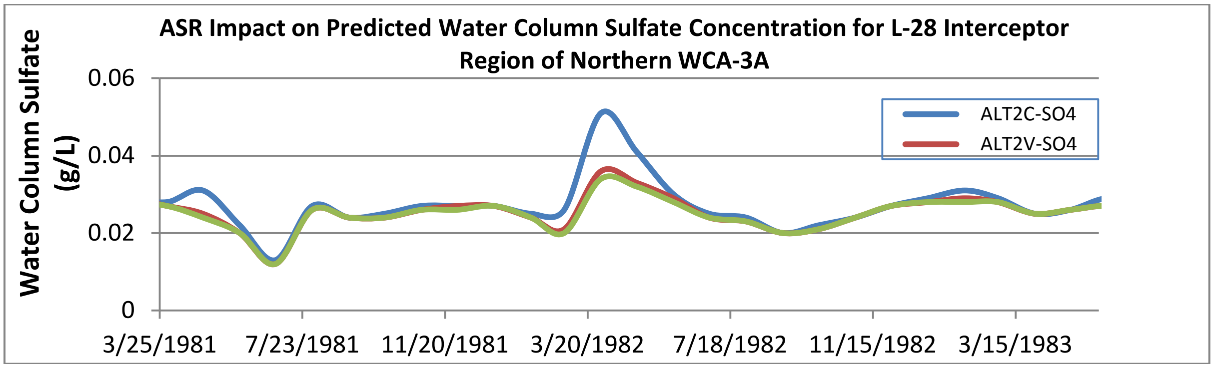


**Figure 8-16 -- ELM-Sulfate predicted $SO_4$ concentrations in WCA-3A near the L-28 Interceptor.**

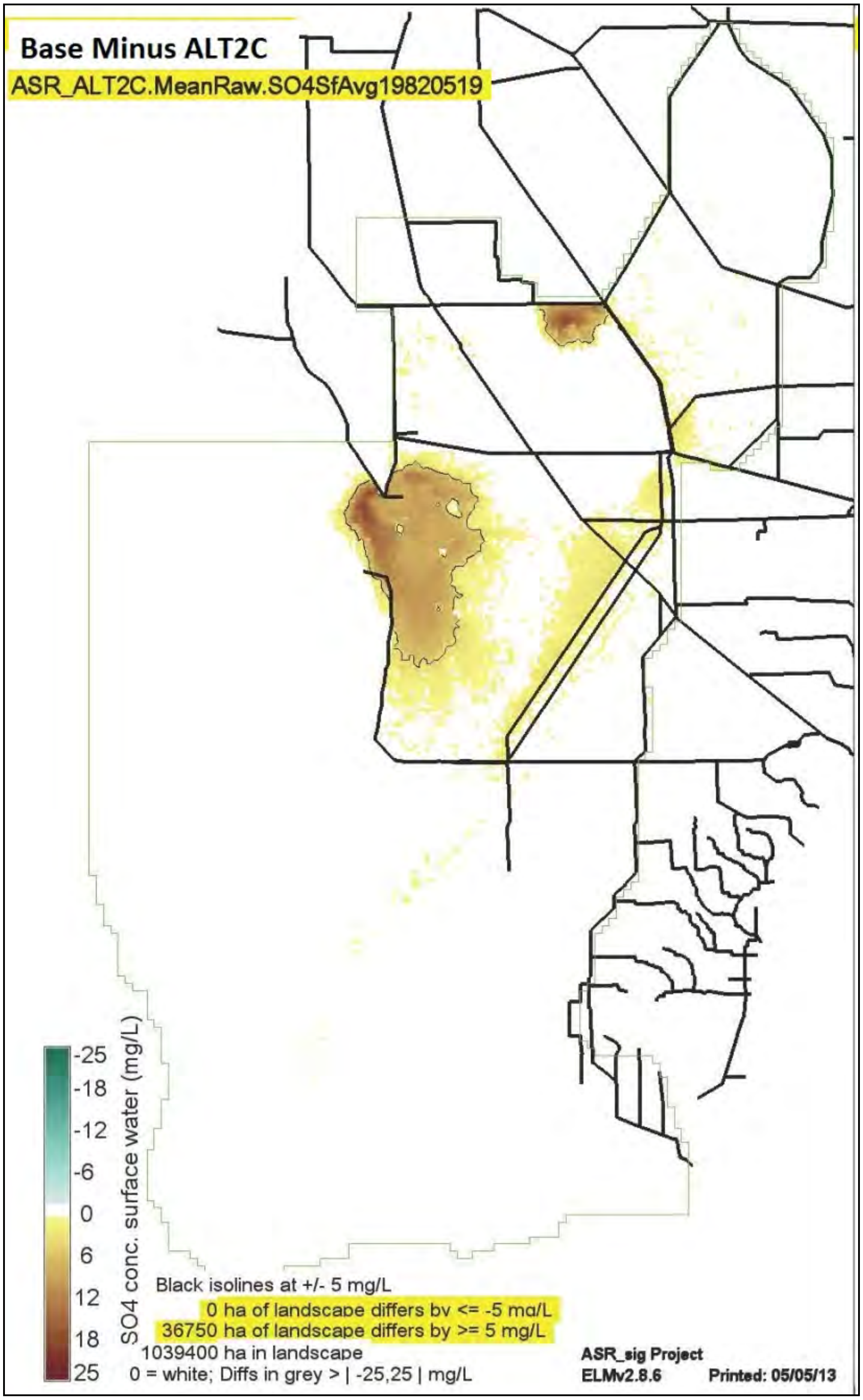


**Figure 8-17 -- Predicted Impact of ALT2C on $SO_4$ Concentration in the Everglades Protection Area on 19 May 1982.** Hectares (ha). Scale shows difference in SO4 concentrations between base and with-project conditions.

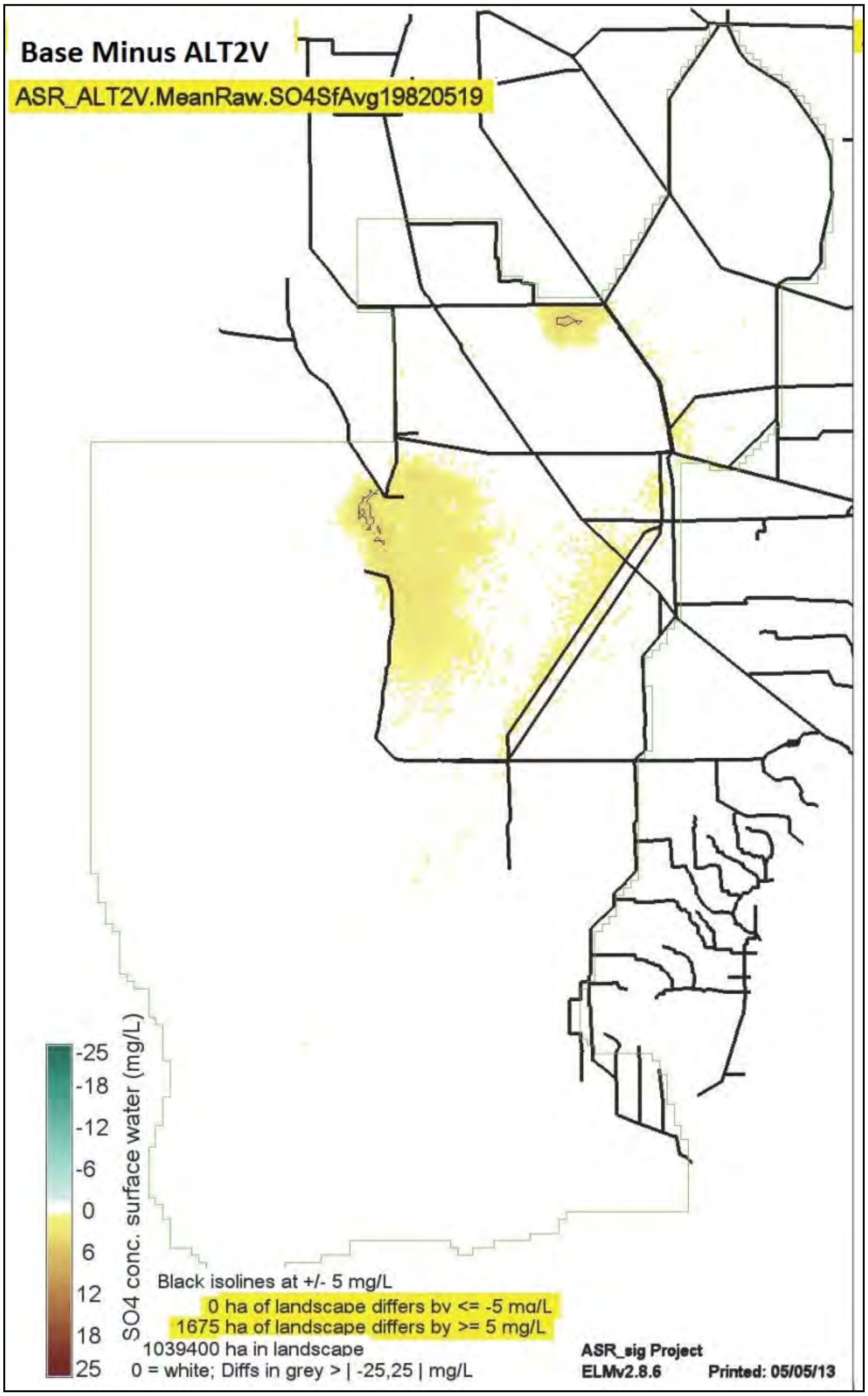


**Figure 8-18 -- Predicted Impact of ALT2V on $SO_4$ Concentration in the Everglades Protection Area on 19 May 1982.** Scale shows difference in SO4 concentrations between base and with-project conditions.

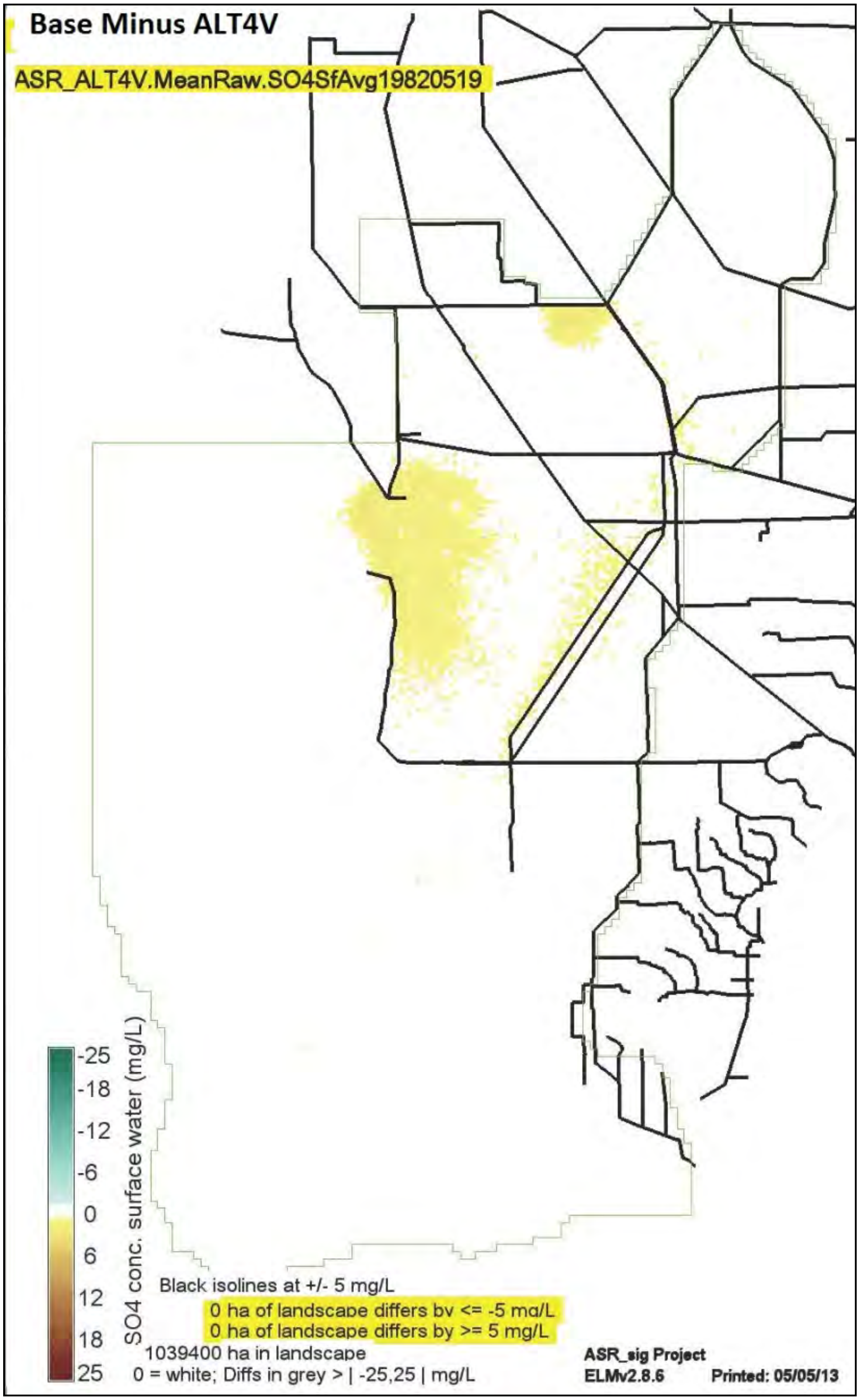


**Figure 8-19 -- Predicted Impact of ALT4V on $SO_4$ Concentration in the Everglades Protection Area on 19 May 1982.**

Proportionately, the potential increase in sulfate load from ASR operations to the Greater Everglades is less than that predicted for Lake Okeechobee because the Lake provides only one-third of the sulfate load to the Greater Everglades with the balance of the sulfate load coming from agricultural operations in the Everglades Agricultural Area and from atmospheric deposition. Although ASR sulfate loading is not predicted to be a dominant source of sulfate to the EPA overall and does not appear to significantly alter the total area of the EPA impacted, it may have ecosystem effects locally. For example, localized ASR sulfate loading near discharge points during certain time periods could produce critical tipping points with regard to stimulation/inhibition of methyl mercury production. Geochemical evolution of the soil-water system assumes that water column conditions, soil chemistry (i.e. DOC, pH, redox) and biological conditions (presence of mercury-methylating sulfate reducing bacteria) are suitable (Orem et al., 2011). The ELM-Sulfate model shows that ASR water entering the EPA does increase overall sulfate loading, but only during certain time periods and primarily in areas directly adjacent to stormwater treatment areas or canal discharge. When normalized to the baseline sulfate scenario, the impacts of ASR sulfate are minimal. This is primarily due to the dominance of EAA discharge with regard to sulfate loading to the ecosystem, and to dilution effects on the ASR discharge to the extensive EPA marshes.

Overall, the areas of changed methyl mercury risk attributable to the ASR operations are predicted to be minimal, and are located near major canal water release points in western WCA3, north-central WCA2, and northern Shark River Slough. Because the relationship between sulfate and methyl mercury production is nonlinear and hump shaped, the model generally predicts both regions of net increases and net decreases in methyl mercury risk in near proximity to each other. That is not to say, however, that sulfate releases from ASR or other canal water sources are not important, because in the absence of sustained sulfate loading to this ecosystem, methyl mercury levels in the EPA would be substantially reduced - once internal recycling of sediment sulfate pools subsided. Given the ELM-Sulfate modeling output, the risk of ASR sulfate related methylation effects is characterized as moderate for ALT2 and ALT3 while the risk for ALT4 and ALT4-S11 are characterized as low due to the reduced ASR flows for these alternatives.

## 8.5 Ecological Risk Assessment for the ASR Regional Study

The ERA evaluated potential beneficial or adverse effects of ASR implementation in the Lake Okeechobee Basin and downstream in the Greater Everglades, including assessment endpoints and ecosystem attributes that are most sensitive and highly valued. The risk assessment process used for this report followed USEPA guidance on ERA studies as illustrated in **Figure 8-19**. As part of an ERA, risk assessors evaluate goals and select assessment endpoints, prepare the conceptual model, and develop an analysis plan. During the analysis phase, assessors evaluate exposure to stressors and the relationship between stressor levels and ecological effects. During risk characterization, assessors estimate risk through integration of exposure and stressor-response information, describe risks by discussing lines of evidence and determining ecological adversity, and prepare a report. The ERA team which included representatives from the USACE, SFWMD, USFWS, FDEP, Florida Fish and Wildlife Conservation Commission (FFWCC), University of Florida, and Golder Associates (contractor to USACE and SFWMD) created a study plan that included identification of stressors and receptors and development of an ecotoxicology program and water quality and ecological monitoring.

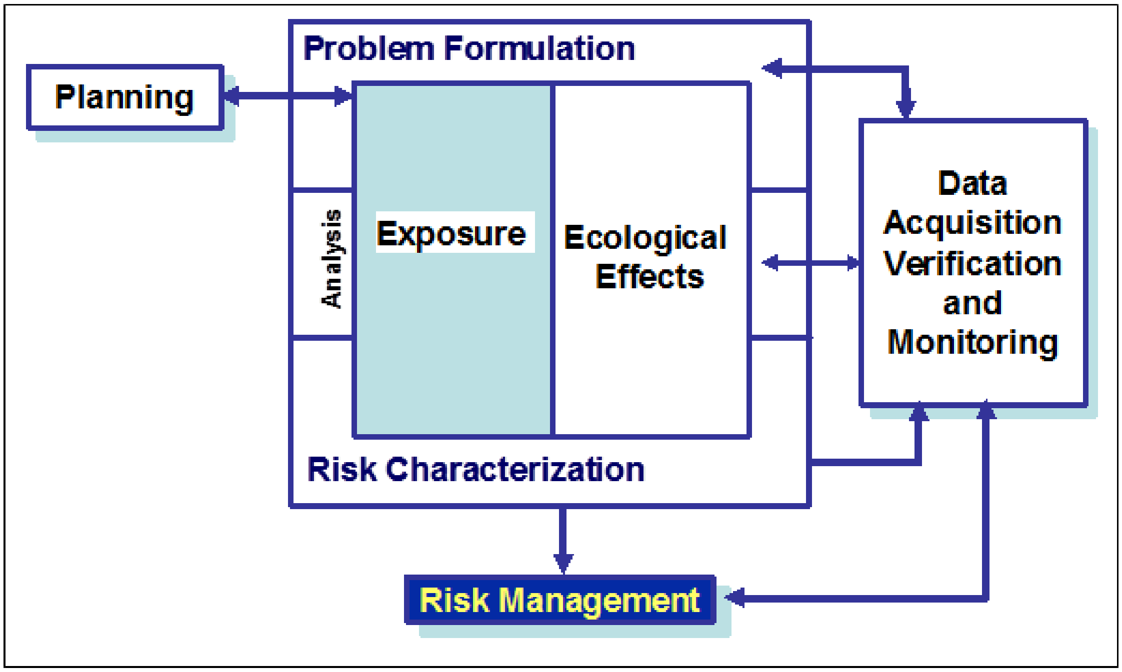


**Figure 8-20 -- Ecological Risk Assessment Framework (USEPA, 1998).**

The ERA team developed a list of stressors using their knowledge of south Florida freshwater and estuarine habitats, surface water and groundwater quality, site-specific hydrogeology, and operational water quality data collected at utility-owned ASR sites located in Florida. The preliminary water quality stressors were organized into five groups:

- general water quality constituents
- nutrients
- dissolved solids
- metals
- radionuclides

The team also identified and evaluated physical stressors such as temperature effects and impingement and entrainment of larval fish. Based on the ERA team's understanding of ASR stressors modes of action, fate and effects in south Florida ecosystems, along with water quality, the following assessment endpoints were selected:

- Reproducing populations of native fish
- Survival of fish and aquatic Invertebrates
- Periphyton and algae species diversity and abundance
- submerged aquatic vegetation (SAV) abundance
- Human health and wildlife protection

The links between the stressors and receptors were codified in the conceptual ecological model shown in **Figure 8-20.** A list of effect hypotheses was developed to characterize the risks associated with ecosystem receptor exposure to ASR recharge and recovery flows. Stressor response and risks were characterized in terms of high, moderate, low, and minimal using the following definitions:

- **High** – Short-term or long-term effects are probable and would result in substantially lower abundance, diversity, or health of receptor organisms. These effects could influence the decision about whether or not to proceed with an ASR implementation alternative in a given locality, regardless of any possible mitigation.
- **Moderate** – Short-term or long-term effects are possible and may result in substantially lower abundance, diversity, or health of receptor organisms. These effects are sufficiently important to consider mitigation if ASR is implemented in that locality.
- **Low** – Short-term or long-term effects are not expected that would result in substantially lower abundance, diversity, or health of receptor organisms. These effects probably would not require modification of ASR implementation beyond monitoring to validate the low risk characterization.
- **Minimal** – Short-term or long-term effects are most likely not measurable.

The uncertainty of the effects characterizations are defined as the following:

- **High** - The predicted risk is based upon limited information; therefore, additional information should be collected prior to implementation of ASR.
- **Moderate** - The predicted risk is based upon likely sufficient information, but should be validated further prior to implementation of ASR.
- **Low** - The predicted risk is based upon substantial information and likely does not need further verification.

## 8.6 ERA Risk Characterization

Risk characterization is the final phase of the ERA and it summarizes the predicted adverse ecological effects of regional ASR implementation as related to the assessment endpoints selected. Model simulation outputs and ecotoxicological study results for the Lake Okeechobee Basin were the basis for estimating the exposures to the near-field, mid-field, far-field, and far-far field receiving water bodies for the ASR scenarios evaluated in this ERA.

