Appendix J
LAKE OKEECHOBEE AQUIFER STORAGE AND RECOVERY PILOT PROJECT
TECHNICAL DATA REPORT

Kissimmee River ASR System
Hillsboro Canal ASR System
In support of the Comprehensive Everglades Restoration Plan (CERP), the U.S. Army Corps of Engineers, U.S. Fish & Wildlife Service, South Florida Water Management District, and others, are currently engaged in the execution of four Aquifer, Storage and Recovery (ASR) pilot projects located throughout the Everglades region. Through data collection efforts and thorough testing, the four pilot projects will enable the project team to better grasp the technical uncertainties associated with implementing ASR on a grand scale. At the same time, the ASR Regional Study is focused upon the development of a numerical model to provide a better understanding of the south Florida environment’s ability to support a proposed 333 well ASR system, the largest such system in the world. One effort that has been completed as part of the Regional Study is the preliminary optimization of ASR well site selection in support of the proposed 333 well system. After developing an ASR site selection suitability index, an interagency team utilized Geographic Information Systems (GIS) and the new site suitability methodology to evaluate and propose an initial array of potential ASR well locations. The suitability index was based on the premise of maximizing ASR effectiveness while minimizing any attendant impacts.
INTRODUCTION

The Greater Everglades Ecosystem, located in southern Florida, is a myriad of tree islands, marl prairies, wet prairies, sawgrass ridges, open-water sloughs, estuaries and coral reefs. The Everglades is a broad, flat expanse of wetlands inhabited by innumerable plants and animals. Dubbed the “River of Grass” by Marjorie Stoneman Douglas (Douglas, 1947), the sustainability of the Everglades ecosystem is in trouble. The distribution of water, its timing, quality and quantity, have all been changed over the last 100 years by a combination of water resources development, agriculture, and urbanization (Davis, 1994).

The Central and Southern Florida Project Comprehensive Review Study (USACE & SFWMD, 1999), developed jointly by the South Florida Water Management District (SFWMD) and the U.S. Army Corps of Engineers (USACE), presents a framework for Everglades restoration. Now known as the Comprehensive Everglades Restoration Plan (CERP), this plan contains 68 components, including structural and operational changes to the Central and Southern Florida (C&SF) Project. The primary purpose of CERP is to restore the Everglades by improving the quantity, quality, timing and delivery of water for the natural ecosystems of south Florida that comprise the Everglades. A key component in the overall restoration strategy is the provision of more dynamic storage of freshwater. Additional storage of freshwater should provide supplementary opportunities to restore Everglades hydrology and concomitant ecology.

The CERP water storage strategy proposes the use of both above-ground storage reservoirs and underground storage via deep wells. The deep wells proposed are Aquifer, Storage and Recovery (ASR) wells. ASR is a simple concept, in which water is stored in subsurface aquifers when excess water is available and extracted during times of need. According to the British Geological Survey (Jones et al., 1999), ASR is a sub-set of artificial recharge and is defined as:

“Storage of treated, potable water in the aquifer local to the borehole(s) that is (are) used for both injection and abstraction. A high percentage of the water injected is abstracted at a later date and the scheme may utilize an aquifer containing poor quality or brackish water, although this does not exclude the use of aquifers containing potable water. ASR schemes enable maximum use to be made of existing licensed resources”.

Pyne (1995) has defined ASR as “the storage of water in a suitable aquifer through a well during times when water is available, and recovery of the water from the same well during times when it is needed.”

Artificial recharge of groundwater through wells has been explored in diverse settings worldwide (Harpaz, 1971; Bichara, 1974; Khanal, 1980; Bouwer et al., 1990; Bureau of Reclamation, 1997, Calleguas, 2004). Groundwater recharge has been utilized in South Florida since 1983 with the construction of the first ASR system located near Lake Manatee (CH2M Hill, 1984). Scientific investigations of groundwater recharge and recovery from the confined Floridan Aquifer System (FAS) were initiated in the early 1980s (Merritt et al., 1983) by the U.S. Geological Survey and the U.S. Army Corps of Engineers. The successful operation of pilot artificial recharge sites and operational experience at Lake Manatee and other south Florida ASR sites led to significant development of the technology within the study area. In the late 1990s, as Federal, State and local agencies struggled to develop a coherent and holistic restoration plan for the Everglades, it became apparent that ASR technology could play an important role.