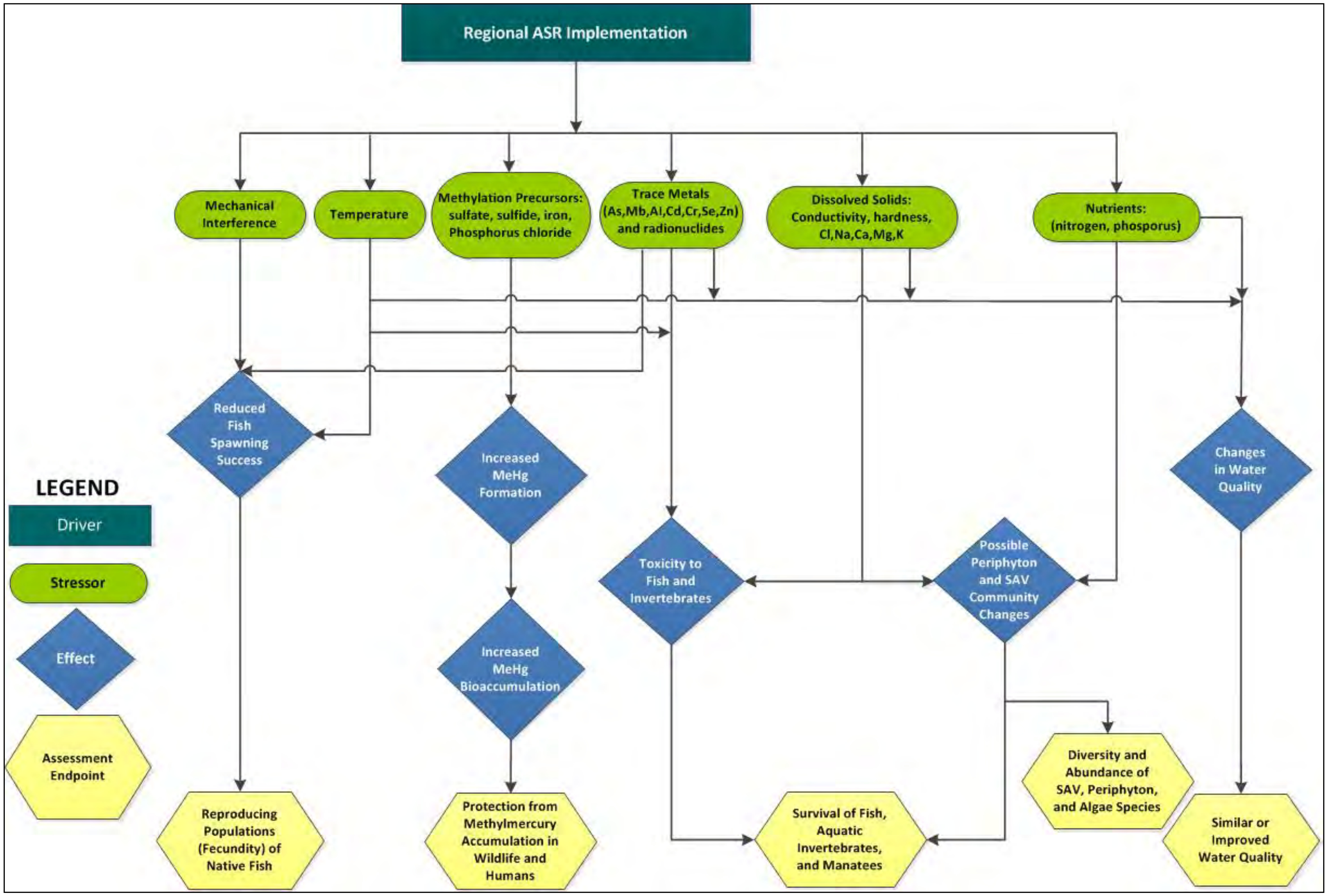


**Figure 8-21-- ASR Regional Study ERA conceptual ecological model.**

### 8.6.1 Near-Field Water Quality Risks (Single ASR Discharge)

The near-field receiving water body is defined as the waters within the probable mixing zone of a single ASR well discharge. **Table 8-2** summarizes the risks and benefits to the near-field environment from discharges from single ASRs. Water quality and toxicity data collected at KRASR and HASR sites indicate that arsenic, gross-alpha, and chronic toxicity are the most likely water quality effects that could be observed within the recovered water discharge mixing zone (Section 4, Appendix A). These parameters are discussed in detail below:

- **Arsenic** - The levels of arsenic discharged present a **minimal** risk of acute toxicity to aquatic species in the near-field receiving waters; but the initial cycles do present a **moderate** risk for arsenic bioaccumulation in biota in the near-field due initial higher concentrations.
- **Gross Alpha** - Gross-alpha measurements at KRASR showed an exceedance of the Class III standard of 15 picocuries/L with a single measurement of 18 picocuries/L (cycle test 3 at KRASR), though the average concentration was below 7 picocuries/L. Since no other exceedance of the gross alpha standard was observed at KRASR or HASR, the risk of exceeding the surface water standard for this parameter in the near-field is considered to be **moderate**. Bioconcentration studies using mussels were conducted during cycle tests 1 and 2, and they did not show any bioconcentration of radium gross-alpha in the mussel tissues. The risk of radium bioconcentrating from ASR recovered water discharges in aquatic biota is considered **minimal**.
- **Chronic Toxicity** - There appears to be a change in recovered water quality that occurs late in the cycles that results in a minor, but statistically significant, reduction in reproduction of *C. dubia*. Six out of 16 tests showed a reduction in reproduction of *C. dubia* during the later periods of cycling, therefore this observation is credible. This is a very sensitive test species and fecundity is also a sensitive endpoint. The tests that showed an effect on reproduction at full strength recovered water, also showed that a dilution less than or equal to 50 percent recovered water did not elicit this effect on reproduction. The only exception was the May 2011 test (during cycle 3), that showed an $IC_{25}$ of 7.2 percent recovered water; meaning that reproduction was inhibited by 25 percent at 7.2 percent recovered water. The same set of May samples showed the only acute effect observed on *C. dubia*. Subsequent samples taken in June 2011 did not replicate this chronic effect.

The source of the chronic toxicity is not known with certainty; it is possible that it could be related to elevated sulfide concentrations that occur during the later portion of a recovery event. Five out of the 6 tests showed that this effect on reproduction was no longer observed at 50 percent dilution. The risk of chronic toxicity in the receiving water is expected to be **moderate,** of short duration and localized to the vicinity of the discharge.

**Table 8-2 -- Risks and Benefits to Near-Field Water Quality from Recovered Water Discharges from a Single ASR Well.**

| Consequence | ALT2, ALT3, ALT4, ALT4-S11 | Uncertainty |
|---|---|---|
| **Risks to Near-Field Water Quality (Mixing Zone – Single ASR Discharge)** | | |
| Risk of violating Class I Surface Water Quality Standard for arsenic | Moderate to low | Moderate |
| Risk of acute toxicity – Arsenic<br>Risk of bioconcentration – Arsenic | Minimal<br>Moderate | Low<br>Low |
| Risk of violating Class I/III Surface Water Quality Standard for gross alpha | Moderate | Low |
| Risk of bioconcentration – Gross-alpha | Minimal | Moderate |
| Risk of violating other Class I/III Water Quality Standards | Low | Low |
| Risk of beneficial or detrimental impact to surface water quality due to reduced phosphorus concentrations | Low | Low |
| Risk of ASR sulfate loads and concentrations adversely impacting mercury methylation / bioaccumulation | Low | Low |
| Risk of acute toxicity | Minimal | Low |
| Risk of chronic toxicity | Moderate | Low |
| **Benefit to Near-Field Water Quality** | | |
| Water Clarity | High | Low |

### 8.6.2 Mid-Field Water Quality Effects (Multiple ASRs in the Lower Kissimmee River)

The mid-field receiving water body is defined in this ERA as the waters immediately downstream of the ASR discharge mixing zone. The primary mid-field receiving water body evaluated in this ERA was the Kissimmee River, though the water quality risks presented here are generally applicable to other receiving water bodies immediately downstream of an ASR discharge site mixing zone. This discussion includes all the multiple ASR scenarios modeled. The mid-field risks are summarized in **Table 8-3**.

- **Water Quality Parameters -** For the mid-field zone, the risk of violating water quality standards for arsenic, gross-alpha, and other Class I/III parameters was considered to be higher for the alternatives with greater recovered flow (ALT2 and ALT3) for the Kissimmee River since the mixing zones for these alternatives may include a significant portion of the total volume and area of the lower Kissimmee River Basin during low flow periods at the S-65E structure. With multiple ASR discharges in close proximity, the recovered water will not dilute as quickly as in the single ASR evaluation; however, after several cycles, the concentration of arsenic in the recovered water would decrease and this risk would be low.
- **Acute and Chronic Toxicity -** The risk of observing acute toxicity in the receiving water mid-field is characterized as **minimal**, since this risk was minimal at the point of discharge. The risk of

observing chronic toxicity in the mid-field is considered **moderate to low** since at times the complete receiving water canal may be comprised primarily by ASR recovered waters under some of the scenarios evaluated.

- **Sulfate -** The risk in the Kissimmee River that elevated sulfate loading originating from the ASRs will increase in the mid-field zone is **high** for those alternatives such as ALT2 and ALT3 that discharge large quantities of ASR flow into the Kissimmee River. It is plausible for ALT2 and ALT3 that the increased concentration of sulfate in the mid-field zone during ASR recovery events could alter the dynamics of mercury methylation in the river. The risk is low for ALT4 and ALT4S-11, due to lower recovery volumes.

Given the complexity of the mercury cycle in the environment, it is difficult to conclude with any certainty the risk that additional sulfate could present on mercury methylation and subsequent bioaccumulation of mercury by aquatic biota in the mid-field zone. Given that Pool E shares many of the same physical and chemical attributes of Lake Okeechobee, the impact of ASR-related sulfate on mercury methylation in this portion of the lower Kissimmee River would likely be similar to that predicted for Lake Okeechobee. For Lake Okeechobee ASR sulfate is not expected to impact mercury methylation dynamics.

- **Water Hardness -** Based on recovered water having about three times the concentration of hardness (200 mg/L) as the receiving water (60 mg/L), the risk of increased hardness in the mid-field is estimated to be **high** for ALT2 and ALT3, **moderate** for ALT4, and **low** for ALT4-S11 based on the relative volume of recovered ASR water for each of these alternatives. All water quality impacts in the mid-field zone associated with ASR are coincident with recovery events and are unlikely to persist after recovery ceases. Discharges of greater concentrations of hardness from deeper ASR wells completed in the APPZ is likely to be limited by the need to cease ASR recovery once on-site continuous measurement of specific conductivity exceeds 1,275 µS/cm.
- **Color and Turbidity -** For the mid-field zones modeled in the Kissimmee River, the potential for improved water clarity during recovery and discharge is assumed to be **high** for ALT2 and **moderate** for ALT3. Increased water clarity carries with it the risk of triggering cyanobacterial blooms, particularly under the nutrient-enriched conditions of the receiving waters and especially if the zone of clarity extends beyond the edge of the nearshore zone that typically is colonized by SAV. ALT4 and ALT4-S11 are not likely to show improved water clarity (over the background receiving waters) because of significantly less ASR recovered flows in these scenarios.

### 8.6.3 Far-Field Water Quality Effects (Lake Okeechobee)

The far-field receiving water body is defined in this ERA as the waters immediately downstream of the mid-field receiving water body. The transition between the mid-field and far-field water bodies is located where additional mixing and dilution occurs as a result of other water flows or available storage. The only far-field receiving water body evaluated in this ERA is Lake Okeechobee.

**Table 8-3 -- Risks and Benefits to the Mid-Field Water Quality from Recovered Water Discharges from Multiple ASR Wells in the Lower Kissimmee River.**

| **Risk to Mid-Field Water Quality (Multiple ASR Wells in the Lower Kissimmee River)** | | | | | |
|---|---|---|---|---|---|
| **Consequence** | **ALT2** | **ALT3** | **ALT4** | **ALT4S-11** | **Uncertainty** |
| Risk of violating Class I Water Quality Standard for arsenic | Moderate | Moderate | Low | Low | Low |
| Risk of violating Class I/III Water Quality Standards for gross alpha | Moderate | Moderate | Low | Low | Low |
| Risk of violating other Class I/III Water Quality Standards | Moderate | Moderate | Low | Low | Low |
| Risk that sulfate load and concentration adversely impact mercury methylation | Moderate | Moderate | Low | Low | Moderate |
| Risk of ecologically significant increased hardness load | High | Moderate | Low | Low | Low |
| Risk of acute toxicity | Minimal | Minimal | Minimal | Minimal | Low |
| Risk of chronic toxicity | Moderate | Moderate | Low | Low | Low |
| **Benefit to Mid-Field Water Quality** | | | | | |
| Potential for increased water clarity (reduced color and turbidity) | High | Moderate | Low | Low | Low |

The most important predicted water quality changes for Lake Okeechobee were:

- The potential for reduced total phosphorus loading
- The potential for improved water clarity
- The discharge of ASR-related sulfate
- Ecologically significant increase in Lake water hardness

**Table 8-4** summarizes the risks and benefits to Lake Okeechobee water quality from ASR recovered water discharges.

- **Total Phosphorus** - A mass balance assessment and the results from the LOEM model were evaluated to assess these potential water quality changes. The storage and discharge of ASR flows within the Lake Okeechobee basin will reduce total phosphorus loading to the Lake by an average of 30 mTons/yr for ALT2, ALT4, and ALT4-S11. ALT3 would provide a reduction of an average of 19 mTons/yr of total phosphorus. The reduction in lake phosphorus load due to ASR operations is an important **benefit** of CERP ASR in this basin given it represents 7 to 10 percent of the current annual Lake phosphorus load and as such, assists potential attainment of the annual TMDL load for the Lake of 130 mTons/yr.
- **Color and Turbidity** - Discharge of ASR recovered water into Lake Okeechobee has a **low** probability of significantly improving water clarity regardless of ASR alternative due to mixing with a much larger volume of Lake water and because turbidity caused by wind and wave tends to control water clarity within the Lake.

- **Sulfate -** Simulation results indicate that mean Lake sulfate concentrations will increase from the long-term background of 30 mg/L to 50 mg/L, 34 mg/L, and 31 mg/L, for scenarios ALT2C, ALT2V, and ALT4V, respectively. Based on the ALT4V results that show minimal changes, no change in the long-term average sulfate concentration would be expected from ALT4-S11 given its reduced recovered water volume discharged to the Lake. The additional sulfate loading for any of these alternatives is expected to have **minimal** impacts on methyl mercury production in Lake Okeechobee if the relationship between sulfate and methyl mercury is similar to that observed in the WCAs and ENP. Factors that reduce the risk of increasing methylation in the lake include: non-organic lake sediments, elevated sulfate concentrations above methylation inhibition concentrations, minimal evidence of microbial sulfate reduction, and absence of thermal stratification in the lake.
- **Water Hardness -** Lake Okeechobee water hardness would be impacted by several of the ASR implementation alternatives. Lake hardness is normally in the 110 to 140 mg/L as $CaCO_3$ range with a standard deviation of 25 mg/L. Using the simplified mass balance approach, the extended ASR recovery event in 1982, would increase hardness load by 70 percent for ALT2, 35 percent for ALT3 and ALT4, and 15 percent for ALT4-S11. If the increase in load is conservatively equated as an equivalent increase in concentration, ALT2 would result in a maximum hardness concentration of more than 200 mg/L as $CaCO_3$ while ALT3/ALT4 would result in a maximum concentration around 160 mg/L as $CaCO_3$. Based on the LOEM simulation results for chloride and sulfate, it is likely that increased lake hardness associated with ASR would be temporary and hardness concentrations would revert to baseline conditions within 6 to 12 months of the end of a recovery event. With reduced ASR discharges, the risk of adverse ecological impacts from ALT4-S11 related hardness is considered to be low though there is a moderate level of uncertainty with this estimate.

**Table 8-4 -- Risks and Benefits to Far-Field Water Quality from Recovered Water Discharges into Lake Okeechobee.**

| **Risk to Far-Field Water Quality (Lake Okeechobee)** | | | | | |
|---|---|---|---|---|---|
| **Consequence** | **ALT2** | **ALT3** | **ALT4** | **ALT4S-11** | **Uncertainty** |
| Risk of increasing Lake sulfate concentrations | High | Moderate | Low | Minimal | Moderate |
| Risk that increased Lake sulfate concentrations result in increased mercury methylation | Low | Low | Low | Lowest | Moderate |
| Risk of ecologically significant increased hardness load | High | Moderate | Moderate | Low | Moderate |
| **Benefits to Far-Field Water Quality (Lake Okeechobee)** | | | | | |
| Potential for Decreased Total Phosphorus Loading | Moderate | Low | Moderate | Moderate | Moderate |
| Potential for Increased Water Clarity (reduced color and turbidity) | Low | Low | Low | Minimal | Low |

### 8.6.4 Far, Far-Field Water Quality Effects (Greater Everglades)

The far far-field receiving water body is defined in the ERA as the waters immediately downstream of the Lake Okeechobee. The transition between the far-field and far far-field water bodies is located where additional mixing and dilution occurs as a result of other water flows or available storage. The only far far-field receiving water body evaluated in the ERA is the Greater Everglades.

The most important risks to water quality for the Greater Everglades are the increase in sulfate load attributed to ASR discharges and the risk of significant increases in water hardness. **Table 8-5** summarizes the risks and benefits to the Greater Everglades from ASR recovered water discharges.

- **Sulfate -** Proportionately, the potential increase in sulfate load from ASR operations to the Greater Everglades is less than that predicted for Lake Okeechobee because the Lake provides only one-third of the sulfate load to the Greater Everglades with the balance of the sulfate load coming from agricultural operations in the Everglades Agricultural Area and from atmospheric deposition. The impact of ASR related sulfate discharges into the Greater Everglades is primarily expected to be a change in the locations where water column sulfate is within the “goldilocks” concentration range that optimizes mercury methylation chemistry.

Overall, the areas of changed methyl mercury risk attributable to the ASR operations are predicted to be minimal, and are located near major canal water release points in western WCA3, north-central WCA2, and northern Shark River Slough. Because the relationship between sulfate and methyl mercury production is nonlinear and hump shaped, the model generally predicts both regions of net increases and net decreases in methyl mercury risk in near proximity to each other. That is not to say, however, that sulfate releases from ASR or other canal water sources are not important, because in the absence of sustained sulfate loading to this ecosystem, methyl mercury levels in the EPA would be substantially reduced - once internal recycling of sediment sulfate pools subsided. Given the ELM-Sulfate modeling output, the risk of ASR sulfate related methylation effects is characterized as moderate for ALT2 and ALT3 while the risk for ALT4 and ALT4-S11 are characterized as low due to the reduced ASR flows for these alternatives.

- **Water Hardness** - Given that the Greater Everglades was historically a soft water system, the discharge of hard water into this region could result in risk to aquatic plant communities. Loxahatchee National Wildlife Refuge (WCA-1) is considered to be a soft water system so intermittent discharges of ASR related hardness would present a moderate risk to aquatic plant communities particularly for ALT2 and ALT3. Interior portions of WCA-2, WCA-3, and ENP are still considered to be soft water systems during average hydrologic conditions though during droughts the surface water tends to become more mineralized. Current discharges of hard water from the EAA likely affects the aquatic plants in these areas particularly near canals. ASR related hardness would result in additional affects; however, given the intermittent nature of the ASR flows and the fact that hardness concentrations would remain within the present range of EAA hardness concentrations measured at the inflow to STA 3/4 (360 mg/L ± 70 mg/L), the increase in risk is estimated to be low particularly for ALT4 and ALT4-S11.

**Table 8-5 -- Risks and Benefits to Far Far-Field Water Quality from Recovered Water Discharges on the Greater Everglades**

| Risk to Far-Far Field Water Quality (Greater Everglades) | | | | | |
|---|---|---|---|---|---|
| **Consequence** | **ALT2** | **ALT3** | **ALT4** | **ALT4S-11** | **Uncertainty** |
| Risk that sulfate load and concentrations increase | Moderate | Moderate | Low | Minimal | Moderate |
| Risk of increased mercury methylation | Low | Low | Low | Minimal | Moderate |
| Risk of ecologically significant increased hardness load | Moderate | Moderate | Low | Low | Moderate |

## 8.6.5 Risks and Benefits of ASR Recovered Water Discharges to Aquatic Species and Communities

### 8.6.5.1 Algal Communities and Submerged Aquatic Vegetation in Lake Okeechobee

In-situ periphytometers were installed at three positions in the Kissimmee River at locations relative to the point of discharge (POD) at KRASR: upstream, at the cascade aerator, and downstream. The data collection objective was to quantify the effects of recovered water on in-stream periphyton communities. Because data were limited, comparisons of periphyton community diversity and abundance among locations could not be made for each operating phase (recharge, storage, and recovery). However, when the data were pooled there were no statistically significant differences in the community structure among the upstream, ASR discharge, or downstream locations. Periphyton communities may not readily reflect the effects of surface water-quality changes. However, if the quality of ASR recovered water influences periphyton community composition, it should have been evident from differences in diversity when upstream and downstream samples were compared. In addition, there was no indication of a shift to toxin-producing, cyanobacteria-dominated phytoplankton communities when baseline data are compared with recovery phase data. Given the low nutrient concentrations in the recovered water, the risk of a shift to cyanobacteria-dominated phytoplankton communities is low. In the nearshore region of the Lake Okeechobee, both the phytoplankton and periphyton communities have been dominated by diatom taxa since fall 2003 (phytoplankton) and summer 2002 (periphyton), so at least some overlap in community structure between the phytoplankton and periphyton communities has been documented, at least through fall 2012.

The LOEM model was used to predict the potential for changes to Lake Okeechobee SAV biomass and coverage (**Table 8-6**). These LOEM predictions are largely based upon ASR-related changes to lake stage conditions.

While ASR discharges might increase water column transmissivity (light penetration), this typically translates into increased photosynthesis and does not necessarily translate into more abundant SAV. Increased frequency of cyanobacterial blooms or an expansion of emergent aquatic vegetation also are likely outcomes depending on the precursor community, duration of clear conditions, nutrient levels, for example.

**Table 8-6 -- Effect of ASR implementation on Algal Communities and Submerged Aquatic Vegetation in Lake Okeechobee.**

| Effect on Algal Communities and SAV in Lake Okeechobee | | | | | |
|---|---|---|---|---|---|
| **Benefit** | **ALT2** | **ALT3** | **ALT4** | **ALT4S-11** | **Uncertainty** |
| Shift in Algal Communities | Low | Low | Low | Minimal | Moderate |
| Increase in SAV Biomass | Low | Not Simulated | Low | Minimal | Moderate |
| Increase in SAV Coverage | Moderate | Not Simulated | Moderate | Low | Moderate |

### 8.6.5.2 Kissimmee River and Lake Okeechobee

**Table 8-7** summarizes the potential risks and benefits to aquatic biota from ASR implementation in the Lake Okeechobee Basin. This information is presented by assessment endpoint and attributes. The detailed basis for this table is found in the ERA report **(Appendix F)**.

**Table 8-7 -- Potential Risks and Benefits to Aquatic Biota from ASR Implementation in the Lake Okeechobee Basin.**

| Kissimmee River and Lake Okeechobee | | | | | | |
|---|---|---|---|---|---|---|
| **Consequence/Benefit** | **ALT2** | **ALT3** | **ALT4** | **ALT4S-11** | **Uncertainty** | **Actions to reduce risks to receptors** |
| Risk of effects to fishery by inadequate aeration of ASR discharge | Minimal | Minimal | Minimal | Minimal | Low | |
| Risk of fishery being affected by inadequate de-gassing ($H_2S$, $NH_3$) of ASR discharge | Low | Low | Low | Low | Low | Cascade aerator needs to be redesigned to degas sulfide better |
| Risk of chronic or acute toxicity to fishery or aquatic life from ASR discharges (except for mercury) | Low | Low | Low | Low | Low | |
| Risk of ASR discharge plume size covering entire river width during low river flows (30 cfs) | High | High | High | Low | Moderate | Better plume measurements over varying conditions and modeling of long-term discharge events |
| Risk of ASR discharge plume length exceeding 800 meters during low river flows (30 cfs) | High | High | Moderate | Low | Moderate | Better plume measurements or modeling |
| Risk of sub-lethal adverse effects from increased alkalinity and hardness | Low | Low | Low | Low | Low | |
| Risk of effects from increased alkalinity and hardness | Moderate | Moderate | Low | Low | Low | |
| Risk of any fishkill from loss of dissolved oxygen refugia (gamefish, minnows) | High | Moderate | Low | Low | Low | Could use operations control to reduce abrupt termination of recovery flow |
| Risk of any fishkill from loss of dissolved oxygen refugia (bowfin, gar) | Low | Low | Low | Low | Moderate | Could use operations control to reduce abrupt termination of recovery flow |
| Risk (>15 percent of years) with a predicted fishkill from loss of dissolved oxygen refugia (gamefish, minnows) | Low | Low | Low | Low | Moderate | |

**Table 8-7 -- Potential Risks and Benefits to Aquatic Biota from ASR Implementation in the Lake Okeechobee Basin, *continued.***

| Consequence/Benefit | ALT2 | ALT3 | ALT4 | ALT4S-11 | Uncertainty | Actions to reduce risks to receptors |
|---|---|---|---|---|---|---|
| Risk to fishery via water temperature modifying timing of fish spawning at least once (cold water spawners)[1] | High | Moderate | Low | Low | Moderate | |
| Risk to fishery via water temperature modifying timing of fish spawning (moderate temperature water spawners)[2] | Low | Low | Low | Low | Moderate | |
| Risk to fishery via water temperature modifying timing of fish spawning (warm water spawners)[3] | Low | Low | Low | Low | Low | |
| Risk that temperature modification of spawning will have measurable effects (cold water spawners) [1] | Moderate | Moderate | Low | Low | Moderate | |
| Risk that temperature modification of spawning will have measurable effects (brook silverside or other annual species) | Moderate | Moderate | Low | Low | Moderate | Determine the rate of migration of silversides into the river |
| Risk of larval fish impingement or entrainment during ASR recharge (non-catfish species) | High | Moderate | High | High | Moderate | |
| Risk of larval fish impingement or entrainment during ASR recharge (catfish species) | Low | Low | Low | Low | Low | |
| Risk that larval fish impingement or entrainment will affect fishery (non-catfish species) | Moderate | Moderate | Moderate | Moderate | High | Increased collection of impingement and entrainment data |
| Risk of adverse effects to fish or aquatic life from sedimentation from ASR discharges | Low | Low | Low | Low | Low | |
| Risk of adverse effects to fish or aquatic life from color or turbidity from ASR discharges | Low | Low | Low | Low | Low | |
| Risk of adverse effects from ASR discharges on manatees from loss of temperature refugia | Minimal | Minimal | Minimal | Minimal | Low | Could use operations control to reduce abrupt termination of recovery flow |
| Risk of adverse effects from ASR discharges on benthic invertebrates | Low | Low | Low | Low | Low | |
| Risk of not detecting future ASR effects due to poor benthic community | Moderate | Moderate | Moderate | Moderate | Low | |
| Risk of invertebrate impingement or entrainment during ASR recharge | High | High | High | High | Low | |
| Risk of invertebrate impingement or entrainment resulting in measurable biological effect | Moderate | Low | Moderate | Moderate | High | |
| Risk of adverse effects of ASR discharges on Lake Okeechobee Fishery and invertebrate community | Low | Low | Low | Low | Moderate | Sampling water quality parameters under higher ASR discharge conditions in areas of Lake Okee, closer to the confluence of the Kiss. R. |

[1] Species includes black crappie, redear sunfish, redfin and chain pickerels, brook silverside, and pirate perch

[2] Species includes redbreast sunfish, threadfin and gizzard shads, swamp darter, pygmy sunfishes, and chain pickerel

[3] Species includes bluegills, bluespotted sunfish, catfish (all 5 species), killifish, and taillight and golden shiners

1

## 8.7 ERA Discussion and Summary

The ERA focused primarily on ecological and water quality impacts associated with CERP ASR in the Lake Okeechobee Basin. The risks posed by CERP ASR in the Caloosahatchee, C-51, North Palm Beach, and Site 1 basins were not explicitly addressed in the report. However, given the similarities between the Lake Okeechobee basin and these basins, the risks characterized for the Lake Okeechobee basin serve as reasonable estimates for these basins. The ERA and the Regional ASR Simulation Modeling report (summarized in **Chapter 7)** indicate that CERP ASR is not feasible at the scale contemplated at least for the Lake Okeechobee Basin. While the hydrogeologic modeling did show that CERP ASR recharge quantities can be achieved through the use of wells completed into all aquifers of the FAS including the APPZ and BZ), the recovery volumes contemplated in CERP are not achievable within the hydrogeologic constraints imposed by the Martin and St. Lucie County artesian pressure protection rules that require the maintenance of artesian conditions in the FAS. If mitigation actions are undertaken, none of the ASR alternatives assessed in the ERA would likely result in large-scale irreversible ecological harm. That said, the ALT4 and ALT4-S11 scenarios pose the least risk to fisheries in the Kissimmee River and Lake Okeechobee as well as the least risk of increased methylation within the Greater Everglades.

The cause of intermittent chronic toxicity measured at the KRASR facility during the recovery phases was not determined in the ERA. Given the incidence of chronic toxicity, the FDEP may require that any future CERP ASR facility be located where sufficient dilution water is available for a mixing zone. The dilution volume specified in the KRASR NPDES permit was 3.9 times the ASR discharge volume. Assuming that future CERP ASR facilities would need the same dilution volume, a five-well cluster ASR system would have to be located where a minimum of 150 cfs is continuously available during recovery events. The requirement for dilution water may be problematic since this flow quantity would have to be available during droughts and the dry season. It is likely that Kissimmee River Basin and perhaps the C-43 and C-44 basins could support dilution flow requirements; however, several of the sub-basins around Lake Okeechobee such as Nubbin Slough, Taylor Creek, C-40, and C-41 may not be capable of supplying this water during the dry season or during droughts.

From an ecological and water quality perspective, water managers should continue to consider CERP ASR as a viable technology to achieve the ecological and water supply objectives of Everglades Restoration. Given that the findings of the ERA are presented with an acknowledgement of uncertainty in the risk characterizations, implementation of the CERP ASR should be incremental and geographically disperse until the uncertainties identified here are resolved.

The fact that the most feasible alternative (ALT4-S11) with regard to hydrogeologic conditions is also the alternative that would result in the least toxicological and water quality harm is re-assuring. However, this alternative fails to improve water supply and lake ecosystem performance metrics due the greatly reduced volume of water recovered from ASR storage. The Corps and SFWMD should undertake a revision of the CERP plan to determine what changes are necessary to CERP in light of reduced ASR performance. Implementation of incremental CERP ASR facilities need not wait for this update.

# 9 Synthesis of Technical Responses to ASR Issues and CROGEE Recommendations

As mentioned in **Section 1.3**, the final report from the ASR Issue Team (1999) recommended further study of seven issues to reduce uncertainty in regional ASR implementation:

1. Characterization of the quality and variability of source waters that could be pumped into the ASR wells.
2. Characterization of regional hydrogeology of the Floridan aquifer system.
3. Analysis of critical pressure for rock fracturing.
4. Analysis of local and regional changes in groundwater flow patterns.
5. Analysis of water-quality changes during storage in the aquifer.
6. Potential effects of ASR on mercury bioaccumulation for ecosystem restoration projects.
7. Relationships among ASR storage interval properties, recovery rates and recharge volume.

In addition to these seven "original" issues, the CROGEE had several recommendations resulting from their review of the PMPs for the ASR pilot projects (NRC, 2001) and the ASR Regional Study (NRC, 2002). This section organizes the findings from this project into responses to each one of the original seven issues and subsequent CROGEE recommendations and includes a discussion of the limitations of the findings.

## 9.1 ASR Issue Team Recommendations

Each of the following was identified as a major issue in ASR Issue Team (1999).

### 9.1.1 Characterize the Quality and Variability of Source Waters that Could Be Pumped into the ASR Wells

Baseline source (surface) water quality characterization took place for a three-year period at both KRASR and HASR systems prior to their construction and operation. Specifically, two projects were completed (PBS&J, 2003; Tetra Tech, 2005a) to provide information supporting design of the disinfection systems, and to characterize adjacent waterways for surface water and sediment quality prior to exposure to ASR recovered water. These studies defined source water quality using major and trace inorganic constituents, priority pollutants, water quality parameters (pH, temp, specific conductance, color, turbidity), organic compounds (pesticides, herbicides, volatile and semi-volatile organics, total and dissolved organic carbon) and selected radionuclides. Wet season and dry season trends in selected constituents also were analyzed statistically. An extensive database of information was accumulated during this effort, which is now archived on the SFWMD database DBHYDRO. Basic source water characteristics were interpreted in the CERP ASR Pilot Project Technical Data Report (USACE and SFWMD, 2013). More detailed trends for selected constituents were described in **Chapter 5** of this report. Essentially, the source water at both sites is fresh and oxic, but is characterized by high and variable concentrations of organic carbon, iron, carbonate alkalinity, and nutrients, typical of most surface waters in south Florida.

Highly colored source water will reduce effectiveness of UV disinfection systems, and can contribute to reduced performance of filter systems. Highly colored water also provides a source of organic carbon, which stimulates microbiological activity in the ASR well bore and can lead to clogging (USACE and SFWMD, 2013). Addition of oxic, organic carbon-rich water into the carbon-limited FAS will stimulate native microorganisms, and can alter groundwater geochemical reactions **(Chapters 5 and 6)**.

Average color values were consistently greatest at KRASR, particularly during the wet season when compared to trends at all other existing and proposed ASR systems. Color values exhibit a saw-toothed trend, with higher values during the wet season, and lower values during the dry season and following the 2007-2008 drought. Color values in excess of 50 PCU can challenge the effectiveness of UV disinfection, resulting in detectable coliforms at the ASR wellhead during recharge. There were two instances (over 4 years of operation) where color values were greater than 400 PCU at KRASR, resulting in ASR system shutdown. These instances are rare, but highly colored source water will require more robust disinfection systems at ASR systems located north and west of Lake Okeechobee.

Turbidity generally is not an issue at any of the existing or proposed ASR system locations except for Port Mayaca (PMASR). Maximum source water turbidity values are below the 29 NTU regulatory threshold at all systems except PMASR, where values as high as 386 NTU were measured during the period of record (2000-2014). Suspension of flocs on the eastern side of Lake Okeechobee, and mixing between turbid water of the St. Lucie Canal and Lake Okeechobee near PMASR contribute to high turbidity values. ASR systems located along the eastern shore of Lake Okeechobee or the St. Lucie Canal will require robust filtration systems to prevent clogging of the well bore due to the presence of suspended solids.

Iron-rich source water can affect ASR system operations and also can influence geochemical reactions in the aquifer. Iron can precipitate from oxic source water to clog an ASR well, and also can stimulate iron-reducing bacteria to form biofilms throughout the ASR system. Iron concentrations are below SDWA secondary criterion (300 µg/L) at southern ASR system locations (CRASR and HASR). Source water iron concentrations exceed the SDWA criterion at northern ASR system locations (KRASR and PMASR), such that WQCEs will be required when these source waters are recharged. The greatest iron concentrations measured throughout Lake Okeechobee and tributaries occur at PMASR, where iron probably is associated with organic-rich suspended material.

Carbonate alkalinity in source water does not affect ASR system operations, because concentrations are too low overall to cause scaling. Carbonate alkalinity values are lowest in northern Lake Okeechobee and the Kissimmee River, where surface sediments consist primarily of quartz sands and silts. Farther south, limestone becomes a dominant component of surface sediments, resulting in higher carbonate alkalinity concentrations in surface water. Low carbonate alkalinity values in source water will increase calcium carbonate dissolution in the ASR storage zone, as summarized in **Section 5.7.**

### 9.1.2 Characterize the Regional Hydrogeology of the Floridan Aquifer System

A hydrogeologic literature compilation and database – including lithology, stratigraphy, geophysics, hydrostratigraphy, and geotechnical testing information - was assembled for use by the project team, and the scientific community at large (**Chapter 3**). With the assistance of the USGS, a preliminary regional hydrogeologic framework was published (Reese and Richardson, 2008), which provided a comprehensive view of the hydrostratigraphy and hydraulic properties of the FAS. Definition of the preliminary hydrogeologic framework proceeded in tandem with development of the initial (coarse grid) and final (fine grid) groundwater flow models to simulate various configurations of ASR, as discussed in the response to Item 4 below.

The preliminary hydrogeologic framework identified several areas, both geographic and conceptual, where significant gaps in understanding of the FAS existed. The projects' subsequent field data collection and analysis program focused on filling those gaps -- through the construction of test exploratory wells, geophysical log analysis, core analysis, aquifer tests, seismic surveys, and expansion of water quality and level monitoring networks, tomography, and lineament analysis. Additional hydrogeologic data and interpretations defined after publication of the preliminary hydrogeologic framework were summarized in a successor publication (Reese, 2014). Here, a more detailed hydrogeologic synthesis was presented for the FAS beneath Lake Okeechobee.

Among the more significant findings from the hydrogeologic framework reports is the regional delineation of the APPZ, which may represent a significant storage zone for future ASR development. Additionally, the subsurface structure of the FAS and overlying units beneath Lake Okeechobee was delineated through the use of marine seismic data, which also revealed the presence of zones of displacement indicating the presence of faults and karst collapse structures within the limestone formations.

This focus area resulted in significant advances in the understanding of the FAS in the region. Due to funding and schedule limitations, however, we did not complete all of the field tasks, or analyses envisioned in the PMP. This left insufficient data, for example, to fully realize the potential of the sequence stratigraphic or borehole fracture analyses that were proposed in the ASR Regional Study, but foundations were laid for that work that others could build on in the future. Among the few tasks that were not completed were the performance of dynamic tracer tests at the ASR pilot systems and other multi-well systems. These tests were intended to have provided quantitative data on the effect of anisotropy within the FAS, which would have greatly benefited the groundwater modeling effort and the understanding of the effect of storage and recoverability at operational ASR systems. It is hoped that this work will continue if and when CERP ASR is implemented.

It is recognized that the regional hydrogeology of the FAS can never be fully characterized. Every new well that is drilled into the aquifer presents new data that adds to our body of understanding. As a case in point, the exploratory well at the CRASR pilot system encountered an unconsolidated, sandy zone of the Lower Hawthorn Group (Arcadia Formation) that prohibited the construction of a large capacity ASR system at Berry Groves (CRASR). While these conditions have been encountered elsewhere in south

Florida, the currently available forensic geological or geophysical methods that are available to workers do not provide the precision to predict these conditions prior to constructing capital-intensive exploratory wells at sites considered for ASR implementation. While it is not possible to eliminate hydrogeologic uncertainty in development of CERP ASR, this project has provided the data and tools necessary to provide an objective assessment of that uncertainty.

### 9.1.3 Analysis of Critical Pressures for Rock Fracturing

ASR system operation can increase or decrease aquifer pressure, with the potential to induce rock fracturing during recharge and subsidence during recovery. In support of the ASR Regional Study, an initial desktop evaluation was completed to estimate the potential for hydraulically induced fracturing of the FAS rock matrix and subsidence due to consolidation of the Hawthorn Group (Brown et al., 2005). Geibel and Brown (2012) expanded the original work of Brown et al. (2005) to determine the critical threshold of water pressure that marks the onset of hydraulically induced fracturing of the UFA rock matrix and the overlying Hawthorn Group sediments at the proposed CERP ASR systems. A geotechnical evaluation was conducted for seven potential ASR sites: Caloosahatchee River, Moore Haven, Kissimmee River, Port Mayaca, Hillsboro, Seminole-Brighton, and Paradise Run.

#### 9.1.3.1 Desktop Study Results

The results of the desktop evaluation **(Section 4.2)** indicate that only a few of the categories of pressure-induced changes examined have the potential to constrain ASR development in south Florida. First, practical limitations involving basic pump availability, pipe pressure limitations, and electricity demand will constrain the total allowable head (or pressure) at each ASR wellhead. Second, pressure-induced change limitations outlined here will slightly constrain ASR operations.

For ASR wells located north of Lake Okeechobee, it is recommended that the average hydraulic head of well clusters be limited to a maximum of 183-ft NGVD29 (80 psi) or less. This threshold exceeds the typical ASR wellhead pressures observed during the recharge phase of cycle testing at KRASR. Maximum ASR wellhead pressures observed during recharge were approximately 60 psi during cycle test 1, and decreased to approximately 25 psi during cycle test 4 (USACE and SFWMD, 2013). The maximum ASR wellhead pressure allowed by the Underground Injection Control (UIC) permit is 66 psi at this location.

For ASR wells located east or south of Lake Okeechobee, it is recommended that the average hydraulic head of well clusters be limited to a maximum of 225 ft NGVD29 (97.5 psi pressure) or less. Analysis of allowable thresholds south of Lake Okeechobee suggest permissible hydraulic head up to 275 ft NGVD29. However, under this scenario, pressures greater than 100 psi would be generated and would require specialized well casing and piping materials to be installed at significantly higher cost. Maximum ASR wellhead pressures observed during the recharge phases at HASR also were less than 66 psi (USACE and SFWMD, 2013).

#### 9.1.3.2 Geotechnical Analysis of Rock Fracturing Potential

Geotechnical laboratory rock strength tests were performed on representative cores obtained from storage zone lithologies at potential ASR systems in south Florida **(Section 4.3)**. Three primary failure methods (shear, tensile, and microfracture) were evaluated as mechanisms of hydraulically induced fracturing. The mechanical properties and in-situ stresses on representative rock samples from the Lower Hawthorn Group (Arcadia Formation), Ocala Limestone, and Avon Park Formation were measured or calculated.

UFA rock matrix mechanical properties and in-situ stresses were characterized to determine the pressure (P) values that would induce hydraulic fracturing at the top of the UFA. Shear method results indicate that an extremely high P in the UFA is required to initiate fracturing by shear failure. Tensile method results indicate that a relatively moderate P is required to initiate fracturing by tensile splitting of the well borehole wall. Microfracture method results indicate that a moderately low P is required to initiate fracturing. It is unlikely that extremely high P values will be achieved during ASR operation; therefore, hydraulic fracturing due to shear failure is not a concern. However, moderate P values can potentially be achieved, initiating hydraulic fracturing due to tensile splitting of the well borehole wall. More likely, moderately low P values causing microfracture initiation may be achieved within maximum ASR operational limits. Two additional hydraulically induced fracturing check methods were applied and produced results consistent with the tensile and microfracture primary methods, providing for increased assurance of the predictive P values that may induce fracturing.

The moderately low pressure threshold for initiation of microfracturing ranges between 95 and 166 psi without a 10 percent factor of safety. With a 10 percent factor of safety, the P threshold for initiation of microfracturing ranges between 85 and 149 psi. For comparison, casing pressure tests to evaluate integrity of the ASR well generally are run at 100 psi, and the maximum ASR wellhead pressure defined in HASR and KRASR UIC permits is two-thirds of the casing pressure test (66 psi).

Hydraulically induced fracturing can be initiated at and propagate from the well borehole wall for all three fracture mechanisms, while the ability to initiate and propagate hydraulic fracturing away from the borehole wall and within the FAS can be achieved only by shear failure and microfracture development. Hydraulically induced fracturing is not a concern at any P below the critical threshold level during typical ASR operation. If the critical water pressure threshold is met for the top of the FAS, fracturing is more likely to occur there rather than in deeper portions of the FAS, as increasing overburden stress with depth will largely negate fracture-inducing stresses. If hydraulically induced fracturing of the FAS rock matrix is initiated, it will likely be vertically oriented. However, orientation and propagation may be influenced by anisotropy, planar inhomogeneities, or alignment of the principal stresses in the FAS. The potential for hydraulically induced fracturing of the Hawthorn Group, due to vertically upward propagating fractures initiated in the FAS, is very unlikely. Fractures initiated in the FAS would be arrested at or re-directed along the discontinuity formed by the interface of the FAS and Hawthorn Group. If the fracture were able to propagate through the discontinuity and into the Hawthorn Group sediments, the softer nature of these lithologies would dissipate stress and arrest its propagation.

### 9.1.4 Analysis of Local and Regional Changes in Groundwater Flow Patterns

One of the primary goals of the ASR Regional Study was to develop a peninsula-wide groundwater model from Orlando to Key West for investigation of regional hydraulic impacts of the CERP ASR system, and a collection of smaller, local-scale models for examination of local hydraulic and water quality effects **(Chapter 7)**. The models were developed in support of CERP to characterize impacts of the proposed 333 ASR wells in southern Florida. The modeling project was developed in phases to provide opportunities for testing hypotheses and methods before application to the final model. Each phase was reviewed independently by the PDT and the Interagency Modeling Center (IMC), and comments were incorporated into final documents.