The CERP restoration scheme is an ambitious plan to fully utilize up to 333 ASR wells to store water from Lake Okeechobee and the lower east coast of Florida. To date, the largest existing ASR
system comprises less than 50 wells (Pyne, 1995), making the CERP project unprecedented in size and scope. The original CERP plan proposed 200 of the wells to be located north of Lake Okeechobee, 44 wells to be located within the Caloosahatchee River Basin, and the remaining wells to be located within the urbanized lower east coast. Figure 1 depicts the general locations of the proposed ASR wells within the south Florida study area along with the planned artificial recharge capacity. The exact location of the wells was to be determined at a later time as ASR scientific and engineering studies progressed. The scientific and engineering studies for the CERP ASR program are focused upon planning, design and construction of 4 ASR pilot wells and an ASR Regional Feasibility Study. The ASR Regional Feasibility Study or Regional Study, is designed to reduce technical uncertainties with the proposed CERP ASR plan. The Regional Study includes multiple components such as field investigations, groundwater modeling, geochemical testing, groundwater sampling, bioassays, ecological studies, and limited plan formulation and optimization. The original goals of the Regional Study were outlined in the Project Management Plan (USACE & SFWMD, 2003) and are presented herein:

- Address outstanding issues of a regional nature that cannot be adequately addressed by the authorized ASR Pilot Projects.
- Reduce uncertainties related to full-scale CERP ASR implementation by conducting scientific studies based on existing and newly acquired data and evaluate potential effects on water levels and water quality within the aquifer systems, and on existing users, surface-water bodies, and the flora and fauna that inhabit them.

![Generalized CERP ASR Project Locations and Capacities](image)

Figure 1. Generalized CERP project locations and capacities.
Develop a regional groundwater model of the FAS and conduct predictive simulations to evaluate the technical feasibility of the proposed 333-well CERP ASR system, or if determined to be infeasible, identify an appropriate magnitude of ASR capacity with minimal impact to the environment and existing users of the FAS.

In order to develop a numerical model to satisfy the third goal, identification of more precise locations for the proposed ASR wells was necessary in order to provide accurate data input. An interagency and interdisciplinary team was formed to develop ASR well site selection criteria in order to carry out a preliminary “desktop” optimization of potential ASR well sites for the CERP. The various site selection criteria were focused upon the key performance indicators for CERP ASR projects. Ultimately, the site selection criteria were normalized into an ASR site selection suitability index from 0 to 1.

**PREVIOUS WORK**

The USACE has traditionally utilized site selection evaluations to minimize impacts to environmental systems through application of water resources planning principles promulgated in 1983 (U.S. Water Resources Council, 1983). Water resources projects, including development of flood control and navigation projects, sought to maximize national economic development while minimizing impacts to the “environmental quality account” of each project. Typically, a series of overlap maps were prepared that presented planning factors like topography, soils, hydrology, location of threatened or endangered species, or location of other affected populations. Overlay methodology has been utilized by many Federal and State agencies (FDOT, 1999) and is discussed in more detail by Focazio et al., (2002). Overlay methods have been shown to be well suited for feasibility studies evaluating artificial recharge.

Oklahoma State University used multiple planning factors in its evaluation of artificial recharge feasibility in Northwestern Oklahoma (Pettyjohn and White, 1985) including:

- Source of recharge water
- Proximity to source
- Topography
- Permeability of near-surface materials
- Quality of source
- Quality of water in the aquifer
- Availability of source water

Both the Denver Basin aquifer recharge demo project (Bureau of Reclamation, 1997) and the Washoe County, Nevada recharge demo project (Bureau of Reclamation, 1996) included both regulatory and institutional considerations in their planning efforts. The St. Johns River Water Management District utilized both site selection criteria (overlay methodology) and institutional/regulatory considerations in locating new rapid infiltration basins (Rabbani and Munch, 2000).