#### 9.1.4.1 Groundwater Flow Model Development, Calibration, and D13R Simulations

The project began with a search and compilation of available models and literature **(Section 7.7.3.1)**. This step provided valuable information and background and offered recommendations on implementation details. The literature search was followed by a bench-scale study **(Section 7.7.3.2)**, which evaluated several modeling codes and recommended the use of SEAWAT and WASH123D.

The Phase I models **(Section 7.7.3.3)** were coarsely refined and did not include all of the data used in later versions. Most notably, the pumping data was not yet available at the time of Phase I model development. This model provided information on where best to set boundaries and what types of parameter values might be most useful. The Phase I models were unable to accurately reproduce either the salinity or the heads in the southern part of the model. This difficulty led to additional research and study to determine the cause, and to recommend options for improvement in the Phase II model.

The Phase II models [RASRSM] **(Section 7.3.4)** were much more finely gridded and included all of the available data, including regional pumping. These models were very closely calibrated to all of the available head data. Extensive sensitivity analyses looked at possible variability in the results. These models were subjected to the greatest degree of review and scrutiny both during the modeling process and after completion of the report. This review process was meant to ensure that the result was both accurate and defensible.

The calibration of the RASRSM model was broadened to include the D13R scenario with ASR pumping rates and schedules drawn from SFWMM-D13R **(Section 7.7.5)**. Changes to the ASR well distribution were made to meet PDT-developed performance measures, including the pressure that well pumps would be required to overcome and the effect of the ASR system on the APPA in St. Lucie and Martin Counties. The final results showed that it is unlikely that the UFA will sustain the pumping requirements of 333 ASR wells as defined in the CERP. The model demonstrated that pump pressure requirements and protection of the APPA can be met with approximately 94 (5 mgd) ASR wells in the UFA, 37 (5 mgd) ASR wells in the APPZ and 101 (10 mgd) recharge wells in the BZ if recovery at sites near the APPA is significantly reduced. Recovery efficiency was assumed to be 70 percent in most of the UFA wells, 30 percent in most of the APPZ wells, and 0 percent in the BZ wells.

The suggested arrangement of these wells (Scenario 11) is indicated in **Table 7-3**. Although full recharge potential will be available, a significant reduction in the recovery volumes will limit the effectiveness of the system. The model also indicates that this arrangement of wells will result in significant head impacts over a large area of the Floridan peninsula.

Scenario 11 includes a large number of wells open to the BZ where recovery efficiency was assumed to be 0 percent. Due to the cost of drilling to such great depth, it is unlikely that so many BZ wells could be constructed. Scenario 12 was developed to simulate a more likely scenario including only the UFA and APPZ wells. The comparison of these results to the performance measures is only slightly different from Scenario 11 but it involves a significant reduction in storage capacity for the system.

A Monte Carlo analysis **(Section 7.7.5.5)** of the results of Scenario 11 was used to estimate the uncertainty in the results. The analysis showed that some additional reduction in the number of wells or the extraction rates may be necessary at a few sites due to uncertainty in the pump pressure estimates. The sites most likely to require a small reduction in ASR wells are Lakeside Ranch, Kissimmee River/Paradise Run and Hillsboro (Site 1). Uncertainty in the APPA results was minimal, so it is unlikely that any further reduction will be necessary for the protection of artesian conditions in St. Lucie or Martin Counties. It is recommended that these proposed ASR system sites and well numbers be closely analyzed through pilot studies at the proposed ASR sites with local scale models to predict the local effects of the ASR well system.

#### 9.1.4.2 Limitations on Model Simulations

Models, by nature, are only simplified simulations of reality. The models developed to evaluate CERP ASR, like all models, have limitations. The impact of these limitations on the results was mitigated by extensive calibration, sensitivity analyses, and the use of a large dataset. The datasets used for calibration were sufficient to develop models that provide a reasonable representation of the complex density-dependent groundwater flow system in the study area. The model was reviewed by the IMC at several points during the modeling process. Many of the IMC comments led to additional scrutiny of results or further data analyses to check the validity of assumptions. Overall, the extensive calibration, parameter evaluation through sensitivity analysis, and thorough review resulted in a useful and defensible model for purposes defined above.

However, all models have inherent uncertainty due to the assumptions made in their development. Consequently, the limitations of models should be clearly understood so that the results are only used for the intended purposes. The following is a list of limitations of the CERP ASR models:

- Pumping data were difficult to obtain with accuracy and often had to be estimated. Pumping is a very important sink to the groundwater system in south Florida.
- Storage space and computational time constraints led to the use of month-long stress periods in the regional calibration model, 10-day stress periods in the regional D13R scenarios, and varying stress period lengths (2-31 days) in the local scale models. These stress period sizes preclude

the use of more detailed input data for pumping and boundary conditions and constrain the precision on the results.

- The adjustment of the D13R pumping schedule to the 10-day stress periods resulted in a loss of some short-duration high pumping rates when data were averaged over 10 days. The total volume of water recharged or recovered was preserved, but this adjustment may have eliminated short-duration high pumping stresses in some model pumping cycles. Since the D13R simulations were run for 13 years, these stresses were likely to be evaluated in other pumping cycles when the high pumping rates were more prolonged.
- Salinity data were sparse, especially in the deeper layers, and data were not collected simultaneously at multiple locations. These data were crucial for calculations of density, which impacts flow conditions in a density-dependent model such as this.
- Temperature data were sparse, especially in the deeper layers and data were combined from a long time period. These data were important for calculations of density, which impacts flow conditions in a density-dependent model such as this.
- All sides of the model were given specified head boundary conditions. On the eastern side, these heads corresponded to known sea level data. On the other sides of the model, the specified heads were developed by interpolating available head data obtained at wells near the boundary. This simplification relies on the assumption that the CERP ASR pumping will not impact heads at the boundaries. Additional analysis after completion of the model showed that there was a significant impact but that it was not likely to affect the performance measure outcomes.
- The surficial aquifer was not modeled discretely with recharge entering at the surface, but was applied as a specified head boundary condition interpolated from available head data. This allowed the model to calculate the flux volumes entering the model through the surface. This simplification relies on the assumption that the CERP ASR pumping will not impact heads in the surficial aquifer.
- Spatial discretization was necessarily coarse for the regional model. Cells varied from 2,000 ft to 10,000 ft on a side. This made it impossible to examine near-well effects of pumping or water quality changes. This limitation was addressed in part by using the local-scale models to look at near-field effects. These smaller models had cell sizes varying from 100-ft to just over 500-ft on a side.
- Although extensive geologic data were used to develop the layering and hydraulic parameters for each aquifer and confining unit, simplifications were necessary for development of the model. Also, data becomes significantly sparser with depth. The thickness of the Boulder Zone (BZ), for example, was set at a uniform 500-ft, though in reality, it may be larger or smaller at different areas of the model.
- Transport parameters were very difficult to estimate because of the lack of long-term salinity data at any location. The short time period of the calibration models also made the estimation of these values more complicated. This limitation was resolved through the use of sensitivity analyses on the calibration model and a Monte Carlo analysis on the production runs including the CERP ASR system. Some additional calibration of these values was done with the local scale

models, but generally, the dataset was not sufficient for detailed calibration of transport parameters.

- The conversion of the calibration model to the D13R scenario involved significant interpolation, extrapolation and assumptions to adjust sources/sinks and boundary conditions to the new time period, for which far less data was available.
- The calculation of performance measures on the D13R scenarios involved numerous assumptions. The estimation of required pump pressures ignored head-loss in the pipes, pumps and treatment systems and skin effects at the well. The use of the Theim and Merritt equations assumed homogeneous, isotropic conditions in an infinite aquifer of uniform thickness.
- Data collection glitches contributed to significant periods of missing or unexplained data at the Hillsboro ASR well during the three cycle tests completed there. This made calibration of the Hillsboro local-scale model transport parameters impossible and allowed for only a limited calibration of flow parameters.
- Placement of monitor wells at Hillsboro in a straight line made assessment of anisotropy impossible.
- Additional investigation of the geology at Kissimmee was beneficial to the calibration of the Kissimmee local-scale model, but it was difficult to broaden this data beyond the exact location of the ASR well and the monitoring wells.

Although it is important to be cognizant of these limitations when modeling a groundwater system, these particular models were built with large amounts of data and were subjected to intensive calibration and sensitivity analyses. Assumptions were carefully weighed and analyzed with the available data. These models have been reviewed at several points by numerous knowledgeable, experienced, and credentialed experts in groundwater modeling and the Floridan Aquifer System. Consequently, there is a reasonable level of confidence in the conclusions drawn from this modeling study.

### 9.1.5 Analysis of Water Quality Changes During Storage in the Aquifer

Water quality changes that occur during ASR cycle testing were among the most significant concerns by stakeholders. CROGEE placed evaluation of water quality changes as a high priority as well. For these reasons, an intensive water quality sampling and analysis program was initiated to fulfill the following objectives:

- To characterize the native groundwater quality of potential storage zones in the UFA and APPZ prior to the onset of cycle testing
- To quantify geochemical reactions that result from recharge of source waters into the UFA and APPZ using geochemical modeling methods
- To evaluate water quality changes during storage and recovery for regulatory compliance

During the early stages of the ASR Regional Study (2005-2006), the SDWA regulatory criterion for arsenic in groundwater decreased from 50 µg/L to 10 µg/L. Many municipal (potable water) ASR systems in

Florida were now showing arsenic concentrations that exceeded that standard in the aquifer and also in recovered water. This development increased stakeholder concerns about the ASR Regional Study, particularly given the scale of ASR implementation in the CERP.

#### 9.1.5.1 Initial Desktop Data Compilation and Geochemical Modeling Studies

During the development of the ASR Regional Study (2001-2007), there were approximately 70 ASR systems in Florida that were cycle testing under a construction (versus operating) permit. Most of these systems were located at existing drinking water treatment plants in coastal areas of Palm Beach and Broward Counties on the Atlantic Coast, the Tampa Bay region, and in coastal Lee and Collier Counties along the Gulf Coast. Early efforts to evaluate water quality changes during cycle testing consisted of compiling existing water quality data from cycle testing at representative ASR systems, and developing geochemical models to predict and quantify geochemical reactions that could occur during cycle testing. Results of this initial data gathering effort were summarized in Mirecki (2004), and preliminary geochemical models were reported in Mirecki (2006).

Water quality data are compiled at existing municipal ASR systems primarily for regulatory compliance purposes rather than geochemical modeling. Most datasets obtained from municipal ASR systems were insufficient for a detailed geochemical modeling analysis. However, a few important trends were defined from these initial studies:

- Dissolved oxygen concentrations in recharge water decline rapidly (with a half-life of approximately one day) during storage.
- Increasing dissolved sulfide concentrations suggests that sulfate reducing redox conditions prevail in the UFA storage zone.
- Gross alpha and radium isotope activities can exceed SDWA criteria in native UFA groundwater samples from Lee and Collier Counties. Storage zones in this area can include phosphate-rich lithologies of the lower Hawthorn Group (Arcadia Formation). Consequently, native groundwater shows elevated isotopic activities. Recovered water activities increase due to mixing with native groundwater.
- Arsenic exceedances (greater than 10 µg/L) were detected at a few ASR systems. However, samples analyzed prior to 2005 (when the SDWA criterion lowered) may have been reported as “false negatives”. That is, the sample was interpreted as a “non-detect” using detection levels of 50 µg/L.
- Mixing between fresh recharge water and mostly brackish native groundwater differs among ASR systems. Where recharge water is transported as a plug (North Reservoir ASR system), the result is a sigmoid-shaped breakthrough curves at the distal monitor well and chloride trends that follow a conservative mixing line. Where recharge water transport is affected by hydraulic factors, breakthrough curves are less evident at the distal monitor well, and chloride concentrations deviate from conservative mixing lines (Olga ASR system). After the initial cycle, it becomes more difficult to define mixing models especially if there is not 100 percent recovery during the earlier cycle.

- Inverse geochemical models suggest dissolution of calcium carbonate and gypsum, reductive dissolution of pyrite, precipitation of iron oxyhydroxide, and hydrogen sulfide evolution at the representative ASR systems (Olga, North Reservoir, and Eastern Hillsboro).

#### 9.1.5.2 Native Groundwater Quality Characterization in the FAS

The SFWMD maintains the Regional Floridan Aquifer Groundwater (RFGW) network, which consists of 70 sites monitoring 95 discrete zones within the Floridan aquifer system (UFA and APPZ; **Section 3.3**). Sampling for the CERP native groundwater quality characterization task was coordinated to augment the existing SFWMD RFGW sampling program. Groundwater quality samples were obtained from all wells, although the frequency of sampling differs based on programmatic needs. Regional trends in groundwater quality characteristics for selected inorganic constituents (chloride, sulfate, calcium, carbonate alkalinity, pH, TDS) were depicted in **Section 5.5.** The freshest UFA groundwaters are found in the Kissimmee Valley, along the northwest-southeast trending axis of south central Florida, north of Lake Okeechobee. ASR systems in this area (Paradise Run, KRASR, L-63 Taylor Slough) would be expected to show greatest percent recoveries, as losses due to mixing with brackish native groundwater are minimal.

Nearly all UFA wells north of Lake Okeechobee, the Caloosahatchee River, and the St. Lucie Canal show native groundwater TDS concentrations below 3,000 mg/L. Drinking water regulations are most stringent in these waters because minimal treatment is required for their use as a drinking water source. Nearly all UFA groundwaters show TDS concentrations below the 10,000 mg/L UIC regulatory threshold, so the UFA is defined as a USDW. However, groundwaters having TDS concentrations between 3,000 mg/L and 10,000 mg/L are less cost-effective for use as a drinking water source due to higher pre-treatment costs.

Nearly all APPZ wells north of Lake Okeechobee in the Kissimmee River valley show relatively fresh native groundwater TDS concentrations (less than 3,000 mg/L). The APPZ generally becomes more brackish towards the coasts, with concentrations similar to that of the UFA (except at HASR, where the APPZ is actually fresher than the UFA). Highest TDS concentrations in the APPZ are measured in wells of the Caloosahatchee River valley and south of Lake Okeechobee.

#### 9.1.5.3 Water Quality Changes During ASR Cycle Testing

Deleterious water quality changes due to geochemical reactions between oxic, organic carbon- and iron-rich source water and aquifer material were among the most significant water quality issues to be addressed by the ASR Regional Study. Water quality trends during ASR cycle testing are best characterized by results obtained for the CERP ASR Pilot Projects (USACE and SFWMD, 2013), primarily at KRASR. Many of these geochemical reactions are facilitated by native or possibly introduced microorganisms, which will be discussed below. The major water quality changes interpreted from cycle testing results at KRASR are:

- Arsenic is mobilized during recharge in the UFA due to oxidation of pyrite in limestone aquifer material by dissolved oxygen in source water. However, the redox condition of the aquifer quickly evolves from an oxic condition (during recharge) back to native sulfate-reducing conditions (during storage and recovery). Arsenic subsequently co-precipitates with iron sulfide as the aquifer returns to reducing conditions. As a result, arsenic concentrations in recovered water are less than the SDWA criterion of 10 µg/L.
- The pattern of arsenic mobilization and subsequent sequestration is unique among Florida ASR systems. This is because most ASR systems recharge drinking water, which is oxic and depleted in iron and organic carbon. Without these two constituents, microorganisms in the aquifer are not stimulated (without organic carbon), and iron sulfide precipitation will not occur (in the absence of iron). CERP ASR systems are more likely to show the pattern shown at KRASR because source waters and aquifer conditions are similar **(Section 5.8).**
- Phosphorus concentrations decline during ASR cycle tests. Total phosphorus concentrations in Kissimmee River source water ranged between 4 µg/L (the detection limit) and 250 µg/L. Total phosphorus concentrations in recovered water were below 20 µg/L, through four cycle tests. The mechanism controlling the decline in phosphorus concentrations has not been confirmed, but could result from microbiological uptake or precipitation of calcium phosphate (USACE and SFWMD, 2013).
- Molybdenum is mobilized during ASR cycle testing, likely by pyrite oxidation during recharge. Once released, molybdenum remains as a complex in solution, unlike arsenic. Molybdenum concentrations ranged between 5 and 500 µg/L, with highest values measured during the first cycle test. Molybdenum concentrations in the aquifer declined during subsequent cycle tests. There is no state or Federal SDWA criterion for molybdenum. The World Health Organization maximum guideline for drinking water is 70 µg/L (USACE and SFWMD, 2013).

A large water quality dataset was compiled at KRASR, consisting of weekly to monthly sampling of surface and groundwater samples from the ASR well and up to 4 monitor wells. A smaller water quality dataset focused on regulatory compliance was compiled at HASR. Geochemical reactions and water-quality changes observed at these ASR systems differ from those observed at potable water ASR systems, primarily due to introduction of organic-carbon and iron-rich surface water into the sulfate-reducing (or sub-oxic) UFA. Because some reactions are beneficial (e.g. arsenic control), it is important to determine how representative these results are, and whether they can be extrapolated for regional ASR implementation.

Similar water-quality changes and geochemical reactions can be expected when source water composition and the geochemical environment of the aquifer are similar to those at Kissimmee River and Hillsboro Canal. Of the four locations considered (Kissimmee, Caloosahatchee, Hillsboro, and Port Mayaca), Caloosahatchee River surface water shows significantly lower organic carbon and iron concentrations, but this may be the result of too few samples. Other locations are characterized by large datasets, and show ranges in concentrations that overlap statistically. Lower organic carbon and iron concentrations in the Caloosahatchee River source water may limit or slow the rate of arsenic control in the UFA storage zone in this area.

A large dataset was developed to characterize groundwater quality in the FAS, particularly in the UFA **(Section 5.5).** The redox environment of the aquifer is the primary factor that limits arsenic mobility. Sulfate-reducing conditions (or sub-oxic conditions with hydrogen sulfide present) in the native aquifer (and the evolution of sulfate-reducing conditions during storage) strongly suggests that arsenic will re-precipitate in a solid sulfide mineral when storage durations are greater than one or two months. Sub-oxic or sulfate-reducing conditions were observed throughout the confined portion of the UFA in the interior of south Florida. Coastal locations may be influenced by saltwater intrusion in the Floridan, particularly in Miami-Dade and Broward Counties. It is not clear whether ASR systems that store water in the APPZ will show similar trends.

Predictions of the extent of mixing between recharge and native groundwater, and of percent recovery at other proposed ASR systems in the region cannot be quantified directly from results at the CERP ASR systems. Percent recovery is determined by the permeability of the storage zone, and also TDS or chloride concentrations of the native groundwater. The CERP ASR systems do represent end-members for the ranges of native groundwater TDS and chloride. The maximum percent recovery determined at these systems during cycle testing was 100 percent (low TDS native groundwater), and 42 percent (high TDS native groundwater), which brackets the range of conditions to be expected for storage in the UFA of south Florida.

#### 9.1.5.4 Limitations of these Findings

Due to funding and schedule limitations, not all of the tasks or analyses envisioned in the original PMPs and work plans were completed, but foundations were laid so that others could build on in the future. Tasks that were not completed included construction of pilot projects at Moorehaven, Port Mayaca, and within the Caloosahatchee River basin. These projects would have significantly enhanced our understanding of geochemical reactions taking place within ASR systems completed in a broader variety of lithologic and ambient water quality environments with the FAS.

### 9.1.6 Potential Effects of ASR on Mercury Bioaccumulation for Ecosystem Restoration Projects

During the early planning phases of the ASR Regional Study, it was hypothesized that two processes could occur during ASR cycle testing to increase methyl mercury concentrations in surface waters of the greater Everglades. First, recharging source water with elevated mercury concentrations into a sulfate-reducing aquifer could promote in-situ mercury methylation in the UFA, so that recovered water would be a new, additional source of methyl mercury to the environment. Second, discharge of recovered water with sulfate concentrations greater than those typical of south Florida surface water could enhance mercury methylation where it already occurs, in Everglades wetland sediments. The first process was addressed by Krabbenhoft et al. (2007; **Section 2.3**). The second process was addressed in the Ecological Risk Assessment **(Chapter 8**).

### 9.1.6.1 Mercury Methylation Potential in the FAS

An initial investigation was conducted by the USGS to determine the potential for in-situ mercury methylation using a combination of field sampling and controlled bench-scale experiments (Krabbenhoft et al., 2007). The field sampling survey gathered groundwater samples from the SAS and UFA to quantify background concentrations of mercury and methyl mercury, and to define any spatial trends of these concentrations in the aquifers. Laboratory experiments incubated mercury isotope-spiked Lake Okeechobee surface water in the presence of UFA core material (CRASR) under both oxic and anoxic conditions. The presence of different mercury isotopes as elemental mercury and methyl mercury would serve as a tracer of the mercury methylation process in various incubation trials.

Results of field sampling shows that concentrations of total mercury and methyl mercury in both the UFA and SAS are very low, (mean values 0.41 ng/L and less than 0.07 ng/L, respectively) and exhibit no apparent spatial trends in either aquifer. These concentrations are significantly less than those in south Florida surface waters. Discharge of native UFA or SAS groundwater will not increase the mercury load in surface water.

Results of the incubation experiments shows that mercury and methyl mercury concentrations declined during the experimental procedure, most likely due to sorption onto aquifer material. There was no evidence of transformation of isotopically labeled mercury to methyl mercury, even under sulfate reducing conditions for the 16-week duration of the experiment. These bench-scale experiments suggest that the potential for mercury methylation under sulfate-conditions in the UFA is minimal.

### 9.1.6.2 Mercury and Methyl Mercury Trends during ASR Cycle Tests

Mercury and methyl mercury concentrations were measured throughout the ASR cycle testing program, particularly at KRASR (USACE and SFWMD, 2013). At KRASR, there were statistically significant reductions in mercury and methyl mercury concentrations when recharge water and the recovered water concentrations are compared. These data confirmed the findings of Krabbenhoft et al. (2007). The controlling mechanism for the decline has not yet been identified, but reduction could result from 1) dilution, 2) sorption to aquifer lithology, 3) co-precipitation as a solid sulfide. At HASR, there was no significant difference in mercury and methyl mercury concentrations between recharge and recovered water. However, this system was subjected to fewer cycles, with lower recharge and recovery volumes, therefore decreasing the time that reactions might have occurred, and the number of data points collected. The mechanisms that govern mobilization and sequestration of Hg must be further studied before results from the current test wells can be extrapolated to other locations with any degree of certainty.

### 9.1.7 Relationships Among ASR Storage Interval Properties, Recovery Rates, and Recharge Volume

This seventh, and last, issue identified by the ASR Issue Team is by far the broadest and most comprehensive of their report. The discussion of this issue details 10 'further investigations needed.' To confirm the efficacy of ASR as it pertains to aquifer hydraulic and hydrogeologic conditions. Some of these investigations (develop storage zone testing protocol, develop a cycle testing protocol, and develop techniques to address operational problems) are operational in nature, and were considered in the planning phase for each CERP ASR system. Cycle testing objectives, and groundwater and surface water sampling plans also were developed by the PDT, and were documented in USACE and SFWMD (2013) for both CERP ASR systems. Because both systems were designed to operate at 5 MGD pumping capacity, it was not possible to determine relationships between pumping rate and recovery efficiency beyond the observations at the CERP ASR pilot systems without compromising other project objectives. However, hydrogeologic, design, and operational factors that control ASR system performance at other south Florida ASR systems was discussed by Reese and Alvarez-Zarikian (2006).

One of the major project goals of the ASR Regional Study was to characterize hydrogeologic properties of permeable storage zones in the FAS, as they pertain to ASR feasibility. This effort has been documented extensively in **Chapters 3** and **7** of this report. Development of the regional hydrogeologic framework (**Chapter 3)** for the FAS in south Florida is a major contribution, not only for ASR feasibility but also for the hydrogeologic community of south Florida. The Regional ASR groundwater flow and transport model (**Chapter 7**) provides a detailed numerical analysis of ASR feasibility on a regional scale.

Confined aquifers are the best storage zone for ASR systems, because upward migration and leakage are restricted. If the upper or lower confining units lose integrity, the result is a loss of recharge water, reduced recovery, or inter-aquifer mixing. The material strength of the overlying confining unit was characterized throughout south Florida, with the conclusion that typical pressures encountered during ASR operations are unlikely to fracture the overlying confining unit. Pressure measurements in a well screened in the overlying confining unit at KRASR showed no pressure changes related to recharge or recovery. Leakage through the underlying confining unit, and mixing between the UFA and APPZ was not observed at either CERP ASR system. This confining unit (MCU1) generally is interpreted as leaky, but no evidence of mixing was observed at KRASR, where a dual-zone well is open to both the UFA and APPZ. Hydrologic parameter estimates for the MCU1 are not well characterized. Additional data for the MC1 and MC2 will be required at ASR systems where both the UFA and APPZ will serve as storage zones.

Water quality changes at the ASR wellhead (and at distal locations throughout the KRASR wellfield) were characterized in a robust, extensive groundwater quality dataset obtained over four cycles. These and supplemental surface water quality data were incorporated into subsequent modeling efforts conducted for an ecological risk assessment.

The ASR Issue Team's suggestion to "Characterize the typical time variability of recovery water demands for urban, agricultural and ecosystem needs" is beyond the scope of the ASR Regional Study. As part of their water-supply planning efforts, the SFWMD develops a water supply plan for each major basin. These studies evaluate current usage, and predict future demands on water supply. ASR is considered in this evaluation, and ASR also is a component of several Alternative Water Supply Development projects defined in the plan. Additional water supply planning for ecosystem restoration goals is defined in the Comprehensive Everglades Planning Process (CEPP), which is an update to the CERP. ASR is not considered as a water management strategy at present in the CEPP.

**T**he Issue Team's request to "Conduct full-scale demonstration testing of several large diameter ASR wells constructed in the upper interval at 5 to 10 sites..." was the driving force for the CERP ASR pilot system design, construction, and operation as described in USACE and SFWMD (2013). As mentioned in several places in this report, the PDT hoped to perform cycle tests at 3 to 5 sites, but resource constraints limited ASR system construction to two locations. If ASR is again viewed as a substantial part of Everglades restoration, additional sites for cycle testing should be considered.

Data collected from operation of the ASR pilot projects, new exploratory wells, and aquifer tests, as well as information acquired from operational ASR systems throughout South Florida have provided a comprehensive understanding of the variability of conditions that might affect CERP ASR performance. The KRASR and HASR pilot systems were some of the very first ASR systems built within the “interior” of south Florida. Prior to that time, most existing ASR systems had been built by utilities within urban areas along the coasts. Both pilot projects successfully demonstrated that high capacity (5 MGD) recharge and recovery ASR wells, completed in the upper portion of the FAS can be successfully operated within the interior of the state. Both CERP ASR systems were completed in transmissive limestone intervals, with open holes (without the need of well screens). The use of long open intervals (several hundred feet) is standard in most Florida ASR systems. However, the ASR Regional Study and other efforts by the SFWMD and USGS resulted in some significant advances in our understanding of the Floridan Aquifer System, particularly in regions with sparse data**.** These advances include, but are not limited to, the definition of preferential flow zones within the UFA and the APPZ, both of which represent potential storage zones**.** More cost-effective ASR wells could be constructed to focus on preferential flow zones and shorter open intervals without reducing well capacity.

There were substantial differences between the salinity of the native ground waters at the pilot ASR locations, which had a bearing on the percent recovery exhibited at each system. With regard to native groundwater quality, the two pilots could be considered as two end members. Native water within the storage zone at KRASR is relatively fresh (TDS less than 800 mg/L) whereas at HASR, native water within the storage interval was brackish (TDS of approximately 5,000 mg/L). The fresher native water at KRASR enabled 100 percent recovery by volume, whereas the brackish water at the HASR necessitated the termination of recovery of only 20 to 40 percent of the recharge water volume. Further improvement of percent recovery at the HASR is anticipated with further cycle testing and recharge of larger surface water volumes.

During extended periods of recharge, both KRASR and HASR systems experienced plugging of the storage zone due to the buildup of biological films or fine grained solids. Borehole plugging is a relatively common occurrence at ASR systems across the state, and is often controlled by periodic back-flushing of the wells, to lift out the solids. Both ASR systems responded positively to acidization processes (conducted between cycles) to improve recharge capacity.

Both pilot systems were designed with recovery pumps installed within the ASR wells, to provide consistent recovery rates of 5 MGD. However, the UFA at both locations exhibited an ambient positive piezometric head of approximately 12 to 20 psi. In the future, some analysis should be considered to allow the ASR wells to recover naturally, solely using the artesian pressure of the formation. This might have the benefit of reducing capital and maintenance costs of the ASR systems and decreasing energy consumption.

#### 9.1.7.1 Limitations of These Findings

During construction of several of the exploratory wells, it became evident that the deeper, “middle” portion of the FAS contained strata that were available for ASR storage, including the APPZ. A pilot ASR system was not built to include a storage zone within this zone. Consequently, the potential use of superposed aquifers for storage at a single ASR system could not be evaluated**.**

Additionally, among the tasks that were not completed included the dynamic tracer tests at the pilot system locations and other multi-well systems. Tracer tests would have provided data on the effect of anisotropy within the FAS, which would have benefited the groundwater modeling effort and our understanding of the effect of storage and recoverability at operational ASR systems.

## 9.2 Responses to NRC (2001) Recommendations

The NRC (2001) report was the stimulus for creation of the ASR Regional Study. In this report, CROGEE identified three areas that needed more detail in order to reduce uncertainty of such a large, expansive proposed ASR program. These areas are: 1) regional science issues; 2) water quality issues; 3) local performance/feasibility issues. The following sections respond to CROGEE concerns.

### 9.2.1 Regional Science Issues

These issues that focus on the scale of ASR implementation across south Florida.

#### 9.2.1.1 Compile a List of Available Data and Data Needs for Regional Assessment

Data compilation and identification of data gaps was initiated as one of the initial studies of the ASR Regional Study. A large database of available ASR literature was completed (**Section 2.1**), which complemented a more focused literature review supporting development of the ASR Regional Groundwater flow model (CH2M Hill, 2005). Identification of hydrogeology and groundwater quality data gaps in the FAS was addressed continually throughout the project. The ASR Regional Study was coordinated with the SFWMD Regional Floridan Ground Water (RFGW) monitoring program, so that ongoing well construction, hydrologic testing, and water quality sampling data could be incorporated into the regional hydrogeologic framework (Reese and Richardson, 2008; Reese, 2014). All data and deliverables were added continually to the SFWMD DBHYDRO database for public distribution.

#### 9.2.1.2 Develop a Regional Scale Groundwater Model in Parallel with Initial Data Compilation and Identification of Data Gaps

The ASR Regional groundwater flow model is a major deliverable of the ASR Regional Study **(Chapter 7; Section 9.1.4.1)**, and was initiated concurrently with data compilation supporting development of the regional hydrogeologic framework (**Section 3.1, Section 9.1.2).** The groundwater model was developed in phases in coordination with the hydrogeology effort. The development, calibration, and sensitivity analysis of the model, and resultant simulations are discussed extensively in **Chapter 7** and summarized in **Section 9.1.4.1.**

#### 9.2.1.3 Drill Exploratory Wells in Key Areas, Including Core Sampling, Geophysical Logging, Hydraulic Testing and Water Quality Sampling

With the assistance of the USGS, a preliminary regional hydrogeologic literature database and framework was assembled (Reese and Richardson, 2008). That task provided a comprehensive view of the general understanding of the hydrostratigraphy and hydraulic properties of the FAS at the beginning of the ASR Regional Study project. It also identified several areas, both geographic and conceptual, which constituted significant gaps in that understanding. In response to this evaluation, a drilling and testing program was developed that ultimately resulted in the construction of five new exploratory test wells, installation of a continuous corehole, performance of a sequence stratigraphic analysis, expansion of the RFGW monitoring network, and initiation of a quarterly FAS water sampling program. The data collected from these tasks were integrated with geophysical evaluations to create a final hydrogeologic framework, which was subsequently integrated into the final groundwater model simulations. All data are archived on the SFWMD database DBHYDRO.

#### 9.2.1.4 Conduct Seismic Reflection Surveys to Constrain the Three-Dimensional Geometry and Continuity of Hydrostratigraphic Units

New seismic reflection data was collected across Lake Okeechobee, and existing seismic lines were evaluated in an effort to fill in areas where well data were not available. Seismic reflection data were integrated into the final hydrogeologic framework (Reese, 2014). Seismic survey data beneath Lake Okeechobee **(Section 3.7)** show that the three major permeable zones within the FAS (UFA, APPZ and uppermost permeable zone of the LF) are laterally continuous, although lateral hydraulic connectivity within any single permeable zone across the lake has not been established.

#### 9.2.1.5 Use of the Regional Model in Conjunction with other Regional Data Sets to Develop a Rational, Multi-Objective Approach to ASR Facility Siting During Final Design of the Regional ASR Systems

This recommendation is prospective, in that the tools developed during the ASR Regional Study would be applied to the phased roll-out of ASR in the CERP. This recommendation will be applied should that occur in the future. A preliminary siting study was completed early in the ASR Regional Study **(Section 2.4;** Brown et al., 2005**).** Only surface criteria (e.g. real estate availability, source water proximity) were utilized in this effort. The state of knowledge of FAS hydrology and hydrogeology has advanced during the ASR Regional Study, so it is anticipated that FAS aquifer characteristics and hydrostratigraphy will be included as criteria for ASR site selection.

### 9.2.2 Water Quality Issues

These recommendations address the potential effects of recharge water on the geochemical environment of the FAS, and of recovered water on Lake Okeechobee and the greater Everglades ecosystem.

#### 9.2.2.1 Conduct Laboratory and Field Bioassays and Ecotoxicological Studies to Determine Appropriate Recovered Water Standards for Downstream Receptors

Ecotoxicological and bioconcentration studies to characterize baseline conditions were initiated prior to cycle testing at the proposed and constructed ASR pilot systems. These studies evaluated the toxicity of source water prior to storage in the aquifer, and were then repeated using recovered water during cycle tests 1 and 2 at KRASR. Types of tests include standard toxicological tests required for NPDES permits (e.g. 7-day static renewal survival and reproduction tests using *Ceriodaphnia dubia*), and supplemental tests using organisms that were important receptors in Lake Okeechobee or the Greater Everglades (e.g. 96-hour frog embryo teratogenesis assay, 96-hour chronic growth test with green algae *Selenastrum capricornutum*). The data compilation and limited interpretation of these tests is found in USACE and SFWMD (2013). Incorporation of these results into an ecological risk assessment is found in **Chapter 8** and also **Appendix F.**

Bioconcentration studies were conducted using bluegill fish and freshwater mollusks as test organisms at KRASR. A unique mobile flow-through bioconcentration laboratory was stationed at KRASR, and bioconcentration experiments were conducted using Kissimmee River source water for baseline, a 50:50 mix of source water and cycle test 1 recovered water, and 100 percent cycle test 1 recovered water. An in situ study of bioaccumulation was also conducted KRASR by placing caged mussels in the proximity of the discharge outfall. Analytes of concern for bioaccumulation are trace metals (Al, Sb, As, Cd, Cr, Mo, Ni, Se, Zn) mercury and methyl mercury, and radium isotopes. The data compilation and limited interpretation of these tests is found in USACE and SFWMD (2013). Incorporation of these results into an ecological risk assessment is found in **Chapter 8.**

Periphyton is an important component of the South Florida ecosystem. To evaluate potential effects of recovered water on periphyton diversity and abundance, the periphyton communities were cultured the in Kissimmee River upstream and downstream of KRASR. Periphytometers were deployed prior to cycle testing, and again during cycle test 1 recovery phase. Although loss of periphytometers reduced the statistical significance of pre- and post-cycle test effects, this experiment yielded basic diversity data documenting in-stream conditions at this particular site. The data compilation and limited interpretation of these tests is found in USACE and SFWMD (2013). Incorporation of these results into an ecological risk assessment is found in **Chapter 8.**

In advance of ASR system construction, surface water ecosystems adjacent to the five proposed CERP ASR systems were characterized (Tetra Tech, 2007). This study provided a baseline (pre-operational) data summary of surface water and sediment quality, macroinvertebrate and fish communities, and mercury concentrations in fish. Vegetation community diversity was interpreted at each site using the Floristic Quality Index to identify disturbed versus pristine habitat conditions. In-stream conditions at KRASR were determined after the completion of four cycle tests, although a using a different methodology (Amec, 2013). Incorporation of these results into an ecological risk assessment is found in **Chapter 8.**

#### 9.2.2.2 Characterize Organic Carbon in the Source Water and Studies to Anticipate the Effects of Biogeochemical Processes in the Subsurface

As cycle testing proceeded at the ASR pilot systems, it became increasingly clear that the TOC and DOC constituents in source (surface) water were important drivers of subsurface biogeochemical reactions. TOC and DOC concentrations were measured weekly and monthly during all phases of cycle tests at KRASR, and these data are presented in USACE and SFMWD (2013). Concentrations of TOC and DOC declined during each cycle test, most likely due to sorption to aquifer material and microbe-mediated redox reactions in the UFA. More detailed studies of microbe-mediated geochemical reactions were completed by Lisle (2014) and Harvey et al. (2014).

Lisle (2014) characterized DOC in native UFA and APPZ groundwaters, as part of a larger effort to define microbe diversity in the FAS **(Chapter 6)**. Microbes couple electron donor (oxidation of organic carbon) and electron acceptor (reduction of nitrate, ferric iron, or sulfate, for example) reactions to obtain energy, and these coupled reactions are specific to microbial families. As part of this study, Lisle (2014) quantified carbon utilization and biomass production in microbe communities isolated from six UFA and APPZ wells that were near the CERP ASR systems. The Lisle (2014) study is the most detailed characterization of native microbe diversity of the FAS to date.

In a related study, Harvey et al. (2014) reported characteristics of DOC fractions in Lake Okeechobee surface water samples, and the effect that these DOC fractions would have on transport of *E. coli* introduced into the FAS during ASR cycle testing. Although the transport tests were inconclusive, characterization of the DOC fractions of Lake Okeechobee surface water will be useful for other subsurface microbe studies.

#### 9.2.2.3 Laboratory Studies to Evaluate Dissolution Kinetics and Redox Processes that Could Release Ions, Arsenic, Heavy Metals, Radionuclides and Other Constituents from the Aquifer Matrix

Development of the ASR Regional Study coincided with the recognition that geochemical reactions between recharged water and aquifer material can result in the release of metals and other species during ASR cycle testing. The ASR Regional Study PDT investigated several approaches to determine, in advance of ASR system construction, how to identify those storage zone lithologies that were most likely to adversely affect groundwater quality during cycle testing. Fischler and Arthur (2014) at the Florida Geological Survey (FGS) completed a detailed study to characterize mineralogy and chemical composition of representative samples in cores from the lower Hawthorn Group confining unit, and in the core samples from the Ocala Limestone, Suwannee Limestone, and Avon Park Formation at existing and proposed CERP ASR systems.

Whole rock analyses of 14 samples from three representative cores (PBF-15 at L-8; MW-10 at KRASR; and L-1028 in Lee County) were characterized using scanning electron microscopy, back-scattered electron imaging, electron probe microanalysis and reflected light microscopy methods **(section 5.8.1)**. The results confirmed the frequent occurrence of pyrite in all UFA and APPZ storage zone lithologies. This mineral serves as a source for arsenic, antimony, and possibly molybdenum. Although marine limestones of the Ocala, Suwannee, and Avon Park Formations may have interstitial pyrite, arsenic mobility will be greatest where pyrite occurs in the permeable zones within each formation.

The FGS maintained an active program to evaluate water-rock interactions during ASR cycle testing, which was performed concurrently with the ASR Regional Study. These efforts included bench-top sequential extraction experiments conducted under reducing conditions (Arthur et al., 2007) in addition to field studies. In the bench-top experiments, representative rock samples from the lower Hawthorn Group confining unit, the Ocala Limestone, Suwannee Limestone, and Avon Park Formation at the proposed CERP ASR pilot systems (CRASR, PMASR, KRASR, HASR, MHASR, L-2) were reacted with either source water or native groundwater in sealed reaction vessels in which a reducing geochemical environment was maintained. The objective of these leaching experiments is to quantify the phases that were the most significant source of metals and uranium in aquifer material under simulated ASR cycle test conditions. A detailed mineralogical and whole rock geochemical characterization was part of this effort.

The sequential extraction experiments of Arthur et al. (2007) confirm that organic sulfide-rich fractions of lower Hawthorn Group and FAS limestones account for the greatest proportional release of most trace metals. Uranium was extracted most readily from sulfide phases, but concentrations were greatest in the lower Hawthorn Group samples compared to the limestone samples.

### 9.2.3 Local Performance/Feasibility Issues

Many of these issues are addressed by cycle testing at the CERP ASR systems, and are reported in USACE and SFWMD (2013). However, the following concern was identified in NRC (2001).

#### 9.2.3.1 Include Studies to Understand Mixing of Recharge Water with Saline Groundwater

Mixing models were developed using chloride as a conservative tracer using existing data at several municipal ASR systems (Mirecki, 2006) and also during cycle tests at KRASR (Mirecki et al., 2012). Mixing models and chloride concentration trends are useful for evaluating breakthrough of recharge water in monitor wells, particularly when the chloride composition contrast is great between native and recharge water.

Sigmoid-shaped breakthrough curves suggest that water travels as a plug through the aquifer away from the ASR well **(Section 5.7)**. This is most likely when the storage zone contains discrete permeable zones that are intersected by monitor wells having a short open interval (to eliminate borehole mixing from many permeable zones. This pattern is clearly shown at KRASR as recharge water flows along a preferential flow zone between the ASR well and the 1,100-ft storage zone monitor well (Mirecki et al., 2012). Reese and Alvarez-Zarikian (2007) have identified this preferential flow zone at the top of the UFA as a regional feature that could influence subsurface transport at other interior south Florida ASR systems. In contrast, non-sigmoidal breakthrough curves observed at other ASR systems (Mirecki, 2006) may result from mixing of several flow zones within the large open interval of a monitoring well borehole.

## 9.3 Responses to NRC (2002) Recommendations

The NRC (2002) report summarizes their review of the ASR Regional Study PMP. In this report, CROGEE identified several tasks that should be expanded and further defined. The following sections respond to CROGEE concerns.

### 9.3.1 Increase the Number of Monitor Wells and Conduct Extended Recharge and Storage Durations at Each Site to Ascertain the Vertical and Lateral Heterogeneity of the Sites and to Understand Hydraulic and Biogeochemical Processes

The cycle testing program at both CERP ASR pilot systems increased in duration and volume recharged with each successive cycle. At KRASR, the final cycle test consisted of a six-month recharge period followed by one year of storage, and was one of the largest volume single ASR well cycle tests ever conducted in Florida. Between cycle tests 2 and 3, two additional monitor wells were constructed at KRASR, to evaluate transport of recharge water and water-quality changes over a larger radius from the ASR well. Results of cycle testing at CERP ASR pilot systems are discussed in USACE and SFWMD (2013).

### 9.3.2 Increase Emphasis on Potential Geochemical Reactions via Expanded Monitoring Programs During Cycle Testing

Although only two of the original five proposed CERP ASR systems were constructed and operated, a primary focus of cycle testing at KRASR and HASR was to evaluate water-quality changes during cycle testing. The primary focus at KRASR was to characterize geochemical changes in the storage zone throughout the cycle testing program. An intensive sampling program consisted of weekly, biweekly, or monthly sampling of all wells for major and trace inorganic constituents, nitrogen and phosphorus nutrients, selected radionuclides, stable isotopes (cycle test 1 only), mercury and methyl mercury, and microorganisms. The focus at HASR was to determine regulatory compliance during cycle testing. Results are discussed fully in USACE and SFMWD (2013) and Mirecki et al. (2012).

### 9.3.3 Increase Emphasis on Community-Level and System-Wide Ecological Effects

The Ecological Risk Assessment included an assessment of the impact of ASR on fisheries in the Lake Okeechobee basin as well as an evaluation of potential changes to SAV communities in the Kissimmee River and Lake Okeechobee, as detailed in **Chapter 8** and **Appendix E.**

### 9.3.4 Extend Duration of Bioassay Testing and Monitoring to Allow for Assessment of Long-Term Ecological Effects

Extended duration bioassay testing and monitoring was implemented to the extent practicable given the suite of standardized ecotoxicological tests selected for the project and the timing of recovery events at the pilot facilities (USACE and SFWMD, 2013). The ecological risk assessment team investigated the potential for site-specific in-situ testing using customized microcosms at the KRASR facility. Given the timing and duration of cycle testing events, the variability of the different ecosystems that might be exposed to ASR discharges, and cost considerations, the team determined that standardized eco-toxicological testing would be the best way to evaluate short-term ecological effects because of their reproducibility and general acceptance within the scientific community.

During the 6-month recovery events at KRASR, multiple sampling events were scheduled to collect recovered water and test for toxicity using standard 24 hour and 96 hour tests. Bioaccumulation testing was done using 28-day exposure periods and periphytometers were deployed for 30-day stretches during recovery. In the Ecological Risk Assessment, the evaluation of long-term ecological effects relies upon the interpretation of the shorter-duration eco-toxicological testing performed at KRASR and HASR and the projection of downstream water quality conditions as affected by ASR discharges. The ERA determined that the 200 well ASR scenario (ALT2) could potentially result in long-term ecological effects particularly in the Kissimmee River associated with fisheries while the lesser ASR implementation scenarios would be less likely to result in long-term ecological change particularly in the downstream water bodies such as Lake Okeechobee and the Greater Everglades.

### 9.3.5 Emphasis on Ecosystem Modeling Within the Everglades, to Study the Effects of High Ionic Strength Recovered Water on Community Composition

The Lake Okeechobee Environmental Model (LOEM) discussed in **Chapter 8** and **Appendix E** was used to predict the concentrations of chloride and sulfate within Lake as a result of CERP ASR operations. Under worst case assumptions, this modeling showed that chloride and sulfate concentrations for the full 200 well ASR installation in the Lake Okeechobee Basin would result in a temporary (<12 months) doubling of chloride and sulfate concentrations in the lake. While community composition could be affected by such increases in chloride and sulfate within the Lake, the 200 ASR well scenario in the Lake Okeechobee basin was ultimately considered not feasible for hydrogeologic reasons. For this reason, the ERA did not include ecosystem modeling of the 200-well scenario. Under less intensive ASR implementation scenarios, such as the 100-well scenario and the reduced recovered water volume scenarios, the increase in sulfate and chloride concentrations within the lake generally resulted in maximum chloride and sulfate concentrations that were within the existing range of concentrations or not substantially higher than the baseline maximum concentrations. Given limited increase in chloride and sulfate for the less intensive ASR implementation scenarios, the ERA team determined that the effects of recovered water on community composition would be limited for these alternatives (ALT3, ALT4, ALT4-S11). Similarly, the effect of recovered water on community composition within the Greater Everglades was considered to be minimal for the lesser ASR implementation scenarios because of the dilution of ASR flows by EAA runoff.

### 9.3.6 Expanded Ecological Evaluation of Water Recovered from ASR Systems.

The CROGEE recommended, “ecotoxicological studies, including long-term bioassays, be conducted at the field scale to evaluate the ecological impacts of water-quality changes” caused by the use of ASR technologies in south Florida. During 2004, the SFWMD initiated studies to evaluate ecotoxicological test methods. This work began with screening studies that utilized synthetic recovered water to evaluate toxicological tests that would be useful during actual pilot ASR cycle testing. The preliminary toxicological screening studies identified a set of toxicological tests, bioaccumulation tests, tetrogenetic tests, stream condition analysis, in-situ exposure tests that were utilized at the KRASR and HASR facilities during cycle testing. In general, the testing results indicated no acute toxicity of the recovered water, some limited and sporadic chronic toxicity during the later phase of recovery at the KRASR facility, and limited potential for bioaccumulation of metals by mussels located adjacent to the ASR discharge outfalls. These tests and the results are fully discussed in **Appendix F** (Ecological Risk Assessment Report.)

# 10 Future Directions for CERP ASR

In CERP, the proposed construction of 333 ASR wells represents the greatest proportion of new storage (a 75 percent volume increase; NRC, 2005) added to the south Florida water management system. The project implementation reports of CERP, and its successor CEPP, both contain a component called "Adaptive Management and Monitoring". The focus of an adaptive management and monitoring plan is to encourage efficiencies by incorporating the results of project monitoring to enhance restoration benefits, reduce cost, inform project design, and improve project performance (NRC, 2014).

In the context of the ASR implementation, adaptive management and monitoring consists of feedback between the monitoring results and conclusions developed at the CERP ASR pilot systems (USACE and SFWMD, 2013) with the hydrogeological framework development, groundwater and solute transport modeling, and ecosystem effects evaluation presented in this report. The CERP ASR pilot system results showed that individual ASR systems could be operated successfully with good (although not perfect) regulatory compliance in interior locations of Florida. This study evaluates scenarios where similar systems would be constructed, and predicts potential hydrologic, hydrogeologic, and ecologic changes and effects.

Further development of ASR technology for CERP and CEPP, presumably with a reduced number of ASR systems, would not be constructed as a single effort. Instead, these systems could be developed step-wise, in concert with other water management systems designed and constructed for water supply and ecosystem restoration purposes. This chapter provides a vision of "the next phase" of CERP ASR implementation. It is comprised of projects and studies that should be considered for funding, sequencing and scheduling, that builds on the findings contained within this report. In total, this proposed program describes construction and testing of ASR facilities in locations that have been considered for ASR previously. If completely implemented, the program would result in construction of a total of 70 MGD of ASR recharge capacity at nine localities within south Florida.

## 10.1 Expansion of the Existing Pilot Facilities at HASR and KRASR

These projects would continue cycle testing at the HASR system, in order to increase the volume of freshwater in the storage zone to improve percent recovery. The KRASR system would be expanded with an additional recharge well to increase storage capacity at this location.

### 10.1.1 Additional Cycle Testing at the Hillsboro ASR System

The three test cycles conducted to date at the HASR system indicated that percent recovery improved from approximately 20 percent to 40 percent. Although these results were encouraging, further testing is warranted to determine the ultimate recovery capacity of this system. At least a series of three additional test cycles should be conducted on the system, with the intent of increasing the recharge and storage volumes and durations, to develop a large freshwater zone around the ASR well. A proposed cycle plan should be considered, such as:

**Cycle Test 4:** Recharge – 60 days; Storage – 30 days; Recovery – 30 days
**Cycle Test 5:** Recharge – 90 days; Storage – 60 days; Recovery – 60 days
**Cycle Test 6:** Recharge – 120 days; Storage – 90 days; Recovery – 60 days

Depending on the results of the cycle testing at the Hillsboro facility, future consideration should be given to construction of a second ASR well, to continue to evaluate the potential of full-scale (30 wells) ASR integration into the Site 1 impoundment, as envisioned in the Restudy (USACE and SFWMD, 1999).

The project (cycle testing) duration will be 2 years, starting in 2015. Activities include permitting, operation and maintenance support, system maintenance and repair (as needed), monitoring and project reporting.

### 10.1.2 Expansion of the Kissimmee River ASR System

The KRASR system has successfully demonstrated that ASR systems can be built in the upper FAS adjacent to Lake Okeechobee, with high capacities and percent recovery. A mechanism for arsenic control during cycle testing was defined at this site, along with phosphorus reduction. This early success should be augmented with construction of a second ASR well on the property, completed within the APPZ to determine the recharge, storage and recovery capacities, and percent recovery of that unit and continuation of studies of nutrient reduction via ASR. Construction of an ASR well in the APPZ will expand the total recharge capacity of the Kissimmee facility to 10 MGD.

The project duration is approximately 5 years, starting in 2015. Activities include permitting, design, well construction, facility modification, cycle testing (2 year duration), operation and maintenance, monitoring and reporting.

## 10.2 Construction at Previously Planned CERP ASR Pilot Systems

Only two of five proposed CERP ASR systems were constructed to date. The other three systems – Port Mayaca, Moorehaven, and Caloosahatchee River – remain either in the conceptual or final design phase. If constructed, these ASR systems would fulfill their original intent, and could augment newer water storage structures such as STAs, dispersed lands storage, and reservoirs.

### 10.2.1 Port Mayaca Pilot ASR System

Currently, two wells have been constructed at this facility – a large diameter exploratory well (EXPM-1) and a dual-zone monitoring well (MF-37). The PPDR for this facility proposed construction of a multi-well (three) ASR well, 15 MGD system, utilizing media filtration coupled with a UV disinfection treatment process. Final plans and specifications already exist for the ASR surface facility, although the filtration system should be re-evaluated to benefit from newer technologies. The existing large diameter well can serve as the first of three ASR wells planned for this pilot system. This system will provide data on well interference, aquifer anisotropy, and expected percent recovery of multi-well ASR facilities in proximity to Lake Okeechobee. In addition, an ASR system at this location would provide some reduction in flows to the St. Lucie estuary during periods of high-volume releases from Lake Okeechobee.

The project duration is approximately 6 years, starting in 2016. Project activities include permitting, design evaluation, well construction, surface facility construction, cycle testing (2 year duration), operation and maintenance, monitoring and reporting.

### 10.2.2 Moorehaven ASR Pilot System

The exploratory well (GLF-6) constructed at the Moorehaven pilot site has indicated that favorable zones for ASR existed in both the upper and middle FAS. The PPDR for this facility proposed construction of a one-well ASR facility, utilizing magnetized ion exchange (MIEX) treatment process for DOC removal, coupled with chloramine disinfection. This 5 MGD system will test a treatment (filtration and disinfection) process that was not used at either the Kissimmee or the Hillsboro pilot systems.

The project duration is approximately 6 years, starting in 2016. Project activities include permitting, design, well construction, surface facility construction, cycle testing (2 year duration), operation and maintenance, monitoring and reporting.

### 10.2.3 Caloosahatchee River ASR Pilot System

The exploratory well at the Berry Groves property indicated that conditions within UFA were not favorable for high-capacity ASR. As a result, the Caloosahatchee River ASR pilot project was deferred until such time as another site was identified within the basin that might accommodate ASR. Within the past few years, the SFWMD has partnered with Lee County to initiate a new water treatment project along the Caloosahatchee River, at the Boma property. The SFWMD is developing a pilot STA designed to remove nitrogen from the river water. If the STA pilot feature proves successful and a larger-scale STA facility is built on this land, then an FAS exploratory well could potentially be constructed at the property, with the possibility of constructing a 5 MGD pilot ASR system at the same location. Implementation of the ASR pilot will hinge on the results of the pilot STA testing.

The project duration is approximately 5 years, starting in 2017. Project activities include permitting, design, well construction, surface facility construction, cycle testing (2 year duration), operation and maintenance, monitoring and reporting.

## 10.3 Construction at Sites for CERP ASR Consideration

CERP ASR implementation would follow an adaptive management paradigm, in that additional systems would be constructed sequentially in basins having the greatest need for storage, and as resources become available. The following projects could be developed to fulfill the vision for ASR storage presented in the Restudy.

### 10.3.1 L-8 and C-51 Basin

The Restudy included the conceptual construction of up to 44 ASR wells within the combined L-8 and C-51 Canal basin areas. The exploratory well (PBF-15) constructed adjacent to the L-8 flow equalization basin (FEB) in 2008 indicated that transmissive intervals within the FAS were present between the depths of 900 to 1,575 feet bls. The exploratory well is now completed as a tri-zone monitor well, which should be integrated into a 5 MGD pilot ASR system at that location. The ASR system could be used to store “excess” water that would otherwise not be captured during times when the FEB is filled to capacity. Phosphorus reduction would also be an asset at this location because Lake Okeechobee surface water is conveyed to this location along the L-8 canal.

A component of ASR also should be considered to augment storage in the L-8 basin as part of the Loxahatchee River Watershed Restoration project. The proposed plan captures approximately 15,000 acre-ft of storage in an in-ground reservoir located at the Mecca Farms tract. Additional storage is required in this basin, which could be provided by ASR at the reservoir location.

Project duration is approximately 6 years, starting in 2017. Project activities include permitting, design, well construction, surface facility construction, cycle testing (2 year duration), operation and maintenance, monitoring and reporting.

### 10.3.2 Central Palm Beach County

The Restudy included the conceptual construction of up to 25 ASR wells within the central Palm Beach County agricultural area. These wells would be associated with a reservoir for the purpose of providing supplemental water supply by capturing water currently discharged to the Lake Worth Lagoon. When the location of the reservoir feature is determined, an exploratory well should be constructed at the project site, to characterize the FAS. To date, the closest ASR well system to this area is located 10 miles to the east, at the City of Boynton Beach, which has operated successfully for over a decade. If the results from the exploratory well are successful, then a 5 MGD pilot system should be constructed to evaluate the potential of ASR technology in this area.

Project duration is approximately 6 years, starting in 2017. Project activities include permitting, design, well construction, surface facility construction, cycle testing (2 year duration), operation and maintenance, monitoring and reporting.

### 10.3.3 Taylor Creek (L-63N) Canal ASR System

The L-63N Canal ASR system was constructed and tested by the SFWMD in the mid-1980's and has since been inactive. This ASR system is completed in the APPZ portion of the FAS, which exhibits unusually high transmissivity at this location. As a result, this ASR well has a recharge capacity of nearly 10 MGD. The components for this ASR system are still operational, and can be reactivated with minimal cost. Currently, a UIC construction permit has been issued by the FDEP and a petition for an aquifer exemption is pending with the USEPA. The aquifer exemption will allow this ASR system to be tested without a disinfection process, which would allow for further analysis of the fate of microorganisms in aquifers. Recent correspondence with the USEPA has indicated that a previous aquifer exemption issued for this project is still in effect, and that the system can be operated so long as it maintains compliance with the conditions of that document. The source water at this system contains high concentrations of phosphorus, which also will allow for the further evaluation of nutrient reduction processes that may be active in the subsurface. Project duration is approximately 3 years, starting in 2015. Project activities include permitting, design, well construction, surface facility rehabilitation, cycle testing (2 year duration), operation and maintenance, monitoring and reporting.

### 10.3.4 Construction of a Multi-Well ASR System at Paradise Run

The exploratory well at Paradise Run indicated favorable conditions in the upper FAS and the APPZ for a stacked, multi-well ASR system. The proximity of this site to the highly successful KRASR system would suggest that this site ought to have similar results. A conceptual design evaluation was completed for this project in 2009, and included construction of a 10-well ASR system, wetland treatment process, a siphon to connect Pool E (above the S-65E water control structure) with the former Kissimmee River floodplain for environmental restoration, as shown in **Figure 10-1**. The first phase of this project should be construction and testing of a two-well, 10 MGD pilot system, to evaluate the wetland treatment process, followed by expansion up to a 50 MGD system, if deemed successful. It is possible that this facility could be operated remotely from the KRASR facility by telemetry.

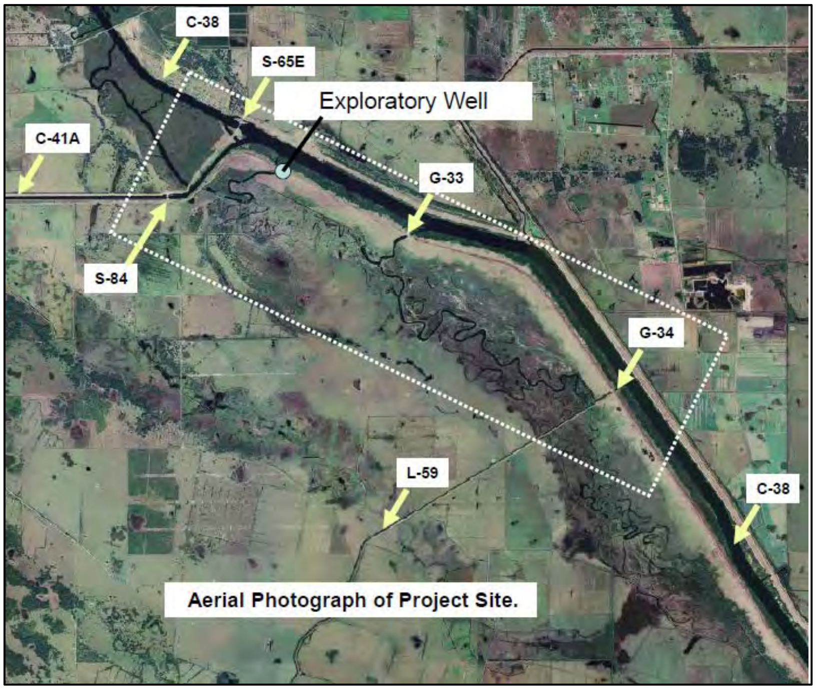


**Figure 10-1 – Aerial photograph showing location of the Paradise Run exploratory well and project location (square), and canals and tributaries to the Kissimmee River (C-38).**

Project duration is approximately 7 years, starting in 2016. Project activities include permitting, design, well construction, surface facility construction, cycle testing (2 year duration), operation and maintenance, monitoring and reporting.

## 10.4 Additional Recommended Technical Studies and Novel ASR Applications

Projects discussed in the following subsections describe technical studies that would improve ASR compliance, or optimize ASR operations.

### 10.4.1 Processes to Reduce Nutrients (P and N) Through ASR

Managing elevated phosphorus concentrations in surface waters that flow into Lake Okeechobee and the water conservation areas is one of the greatest challenges to successful ecosystem restoration. Phosphorus loading and subsequent eutrophication of in Lake Okeechobee during the last few decades has degraded water quality, reduced the extent of submerged aquatic vegetation, and has caused 5 fisheries to decline in abundance. In 2005, FDEP issued a final rule defining a numeric criterion for phosphorus in Class III surface waters of the Everglades Protection Area (F.S.62-302.540). The Everglades Protection Area includes the water conservation areas, Loxahatchee National Wildlife Refuge, and Everglades National Park. This numeric criterion is 10 µg/L, calculated as an annual geometric mean across all stations. Reduction of phosphorus concentration usually is achieved using stormwater treatment areas and use of best management practices. However, results of ASR cycle testing show significant reduction of phosphorus concentration, with recovered water usually in compliance with the numeric criterion.

The processes that are controlling the reduction of P during storage within the FAS are at this time, poorly understood, although are probably a combination of dilution, microbiological uptake, mineral precipitation, and sorption within the aquifer matrix. Additional studies to understand the mechanics and interplay of these processes should be undertaken, so that the long-term effectiveness of ASR in nutrient removal can be included in planning evaluations.

### 10.4.2 Continuing Sequence Stratigraphy and Core Analysis

The USGS work on the ROMP 29A well discussed in **Section 3.6.1** indicated that a sequence stratigraphic approach could lead to improved correlation of flow zones within the FAS. This analysis should be applied to additional wells throughout the south Florida area, to improve our understanding of regional transmissivity patterns, which could aid in siting future ASR system with high recovery efficiencies.

### 10.4.3 Integration of Seismic Data from Broward County

At the time of this writing, Broward County is conducting an extensive marine seismic reconnaissance of the major canals throughout the county. This data collection should result in new insights to the local structure and stratigraphy of the FAS, which should assist in siting new ASR wells based on favorable hydrogeologic conditions.

### 10.4.4 Continuing Evaluation of the Fate of Microorganisms in Aquifers

The microbiological characterization work described in **Chapter 6** has resulted in a greater understanding of the response of microorganisms to deep subsurface conditions. Additional studies should be undertaken at operational ASR systems to determine appropriate disinfection and monitoring strategies to protect underground sources of drinking water, while recognizing that biological processes remain active in the subsurface.

### 10.4.5 The ASR Contingency Study

The storage and supply functions provided by ASR were critical components of the plan originally envisioned by CERP. However, uncertainties associated with its proposed regional scale led to a public perception that there might have been an over-reliance on ASR to maintain substantial storage for ecosystem restoration and other water needs of south Florida. As a result, it was recommended that a "contingency plan" be developed, which would identify options to replace the water storage and supply management functions that would have been provided by ASR components. Investigating a worst case scenario for ASR (no ASR) and/or a reduced scale ASR scenario, and formulating contingency plans to realize CERP performance, will give interested persons a gauge of what revisions to CERP may be necessary or are possible under these conditions, and what the impacts and costs of such revisions could be, pending more definitive answers from the CERP ASR pilot projects and Regional Study. Potential alternative features to replace or supplement ASR could include desalination plants, deep injection wells, increasing the capacity and number of surface storage reservoirs, and increasing Lake Okeechobee water levels. This study should include limited options analysis, assessment of the storage tradeoffs, and evaluation of all storage components in and around Lake Okeechobee.

### 10.4.6 Alternative ASR Implementation and Siting Concepts

The projects and programs listed below represent alternative uses for ASR. Some applications can involve recharge of source water with little to no recovery, at least in the short-term. Other applications include ASR to augment other water management strategies.

#### 10.4.6.1 Compliance with the Leah Schad Memorial Ocean Outfall Program

In 2008, the Florida Legislature enacted an ocean outfall statute (Leah Schad Memorial Ocean Outfall Program; Subsection 403.086(9), F.S.) requiring the elimination of the use of six ocean outfalls in southeastern Florida as the primary means for disposal of treated domestic wastewater. In addition, the affected wastewater utilities have to reuse at least 60 percent of the outfall flows by 2025. The objectives of this statute were to reduce nutrient loadings to the environment and to achieve the more efficient use of water for water supply needs. This statute became effective on July 1, 2008.

The 2008 Leah Schad Memorial Ocean Outfall Program applies to each of the facilities/utilities that have permits to discharge through an ocean outfall. All of the wastewater/reuse facilities utilizing ocean outfalls are located in the LEC Planning Area. The facilities are as follows:

- South Central Regional Water Reclamation Facility (Delray Beach and Boynton Beach)
- Boca Raton Water Reclamation Facility
- Broward County North Regional Water Reclamation Facility
- Hollywood Southern Regional Water Reclamation Facility
- Miami-Dade North District Wastewater Treatment Plant
- Miami-Dade Central District Wastewater Treatment Plant

Each of the utilities using ocean outfalls submitted an annual report on July 1, 2013 to FDEP on the implementation of the ocean outfall statute. The utilities continue to implement and plan for these changes. At least two of the utilities have proposed recharging a portion of their reclaimed water into the FAS, and may integrate ASR into their reclaimed water storage and supply system. Reclaimed water is highly treated, disinfected wastewater. Reclaimed water can be recharged into the FAS where the TDS concentrations exceed 10,000 mg/L. If native FAS TDS concentrations are below 10,000 mg/L, reclaimed water must be treated to drinking water standards prior to recharge.

#### 10.4.6.2 Climate Change and Sea Level Rise

Long-term data show increasing worldwide temperatures and a corresponding sea level rise. For planning purposes, SFWMD is estimating a sea level rise of 5 to 20 inches in south Florida by 2060. The anticipated rise in sea level may change the hydrodynamics of the coastal estuaries, change the location and shape of the freshwater-seawater interface, and increase the intrusion of salt water into coastal aquifers. Analysis is needed to identify the potential impact of sea level rise on utility wellfields and other users at risk of saltwater intrusion within SFWMD. ASR should be considered as a strategy to improve wellfield recharge, hydraulic barrier creation, and as a wet-weather flood control disposal alternative when surface structures and canals cannot otherwise operate against higher ocean levels.

#### 10.4.6.3 STA/FEB Drought Insulation

During future prolonged droughts, water levels in surface reservoirs, impoundments, and FEBs are low or empty, and Lake Okeechobee water level drops below the point at which water can flow by gravity to the south. Delivery of sufficient water volumes to the Everglades STAs becomes difficult. If the submerged aquatic vegetation (SAV) cells dry out, the vegetation dies and the future treatment capability of the STA is greatly diminished. Construction of ASR wells within the STAs could hydrate the SAV cells in a controlled manner, which would ensure that the STAs would be capable of treating stormwater runoff normally at the onset of the wet season. An additional benefit of having ASR wells installed within the internal footprint of the STA is that “institutional controls” would be available, thus facilitating the permitting process should arsenic mobilization be an issue.

## 11 References Cited

AECOM Water, 2008. Hydrogeologic investigation of the Floridan Aquifer System S-65A site [OSF-105. OSF-104], Osceola County Florida. Report prepared for the SFWMD dated November 2008, 52 p. plus appendices. Available for download http://my.sfwmd.gov/dbhydroplsql/show_multimedia.display_list?p_station=OSF-105&p_maxseq=3

AEE, Inc., 2012. CERP ASR Lake Okeechobee submerged aquatic vegetation model: Enhancement and application. Technical report to South Florida Water Management District. Virginia: Applied Environmental Engineering, LLC and Camp Dresser & McKee, Inc.

Anderson, S., 2008. Hydrogeologic Investigation of the Floridan Aquifer System at L-8 (PBF-15), Palm Beach County, Florida. South Florida Water Management District Technical Publication WS-25, 136 p. Available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.display_list?p_station=PBF-15&p_maxseq=5

Arthur, J.D., Coward, J.B., and Dabous, A.A., 2001. Florida aquifer storage and recovery geochemical study: Year three report. Tallahassee, FL: Florida Geological Survey Open File Report 83, 52 pp. Available at http://publicfiles.dep.state.fl.us/FGS/FGS_Publications/OFR/final_ofr83.pdf

Arthur, J.D., Fischler, C., Dabous, A.A., Budd, D.A., and Katz, B.G., 2007. Geochemical and mineralogical characterization of potential aquifer storage and recovery storage zones in the Floridan Aquifer System, Comprehensive Everglades Restoration Plan. Draft final report prepared for the SFWMD dated 17 July 2007, 150 pages plus appendices.

ASR Issue Team, 1999. Assessment and Comprehensive Strategy: A report to the South Florida Ecosystem Restoration Working Group, dated July 1999, 32 p. Available for download at http://www.sfrestore.org/issueteams/asr/

ASTM, 2008. Standard Practices for Preparing Rock Core as Cylindrical Test Specimens and Verifying Conformance to Dimensional and Shape Tolerances, D 4543-08: American Society for Testing and Materials, West Conshohocken, PA, 9 p. DOI: 10.1520/D4543-08.

ASTM, 2013. Standard test methods for compressive strength and elastic moduli of intact rock core specimens under varying states of stress and temperatures, D7012-13: American Society for Testing and Materials, West Conshohocken, PA. DOI: 10.1520/D7012-13.

Bakker, M., Schaars, F., 2002. The Sea Water Intrusion (SWI) Package Manual, Version 0.2.

Barcelo, M.D. and Basso, R.J., 1993. Computer Model of Groundwater Flow in the Eastern Tampa Bay Water Use Caution Area. Southwest Florida Water Management District report dated May 1993, 167 p. http://www15.swfwmd.state.fl.us/LibraryImages/COMPUTER%20MDL%20GRNDWTR%20IN%20EASTERN%20TPA%20BAY.PDF

Beach, M. and Chan, D., 2003. Southern District Groundwater Flow Model Version 1.0, Prepared by the Hydrologic Evaluation Section, Resource Conservation and Development, Southwest Florida Water Management District.

Bennett, M.W., Linton, P.F., and Rectenwald, E.E., 2001. Hydrogeologic investigation of the Floridan aquifer system in western Hillsboro basin, Palm Beach County, Florida. South Florida Water Management District Technical Publication WS-8, 34 p. plus appendices. Available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.display_list?p_station=PBF-10R&p_maxseq=2

Bennett, M.W., Linton, P.F., and Rectenwald, E.E., 2004. Hydrogeologic investigation of the Floridan Aquifer System, Port Mayaca, Martin County FL, 32 p. plus figures, tables and appendices. Report and data available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.display_list?p_station=EXPM-1&p_maxseq=5

Bennett, M.W. and Rectenwald, E.E., 2002. Hydrogeologic investigation of the Floridan Aquifer System, Moore Haven site, Glades County FL (well GLF-6). South Florida Water Management District, 51 p. Available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.display_list?p_station=GLF-6&p_maxseq=7

Bittner, L.D., Richardson, E., Langevin, C.D., England, S.M., and Stevens, G.T. 2008. Using Density Dependent Numerical Models to Evaluate Regional Groundwater Flow Patterns in South Florida. Unpublished presentation.

Bouwer, H., 1978. Groundwater Hydrology. McGraw-Hill, New York NY, 1207 p.

Bower, R.F., Adams, K.M., and Restrepo, J.I., 1990. A Three-Dimensional Finite Difference Ground Water Model of Lee County FL. Technical Publication 90-01. South Florida Water Management District. West Palm Beach FL, 285 p.

Brown, C.J., Weiss, R., Verrastro, R., and Schubert, S., 2005. Development of an Aquifer storage and recovery (ASR) site selection suitability index in support of the Comprehensive Everglades Restoration Project. *Environmental Hydrology*, v. 13, paper 20. Available for download at http://www.hydroweb.com/journal-hydrology-2005-paper-20.html

Brown, C.J., Itani, S., and Zhang, M., 2005. A scientific evaluation of potential pressure induced constraints and changes in the Floridan Aquifer System and the Hawthorn Group. Report prepared by the USACE dated July 2005, 71 p. Available for download at http://www.evergladesplan.org/pm/projects/project_docs/pdp_asr_combined/052808_asr_report/052808_asr_ch4_asr_comb_pressure_final.pdf

Brown, C.J, England, S., Stevens, G.L. Cheng, H-P, and Richardson, Emily, 2006. ASR Regional Study—Benchscale Modeling, Final Report. Final Report dated July 2006, 63 p. Available at http://www.evergladesplan.org/pm/projects/project_docs/pdp_asr_combined/052808_asr_report/052808_asr_ch5_asr_benchscale_study.pdf

Brown, C.J., 2007. A stochastic evaluation of the subsidence potential of the Hawthorn Group in south Florida as a result of the CERP ASR system. In Fox, P. (Editor*), Proceedings of the 6th International Symposium on Managed Artificial Recharge of Groundwater, ISMAR6*. Acacia Publishing Inc., Phoenix, AZ, pp. 590–600.

Bush, P.W., and Johnston, R.H., 1988, Ground-water hydraulics, regional flow and ground-water development of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403-C, 80 p., 17 pls. Available at http://pubs.usgs.gov/pp/1403c/report.pdf

Bustos Medina, D.A., van der Berg, G.A., van Breukelen, B.M., Juhasz-Holterman, M., and Stuyfzand, P.J., 2012. Iron-hydroxide clogging of public supply wells receiving artificial recharge: near-well and in-well hydrological and hydrochemical observations. *Hydrogeology Journal* v. 21: 1393-1412.

Carollo Engineers, 2003. Pilot Studies to demonstrate water treatment technology for surface water and ASR recovered water treatment. Report prepared for the USACE dated April 2003. Variously paginated.

CH2M Hill, 2004. Hydrogeologic investigation of the Floridan Aquifer System at the Kissimmee River ASR site, Okeechobee County, FL. Report prepared for the SFWMD dated December 2004, 27 pages plus figures, tables, and appendices. Report and data available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.display_list?p_station=EXKR-1&p_maxseq=7

CH2M HILL, 2005. Sub-Task No. 3 - Groundwater Numerical Model Development Support and Data Collection Report, Vols. I and II. Report prepared for the USACE dated December2005, variously paginated.

CH2M Hill, 2006. Marine seismic reflection geophysical investigation in Lake Okeechobee and tributaries. Report submitted to USACE dated April 2006, variously paginated plus 1 data CD.

CH2M Hill, 2007a. Rehabilitation and testing of ASR test well L2-PW2 at the L-2 canal site, Clewiston FL. Report prepared for USACE dated March 2007, variously paginated. Available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.display_list?p_station=L2-PW2&p_maxseq=6

CH2M Hill, 2007b. Modification and testing of ASR test well LAB-PW at the Labelle ASR test site in Labelle, Florida. Report prepared for USACE dated May 2007, variously paginated. Available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.display_list?p_station=LAB-PW2&p_maxseq=5

CH2M Hill, 2008. Paradise Run Aquifer Storage and Recovery Test –Monitor Well HIF-42. Report prepared for SFWMD dated November 2008, 74 p. plus figures, tables, and appendices. Report available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.display_list?p_station=HIF-42&p_maxseq=6

Chapelle, F., 2001. Groundwater Microbiology and Geochemistry, 2nd edition. John Wiley & Sons, Inc., 457 p.

Chen, C., and Folt, C.L., 2006. High plankton densities reduce mercury biomagnification. *Environmental Science & Technology,* v. 39: 115-121.

Cunningham, K.J., Carlson, J.L., Wingard, G.L., Robinson, E., and Wacker, M.A., 2004. Characterization of aquifer heterogeneity using cyclostratigraphy, and geophysical methods in the upper part of the karstic Biscayne Aquifer, southeastern Florida. U.S. Geological Survey Water-Resources Investigations Report 03-4208, 66 p., plus appendices and plates. Available for download at http://pubs.usgs.gov/wri/wri034208/

Cunningham, K.J., 2013. Integrating seismic-reflection and sequence-stratigraphic methods to characterize the hydrogeology of the Floridan Aquifer System in southeast Florida. US Geological Survey Open-File Report 2013-1181, 8 p. Available for download at http://pubs.er.usgs.gov/publication/ofr20131181

DHI-WASY GmbH, FEFLOW. www.feflow.com. Accessed 26 March 2014.

Doherty, J., 2003. Ground water model calibration using pilot points and regularization. *Ground Water*, vol. 41, no. 2, p.170.

Domenico, P.A. and Schwartz, F.W., 1998. *Physical and Chemical Hydrogeology*, 2nd Ed. New York, John Wiley & Sons, 506 p.

Driscoll, F.G., 1986. Groundwater and Wells, 2nd Ed., US Filter/Johnson Screens, St. Paul MN, 1089 p.

Ehlig-Economides, C. and Economides, M., 2010. Sequestering carbon dioxide in a closed underground volume. *Journal of Petroleum Science and Engineering,* v. 70(1-2): 123-130.

Entrix, 2010a. Construction of proximal monitor well No. 18 (MW-18), Kissimmee River ASR Pilot Site, Okeechobee County, FL. Report prepared for the US Army Corps of Engineers – Jacksonville District, dated July 2010, 11 p. plus tables, figures, and appendices. Available for download at http://www.sfwmd.gov/dbhydroplsql/show_dbkey_info.show_station_info?v_station=EXKR%25&v_lower_lat=&v_upper_lat=&v_lower_long=&v_upper_long=&v_lower_x=&v_upper_x=&v_lower_y=&v_upper_y=&v_js_flag=Y

Entrix, 2010b. Construction of distal monitor well No. 19 (MW-19), Kissimmee River ASR Pilot Site, Okeechobee County, FL. Report prepared for the US Army Corps of Engineers – Jacksonville District, dated July 2010, 9 p. plus tables, figures, and appendices. Available for download at http://www.sfwmd.gov/dbhydroplsql/show_dbkey_info.show_station_info?v_station=EXKR%25&v_lower_lat=&v_upper_lat=&v_lower_long=&v_upper_long=&v_lower_x=&v_upper_x=&v_lower_y=&v_upper_y=&v_js_flag=Y

Environmental Simulations, Inc. (ESI), 2004. Development of the District Wide Regulation Model for Southwest Florida Water Management District. Report submitted to the SWFWMD dated April 2004, 125 p. Available for download at http://www15.swfwmd.state.fl.us/LibraryImages/DEV%20OF%20THE%20DISTRICT%20WIDE%20REG%20MODEL.PDF

Fischler, C. and Arthur., J.D., 2014. Geochemical, mineralogical and petrographic characterization of rocks comprising the Upper Floridan Aquifer in south Florida. Tallahassee, Fl; Florida Geological Survey, Report of Investigations 113, 147 p. plus appendices. Available at http://publicfiles.dep.state.fl.us/FGS/FGS_Publications/RI/RI-113.pdf

Fitz, H.C., 2013. Everglades Landscape Sulfate Dynamics: Final Summary Evaluation of CERP ASR Alternatives, University of Soil and Water Science Department, Ft. Lauderdale Research and Education Center IFAS, University of Florida. Davie, FL 33314, for USACE under Cooperative Agreement Number W912HZ-11-2-0005

Geibel, N.M, and Brown, C.J., 2012. Hydraulic fracturing of the Floridan Aquifer from Aquifer Storage and Recovery operations. *Environmental & Engineering Geoscience*, v. XVIII(2): 175-189.

Golder Associates Inc., 2006. Conversion of OKF-100. Site Characterization Report. Lake Okeechobee ASR Pilot Project, Kissimmee River Site, Okeechobee County, FL. Report prepared for the USACE dated November 2006, 23 p. plus figures, tables, and appendices. Available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.display_list?p_station=OKF-100&p_maxseq=12

Golder Associates Inc., 2007. Installation of MW0010, Lake Okeechobee ASR Pilot project, Kissimmee River Site, Okeechobee County, FL. Site Characterization Report. Report prepared for the USACE dated August 2007, 23 p. plus figures, tables, and appendices. Available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.display_list?p_station=EXKR-MW1&p_maxseq=1

Goodman, R.E., 1980. *Introduction to Rock Mechanics*. New York NY, John Wiley & Sons, 478 p.

Gordon, C. and Toze, S., 2003. Influence of groundwater characteristics on the survival of enteric viruses. *Journal of Applied Microbiology*, v. 95: 536-544.

Gudmundsson, A., and Brenner, S.L., 2001. How hydrofractures become arrested. *Terra Nova,* v. 13(6): 456-462.

Guo, W., and Langevin,C.D., 2002. *User's Guide to SEAWAT: a Computer Program for Simulation of Three-Dimensional Variable-Density Ground-Water Flow*. US Geological Survey Techniques of Water-Resources Investigation, 77 p. Available at http://pubs.er.usgs.gov/publication/twri06A7

Hamrick, J.M., Wu, T.S., 1997. Computational design and optimization of the EFDC/HEM 3-D surface water hydrodynamic and eutrophication models. In: Delich, G., Wheeler, M.F. (Eds.), *Next Generation Environmental Model and Computational Methods*. Philadelphia: Society of Industrial and Applied Mathematics, pp 143-161.

Handin, J., Hager, R.V., Friedman, M., and Feather, J.N., 1963. Experimental deformation of sedimentary rocks under confining pressure: Pore pressure tests. *Bulletin of the American Association of Petroleum Geologists* v. 47(11): 717-755.

Hantush, M.S. and Jacob, C.E., 1954. Plane potential flow of ground-water with linear leakage. *Transactions, American Geophysical Union*, v.35: 917-936.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- User guide to modularization concepts and the Ground-Water Flow Process. U.S. Geological Survey Open-File Report 00-92, 121 p. Available at http://pubs.er.usgs.gov/publication/ofr200092

Harvey, R.W., Underwood, J., Lisle, J., Metge, D.W., and Aiken, G., 2014. Role of Surface Water DOC in the survival, growth and transport of *Escherichia coli* in a deep limestone aquifer in south Florida. Proceedings of the US Geological Survey Karst Interest Group, Carlsbad NM, April 29-May 2, 2014. Available at http://pubs.usgs.gov/sir/2014/5035/sir2014-5035.pdf

HSA Engineers and Scientists, 2003. Surface water treatability pilot study using microfiltration and cartridge filtration. Report prepared for the USACE dated May 2003, variously paginated.

Hubbert, M. K. and Willis, D.G., 1957. Mechanics of Hydraulic Fracturing. *Petroleum Transactions Society of Petroleum Engineers, AIME*, v.210: 153-166.

Hughes, J.D., Vacher, H.L., Sanford, W.E., 2007. Three dimensional flow in the Florida platform: Theoretical analysis of Kohout convection at its type locality. *Geology*, vol. 35(7): 663-666.

HydroGeoLogic, Inc., 2002. Three-Dimensional Density-Dependent Flow and Transport Modeling of Saltwater Intrusion in the Southern Water Use Caution Area. Report prepared for SWFWMD dated June 2002, 213 p. Available at http://www15.swfwmd.state.fl.us/LibraryImages/04511.pdf

Jaeger, J.C., Cook, N.G.W., and Zimmerman, R.W., 2007. *Fundamentals of Rock Mechanics*, 4th Ed. Malden MA, Blackwell Publishing Ltd., 475 p.

James, R.T. and McCormick, P.V., 2012. The sulfate budget of a shallow subtropical lake. *Fundamentals of Applied Limnology*, v. 181(4): 253-269.

Jin, K.-R., and Ji, Z.-G. , 2013. A long term calibration and verification of a submerged aquatic vegetation model for Lake Okeechobee. *Ecological Processes*, v. 2:23, 13 p. doi:10.1186/2192-1709-2-23

John, D.E. and Rose, J.B., 2004. Survival of fecal indicator bacteria, bacteriophages, and protozoa in Florida's surface and ground waters. Final report prepared for the SFWMD and SWFWMD dated June 2004, 244 p.

John, D.E. and Rose, J.B., 2005. Review of factors affecting microbial survival in groundwater. *Environmental Science & Technology,* v. 39(19): 7345-7356.

Johnson, I.C., 2005. Phase I Report. Screening-Level Method Development. Preliminary Investigation of the Ecotoxicological Effects of Recovered ASR Water on Receiving Aquatic Ecosystems Using Pilot Project Groundwater and/or Recovered Water. SFWMD Contract C-C13401P. US Army Corps of Engineers and South Florida Water Management District.

Johnson, I.C., Friant, S., and J. Heintz, J., 2007. Phase II Report. Ecotoxicological Effects of Recovered ASR Water, Mobile Bioconcentration Laboratory, Mesocosm Methods Evaluation, and Conceptual Ecological Model Development for the ASR Regional Study. SFWMD Contract C-C13401P. US Army Corps of Engineers and South Florida Water Management District.

Jurgens, B.C., McMahon, R.B., Chapelle, F.H., and Eberts, S.M., 2009. An excel workbook for identifying redox processes in ground water. U.S. Geological Survey Open-File Report 2009-1004, 8 p. plus attachments. Available at http://pubs.usgs.gov/of/2009/1004/

Keith, L.A. and Rimstidt, J.D., 1985. A numerical compaction model of overpressuring in shales. *Mathematical Geology,* v. 17(2): 115-135.

King, J.K, Kostka, J.E., Frischer, M.E., and Saunders, F.M., 2000. Sulfate-reducing bacteria methylate mercury at variable rates in pure culture and in marine sediments. *Applied and Environmental Microbiology,* v. 66(6): 2430-2437.

Kohout, F.A., 1965. A hypothesis concerning cyclic flow of salt water related to geothermal heating in the Floridan aquifer. *New York Academy of Sciences Transactions*, ser. 2, vol. 28, no. 2, pp. 249-271.

Kohout, F.A., H.R. Henry, and J.E. Banks, 1977. Hydrogeology related to geothermal conditions of the Floridan Plateau. In: D.L. Smith and G.M. Griffin( Eds.) *The Geothermal Nature of the Floridan Plateau.* Florida Geological Survey Special Publication no. 21, pp. 1-41. Tallahassee FL.

Krabbenhoft, D.P., Aiken, G.R., and Anderson, M.P., 2007. An assessment of the potential effects of aquifer storage and recovery on mercury cycling in south Florida. US Geological Survey Scientific Investigations Report 2007-5240, 27 p. Avail. for download at http://pubs.er.usgs.gov/publication/sir20075240

Kuniansky, E.L., Bellino, J.C., and Dixon, J.F., 2012. Transmissivity of the Upper Floridan Aquifer in Florida and parts of Georgia, South Carolina, and Alabama. U.S. Geological Survey Scientific Investigations Map 3204, 1 pg. Available for download at http://pubs.usgs.gov/sim/3204

Lisle, J.T., 2014. Survival of bacterial indicators and the functional diversity of native microbial communities in the Floridan aquifer system, south Florida. US Geological Survey Open-File Report: 2-14-1011, 78 p. Available at http://pubs.usgs.gov/of/2014/1011/pdf/of2014-1011.pdf

Lisle, J.T., Harvey, R.W., Aiken, G.R., and Metge, D.W., 2010. Microbial and geochemical investigations of dissolved organic carbon and microbial ecology of native waters from the Biscayne and upper Floridan Aquifers. US Geological Survey Open File Report 2010-1021, 33 p. Available for download at http://pubs.er.usgs.gov/publication/ofr20101021

Lisle, J.T., 2014. Survival of bacterial indicators and the functional diversity of native microbial communities in the Floridan Aquifer, south Florida. US Geological Survey Open File Report 2014 –1011, 70 p. Available for download at http://pubs.er.usgs.gov/publication/ofr20141011

Mactec Engineering and Consulting, Inc., 2007. MF-37 Dual-zone monitoring well conversion at Port Mayaca. Report prepared for USACE dated 19 March 2007, 12 p. plus figures, tables and appendices. Available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.display_list?p_station=MF-37&p_maxseq=20

McDonald, M.G., and Harbaugh, A.W., 1988. A modular three-dimensional finite difference ground-water flow model: U.S. Geological Survey Techniques of Water Resources Investigations, Book 6, 586 pp. Available for download at http://pubs.usgs.gov/twri/twri6a1/

McFeters, G.A. and Stuart, D.G., 1972. Survival of coliform bacteria in natural waters: field and and laboratory studies with membrane filter chambers. *Applied Microbiology* v. 24: 823-829. Available at http://pubmedcentralcanada.ca/pmcc/articles/PMC380667/

McGurk, B. and Presley, P.F., 2002. Simulation of the Effects of Groundwater Withdrawals on the Floridan Aquifer System in East-Central Florida: Model Expansion and Revision. Technical Publication SJ2002-5, St. Johns River Water Management District, Palatka FL, 491 p. Available for download at http://www15.swfwmd.state.fl.us/LibraryImages/04511.pdf

Merritt, M.L., 1997. Computation of the Time-Varying Flow Rate from and Artesian Well in Central Dade County, Florida, by Analytical and Numerical Simulation Methods. U.S. Geological Survey Water Supply Paper 2491, 44 p. Available at http://pubs.er.usgs.gov/publication/wsp2491

Meyer, F.W., 1989. Hydrogeology, Ground Water Movement, and Subsurface Storage in the Floridan Aquifer System in Southern Florida, U.S. Geological Survey Professional Paper 1403G, 72 p. Available for download at http://pubs.er.usgs.gov/publication/pp1403G

Miller, J.A., 1986. Hydrogeologic framework of the Floridan Aquifer System in Florida and parts of Georgia, South Carolina, and Alabama. US Geological Survey Professional Paper 1403-B, 91 p. Download available at http://pubs.usgs.gov/pp/1403b/report.pdf

Mirecki, J.E., 2004. Water-quality changes during cycle tests at Aquifer Storage Recovery (ASR) systems of South Florida. US Army ERDC technical report ERDC/EL TR-04-8, 53 p. Available for download at https://www.researchgate.net/publication/259333858_Water_quality_changes_during_cycle_tests_at_ASR_systems_of_south_Florida_-_PDF

Mirecki, J.E., 2006. Geochemical models of water-quality changes during aquifer storage recovery (ASR) cycle tests, Phase I: Geochemical models using existing data. US Army ERDC technical report ERDC/EL TR-06-8, 77 p. Available for download at https://www.researchgate.net/profile/June_Mirecki/?ev=hdr_xprf

Mirecki, J.E., Bennett, M.W., and López-Baláez, M.C., 2012. Arsenic control during aquifer storage recovery cycle tests in the Floridan Aquifer. Groundwater v. 51(4): 539-549. Available at https://www.researchgate.net/publication/232736705_Arsenic_Control_During_Aquifer_Storage_Recovery_Cycle_Tests_in_the_Floridan_Aquifer

Missimer Groundwater Science, 2007. Seminole Tribe of Florida, Brighton Reservation Aquifer Storage and Recovery Exploratory Well Program. Report submitted to the Seminole Tribe dated 28 August 2007, 52 pages plus figures, tables, and appendices. Report available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.display_list?p_station=BREX-1&p_maxseq=6

Morrissey, S.K., Clark, J.F., Bennett, M., Richardson, E., and Stute, M., 2010. Groundwater reorganization in the Floridan aquifer following Holocene sea-level rise. *Nature Geoscience*, v. 3: 683-687.

National Research Council, 2001. Aquifer storage and recovery in the Comprehensive Everglades Restoration Plan. National Academy Press, Washington DC, 58 p. Available for download at http://www.nap.edu/catalog.php?record_id=10061

National Research Council, 2002. Regional issues in aquifer storage and recovery for Everglades restoration. National Academies Press, Washington DC, 63 p. Available for download http://www.nap.edu/catalog.php?record_id=10521

National Research Council, 2005. Re-engineering water storage in the Everglades - Risks and Opportunities. National Academies Press, Washington DC, 125 p. Available for download at http://www.nap.edu/catalog.php?record_id=11215

National Research Council, 2014. Progress Toward Restoring the Everglades: The Fifth Biennial Review, 2014. National Academies Press, Washington DC, 241 p. Available for download at http://www.nap.edu/catalog.php?record_id=18809

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

Orem, W. H., Fitz, C., Krabbenhoft, D., Tate, M., Gilmour, C., and Shafer, M.D., In review. Modeling Sulfate Transport and Distribution and Methyl Mercury Production, Sustainability of Water Quality and Ecology. In: Special Publication, *Modeling ecosystem services: Current approaches, challenges, and perspectives.*

PBS&J (Post, Buckley, Schuh & Jernigan), 2003. Statistical analysis for the CERP ASR pilot program. Report prepared for the South Florida Water Management District, dated June 2003, variously paginated.

PBS&J (Post, Buckley, Schuh & Jernigan) 2004. Tekleen Pilot Project. Report prepared for the SFWMD dated 15 July 2004. Variously paginated.

PBS&J, 2005. Design memorandum for Hillsboro ASR Pilot Project. Report to the SFWMD dated April 2005, unpaginated.

Palciauskas, V.V. and Domenico, P., 1980. Microfracture development in compacting sediments: Relation to hydrocarbon-maturation kinetics. *Bulletin of the American Association of Petroleum Geologists,* v. 64(6): 927-937.

Parkhurst, D.L., and Appelo, C.A.J., 2013, Description of input and examples for PHREEQC version 3—A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations: U.S. Geological Survey Techniques and Methods, book 6, chap. A43, 497 p., Available at http://pubs.usgs.gov/tm/06/a43

Parra, J.O., Hackert, C.L., and Bennett, M.W., 2006. Permeability and porosity images,based on P-wave surface seismic data: Application to a south Florida aquifer. *Water Resources Research*, v.42, W02415, doi:10.1029/2005WR004114, 14 p.

Pavelic, P., Ragusa, S.R., Flower, R.L., Rinck-Pfeiffer, S.M., Dillon, P.J., 1998. Diffusion chamber method for *in situ* measurement of pathogen inactivation in groundwater. *Water Research* v. 32(4): 1144-1150.

Pavelic, P., Dillon, P.J., Barry, K.E., Vanderzalm, J.L., Correll, R.L., and Rinck-Pfeiffer, S.M., 2007. Water quality effects on clogging rates during reclaimed water ASR in a carbonate aquifer. *Journal of Hydrology* v. 334: 1-16.

Pollard, D.D., Segal, P., and Delany, P.T., 1982. Formation and interpretation of dilatants echelon cracks. *Geological Society of America Bulletin,* v. 93: 1291-1303.

Pollard, D.D. and Aydin, A., 1988. Progress in understanding jointing over the past century. *Geological Society of America Bulletin*, v. 100: 1181-1204.

Poteet, J., Weinstein, B., Mayhut, J., and Pearce, M., 2013. Raw water aquifer storage and recovery system at Marco Island Utilities: 15 years of sustainable, low-cost performance. *Florida Water Resources Journal*, March 2013, pp. 18-24.

Pyne, R. David G., 2005. Aquifer Storage Recovery: A guide to groundwater recharge through wells, 2nd edition. Gainesville FL: ASR Systems, 608 p.

Rahn, P. H., 1986, Engineering Geology: An Environmental Approach. New York, NY: Elsevier, 589 p.

Rask, M., Verta, M., Korhonen, M., Salo, S., Forsius, M., Arvola, L., Jones, R. I., Kiljunen, M., 2010. Does lake thermocline depth affect methyl mercury concentrations in fish? *Biogeochemistry*, v.101 (1-3): 311-322.

Reese, R.S., 2000. Hydrogeology and the distribution of salinity in the Floridan Aquifer System, southwestern Florida. US Geological Survey Water-Resources Investigations Report 98-4253, 86 p. plus plates. Available for download at http://pubs.er.usgs.gov/publication/wri984253

Reese, R.S., 2002. Inventory and review of aquifer storage and recovery in southern Florida. U.S. Geological Survey Water-Resources Investigations Report 02-4036, 56 p. Available for download at http://fl.water.usgs.gov/Abstracts/wri02_4036_reese.html

Reese, R.S., 2004. Hydrogeology, water quality, and distribution and sources of salinity in the Floridan Aquifer System, Martin and St. Lucie Counties, Florida. US Geological Survey Water-Resources Investigations Report 03-4242, 96 p. Available for download at http://pubs.er.usgs.gov/publication/wri034242

Reese, R.S., 2014. Hydrogeologic framework and geologic structure of the Floridan Aquifer System and Intermediate Confining Unit in the Lake Okeechobee area, Florida. US Geological Survey Scientific Investigations Map 3288, 8 Sheets plus 12-p. pamphlet. Available for download at http://pubs.usgs.gov/sim/3288/

Reese, R.S., and Alvarez-Zarikian, C.A., 2007. Hydrogeology and aquifer storage and recovery performance in the Upper Florida Aquifer, southern Florida. US Geological Survey Scientific Investigations Report 2006-5239, 74 p. Available for download at http://pubs.usgs.gov/sir/2006/5239/

Reese, R.S. and Cunningham, K.J., 2014. Hydrogeologic framework and salinity distribution of the Floridan Aquifer System of Broward County, Florida. US Geological Survey Scientific Investigations Report 2014-5029, 18 p. plus appendices. Available at http://pubs.er.usgs.gov/publication/ofr20131141

Reese, R.S. and Memberg, S.J., 2000. Hydrogeology and the distribution of salinity in the Floridan Aquifer System, Palm Beach County, Florida. U.S. Geological Survey Water Resources Investigations Report 99-4061, 52 p. plus plates. Available for download at http://fl.water.usgs.gov/PDF_files/wri99_4061_reese.pdf

Reese, R. and Richardson, E., 2004. Task 3.0 Define Preliminary Hydrogeologic Framework, ASR Regional Study. ASR Regional Study PMP.

Reese, R.S. and Richardson, E., 2008. Synthesis of the hydrogeologic framework of the Floridan Aquifer System, and delineation of a major Avon Park Permeable Zone in central and southern Florida. US Geological Survey Scientific Investigations Report 2007-5207, 66 p. Available for download at http://pubs.er.usgs.gov/publication/sir20075207

Rogers, W.W., and Allen, M.S., 2008. Hurricane impacts to Lake Okeechobee: Altered hydrology creates difficult management tradeoffs. *Fisheries*, v. 33(1): 11-17.

Sanford, W.E., Whitaker, F.F., Smart, P.L., Jones, G., 1998. Numerical analysis of seawater circulation in carbonate platforms: I. Geothermal convection. *American Journal of Science*, v. 298(10): 801-821.

Schwertmann, U., 1991. Solubility and dissolution of iron oxides. *Plant and Soil* v. 130(1-2): 1-25.

Sepúlveda, N., 2002. Simulation of ground-water flow in the Intermediate and Floridan Aquifer System in Peninsular Florida. US Geological Survey Water-Resources Investigations Report 02-4009, 130 p. Available at http://fl.water.usgs.gov/PDF_files/wri02_4009_sepulveda.pdf

Shao, D., Kang, Y., Wu, S., Wong, M.H., 2012. Effects of sulfate-reducing bacteria and sulfate concentrations on mercury methylation in freshwater sediments. *Science of the Total Environment,* 424: 331-336.

Sherman, W.C., 1973. Elements of soil and rock mechanics. In: Cummins, A.B. and Given, I.A. (Eds.), *SME Mining Engineering Handbook, Vol. I, Chapter 6*. New York, Society of Mining Engineers, pp. 1-52.

Smith, S.A., 1989. Manual of Hydraulic Fracturing for Well Stimulation and Geologic Studies. Dublin, OH: National Water Well Association, 66 p.

Southwest Research Institute, 2007. Analyses and interpretation of cross-well seismic and well logs for estimating lateral porosity and permeability variations in the inter-well region between wells MF-37 and EXPM-1 at the Port Mayaca site, south Florida. Report submitted to SFWMD dated January 2007, 25 p. Available at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.main_page?p_station=MF37&p_seq=5&p_maxseq=20

Sterrett, R.J., 2007. Groundwater and Wells, 3rd edition. Johnson Screens, a Weatherford Company. New Brighton MN, 812 p.

Sunderland, R.S., 2008. Hydrogeologic Investigation of the Floridan Aquifer System, C-23 Canal Site, Martin County, Florida. South Florida Water Management District Technical Publication WS-24.158 p. Available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.display_list?p_station=MF-40&p_maxseq=11

Sunderland, R.S.A., Collins, B., and Anderson, S., 2011. Hydrogeologic investigation of the Floridan Aquifer System at the S-65C site (Well OKF-105), Okeechobee County Florida. South Florida Water Management District Technical Publication WS-32, 288 pp. Available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.main_page?p_station=OKF-105&p_seq=6&p_maxseq=11

SFWMD, 1999. Documentation for the Lower East Coast Floridan Aquifer Model. Technical report from the Resource Assessment Divison, Lower East Coast Planning Division, SFWMD.

SFWMD, 2005. Documentation of the South Florida Water Management Model, Version 5.5. Available from http://www.sfwmd.gov/portal/page/portal/xrepository/sfwmd_repository_pdf/sfwmm_final_121605.pdf .

Tetra Tech, 2005a. Aquifer Storage and Recovery Regional Study Project – Groundwater Quality Sampling, Analysis, of the Native Floridan Aquifer System. Compilation on disk dated 1 September 2005. All data are now on DBHYDRO http://www.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu

TetraTech, 2005b. Final report for surface water collection and ground water quality sample collection and analysis for the Lake Okeechobee (LOASR), Western Hillsboro (WHASR), and Caloosahatchee River (CRASR) ASR projects. Report prepared for USACE dated March 2005, 36 pages plus figures, tables, and appendices.

TetraTech, 2007. CERP Aquifer Storage and Recovery Baseline Environmental Monitoring Summary Report. Report prepared for SFWMD dated December 3, 2007. Variously paginated plus figures, tables, and appendices.

Tipping, E., Rey-Castro, C., Bryan, S.E., and Hamilton-Taylor, J., 2002. Al(III) and Fe(III) binding by humic substances in freshwaters, and implications for trace metal speciation. *Geochimica et Cosmochimica Acta* v. 66(18): 3211-3224.

URS, 2003. Analysis of existing seismic reflection data in south Florida for ASR Regional Study. Report prepared for the USACE and SFWMD dated January 24, 2003. 8 pages plus appendices

USACE, 2004. Lineament Analysis, south Florida Region. Draft technical memorandum prepared by the USACE-SAJ dated July 2004, 59 p. Available for download at http://www.evergladesplan.org/pm/projects/project_docs/pdp_asr_combined/052808_asr_report/052808_asr_ch4_asr_lineament_tech_memo.pdf and http://www.evergladesplan.org/pm/projects/project_docs/pdp_asr_combined/013007_asr_lineament_dtmt.pdf

USACE, 2006. Draft ASR Regional Study Phase I – Groundwater Modeling. Report prepared for USACE-SAJ and SFWMD by the USACE-NAP, dated December 2006, 132 p. plus figures and tables. Available at http://www.evergladesplan.org/pm/projects/project_docs/pdp_asr_combined/021908_asr_draft_phase1_gw_rpt.pdf

USACE, 2011. Final Groundwater Model Calibration Report – Aquifer Storage and Recovery Regional Modeling Study. Report prepared for USACE-SAJ and SFWMD by the USACE-NAP, dated February 2011, 68 p. plus figures and tables. Available for download at http://www.evergladesplan.org/pm/projects/pdp_32_33_34_44_asr_combined.aspx#groundwater

USACE, 2014. Regional Model Production Scenario Report, ASR Regional Modeling Study. Report dated January 1014, 60 p. plus figures, tables, and appendices. http://www.evergladesplan.org/pm/projects/project_docs/pdp_asr_combined/012014_asr_prod_scenario_report/asr_d13r_main_report.pdf

USACE and SFWMD, 1999. Central and South Florida Project Comprehensive Review Study, Final Integrated Feasibility Report and Programmatic Environmental Impact Statement. Report dated April 1999. Available for download at http://www.evergladesplan.org/pub/restudy_eis.aspx

USACE and SFWMD, 2003. ASR Regional Study Project Management Plan. Report dated August 2003, 125 p. plus appendices. Available for download at http://www.evergladesplan.org/pm/pmp/pmp_docs/pmp_44_regional/pmp_44_main.pdf

USACE and SFWMD, 2004. Lake Okeechobee, Hillsboro, and Caloosahatchee (C-43) River Pilot Project Design Report and Environmental Impact Statement. Report dated October 2004, variously paginated. Available for download at http://www.evergladesplan.org/pm/projects/pdp_asr_comb_deis_ppdr.aspx

USACE and SFWMD, 2013. CERP ASR Pilot Project Technical Data Report. Report dated December 2013, 340 p. Report available for download at http://www.evergladesplan.org/pm/projects/project_docs/pdp_32_lake_o_asr_pilot/TDR_Final.pdf

USEPA, 1998. Guidelines for Ecological Risk Assessment. EPA/630/R-95/002F dated April 1998, 188 p. Available at http://www.epa.gov/raf/publications/pdfs/ECOTXTBX.PDF

USEPA, 2006a. Occurrence and monitoring document for the final Ground Water Rule. EPA 815-R-06-012, 160 p. Available at http://www.epa.gov/ogwdw/disinfection/gwr/pdfs/support_gwr_occurrence-monitoring.pdf

USEPA, 2006b. National Primary Drinking Water Regulations: Ground Water Rule. 40 CFR Parts 9, 141 and 142. Federal Register November 8, 2006, v.71(216): 65573-65660. Available at http://www.epa.gov/fedrgstr/EPA-WATER/2006/November/Day-08/w8763.htm

USEPA, 2013. Test methods for evaluating solid wastes: physical/chemical methods of SW-846 series. Available at SW-846 on-line at http://www.epa.gov/osw/hazard/testmethods/sw846/online/

Vacher, H.L., Hutchings, W.C., and Budd, D.A., 2006. Metaphors and Models: The ASR bubble in the Floridan Aquifer. *Ground Water* v. 44(2): 144-154.

Voss, C. I., and Provost, A.M., 2002 (Version of September 22, 2010). SUTRA, A model for saturated-unsaturated variable-density ground-water flow with solute or energy transport, U.S. Geological Survey Water-Resources Investigations Report 02-4231, 270 p. http://pubs.er.usgs.gov/publication/wri024231

Walker Marine Geophysical Company, LLC, undated. Report on seismic data acquisition for the seismic investigation of Townsend Canal Header East and Header West, 4 May to 7 May 2004. Report submitted to the SFWMD, undated, 8 pages plus figures and tables.

Walton, W.C., 1962. Selected analytical methods for well and aquifer evaluation. Illnois State Water Survey Bulletin 49, 81 p. Available at http://www.isws.illinois.edu/pubs/pubdetail.asp?CallNumber=ISWS+B%2D49

Wang, M., Nim, C.J., Son, S.-H., and Shi, W., 2012. Characterization of turbidity in Florida's Lake Okeechobee and Caloosahatchee and St. Lucie Estuaries using MODIS-Aqua measurements. *Water Research* v. 46(16): 5410-5422.

Ward, W.C., Cunningham, K.J., Renken, R.A., Wacker, M.A., Carlson, J.I., 2003. Sequence-stratigraphic analysis of the Regional Observation Monitoring Program (ROMP) 29A test corehole and its relation to carbonate porosity and transmissivity in the Floridan Aquifer System, Highlands County, FL. US Geological Survey Open-File Report 2003-201, 34 p. plus appendices. Available for download at http://fl.water.usgs.gov/PDF_files/ofr03_201_ward.pdf

Watermark Numerical Computing, 2004. PEST Model-Independent Parameter Estimation User Manual: 5th Edition. http://www.pesthomepage.org/Downloads.php

Water Resource Solutions, Inc. 2004. Geotechnical testing report for the treatment facilities at the Caloosahatchee River ASR pilot facility at Berry Groves, Hendry County. Report prepared for SFWMD dated January 2004, 28 p. plus appendices. Available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.display_list?p_station=EXBRY-1&p_maxseq=14

Water Resource Solutions, Inc., 2005. Berry Groves class V, group 9 exploratory well EXBRY-1, Caloosahatchee River ASR Well Completion Report. Report for SFWMD dated February 2005, 37 p. plus appendices. Available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.display_list?p_station=EXBRY-1&p_maxseq=14

Water Resource Solutions, Inc., 2007. Aquifer performance test: Analyses and results, City of Clewiston, Hendry County, Florida. Report prepared for the SFWMD dated November 2007, 73 p. plus appendices. Available for download at http://my.sfwmd.gov/dbhydroplsql/show_multimedia.main_page?p_station=CLEWROPW3&p_seq=1&p_maxseq=5

WRDA, 2000, 33 CFR 385. http://www.evergladesplan.org/wrda2000/wrda_docs/wrda2000_gpo.pdf

Yeh, G.-T., Cheng, H.-P., Cheng, J.-R., and Lin, H.-C. (1998). A Numerical Model Simulating Water Flow and Contaminant and Sediment Transport in WAterSHed Systems of 1-D Stream-River Network, 2-D Overland Regime, and 3-D Subsurface Media (WASH123D: Version 1.0; July 1998). Report CHL-98-19, U. S. Army Corps of Engineers, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, 320 p. http://acwc.sdp.sirsi.net/client/search/asset/1000555

Zheng, C. and P.P. Wang, 1999. MT3DMS: A Modular Three-Dimensional Multi-Species Model for Simulation of Advection, Dispersion and Chemical Reaction of Contaminants in Groundwater Systems: Documentation and User’s Guide, SERDP-99-1: U.S. Army Engineer Research and Development Center, Vicksburg, MS, 220 p. http://acwc.sdp.sirsi.net/client/search/asset/1004757