With the advent of Geographic Information Systems (GIS), more sophisticated overlay evaluations are now possible. Shahid (2000) discusses the use of overlay methodology in combination with remote sensing and GIS to evaluate vulnerability of groundwater aquifers to pollution. A similar approach was undertaken for this study.
Combining various GIS coverages into normalized site selection indices has been a recent technical advance. Tegelmark (1998) combined factors such as regional climate, topography, soil properties, and vegetation into a suitability index to predict natural Scots pine forest regeneration. Tegelmark used multivariate regression models in combination with overlay maps to find most suitable regions for reforestation. Xinhai et al. (2002), used GIS to combine information on topography, vegetation, rivers, roads, and location of villages/towns in order to develop a suitability index for Crested Ibis habitat. The habitat suitability index was normalized between values of 0 and 1. An integrated map of Ibis habitat quality was prepared and compared to actual distribution of Ibis in regions of China. Tseng et al. (2001) combined five GIS themes into a site selection index for locating optimal artificial reef sites. A decision support system was also used to supplement the GIS themes and ensure objective ranking of various criteria.

**ASR PERFORMANCE FACTORS**

The hydrogeology in most of South Florida consists of layers of aquifers and confining units. The three primary aquifers in the study area include the Surficial Aquifer System (SAS) ranging from 100 to 300 feet thick; the Intermediate Aquifer System (IAS) located within the Hawthorn Group sporadically; and the massive Floridan Aquifer System (FAS) that can be as thick as 1,500 feet. Generally, the SAS is separated from the FAS by an extensive confining unit consisting of interbedded sands, clays and carbonate units. The Intermediate Confining Unit (ICU) occurs between 150 and 850 feet below land surface in the study area and is usually synonymous with the Hawthorn Group. The FAS is a carbonate, confined aquifer and can generally be subdivided into several permeable zones, separated by low-permeability limestones. It is composed of limestone and dolostone units generally dipping to the east and south, and contains brackish to saline water. The permeable zones within the FAS are regionally grouped into upper and lower units, separated by a middle confining unit. These units are informally designated “Upper Floridan Aquifer”, “Middle Floridan Aquifer Confining Unit”, and “Lower Floridan Aquifer” (Miller, 1997). ASR wells located in south Florida generally store water in the brackish FAS (Reese, 2002). The proposed CERP ASR system is evaluating the Upper Floridan Aquifer as a storage zone.

The performance of an ASR system in this environment is a complex process that may be affected by operational design, subsurface heterogeneity, density-dependent flow processes, and biogeochemical processes. One constraint to ASR implementation is aquifer zones with inadequate transmissivity that would not be able to accommodate large storage volumes due to unsustainably high induced aquifer pressures. In addition, highly heterogeneous aquifer zones may lead to enhanced mixing and hydrodynamic dispersion (Merritt, 1986; Anderson and Lowry, 2004). Cavernous or “karst” zones within the ASR storage zone may be especially problematic. Groundwater with high concentrations of total dissolved solids (TDS) may lead to poor quality water being recovered by the ASR well (Pavelic et al., 2002), thereby limiting overall recoverability. In addition, high TDS values may cause buoyancy stratification of stored water due to density differentials between the ambient brackish groundwater and the recharged freshwater (Missimer et al., 2002). Due to the complex hydrogeological environment in south Florida, ASR site selection should be considered carefully to maximize performance while minimizing potential problems.

In addition to hydrogeological related performance factors, other important ASR site selection factors include:

- Availability of source water for recharge
- Quality of the source water
Distance from the source water to the ASR well

- Landuse and availability
- Access constraints (e.g., roads for access and construction)
- Location of ecologically valuable habitats, including endangered species
- Location of system demands
- Location of existing groundwater users
- Availability of power
- Operational flexibility

All of these site selection factors were evaluated in order to optimize the CERP ASR well locations. Of the factors listed, availability of the source water and distance from the source water to the ASR well are undoubtedly the most important factors to consider for a potential ASR system.

**ASR SITE SELECTION PROCEDURE**

The CERP ASR site selection effort was completed in two separate tiers. First, three “pass or fail” criteria were examined to determine all potential suitable lands available within the study area that could support ASR well construction and operation. Lands failing any of the three criteria were deemed unsuitable and were eliminated from further consideration. The remaining areas were then sub-divided into ASR site selection polygons of varying size and complexity. Secondary site selection criteria were then developed and applied to the site selection polygons. These criteria were then combined into an ASR suitability index with a normalized value between 0 and 1.

The three pass or fail criteria were intended to focus the site selection efforts on those lands that showed the most promise to provide the benefits predicted by the CERP plan. The resolution of the land use GIS coverages were considered in the pass or fail criteria. The “minimum mapping area” (e.g., level of accuracy) for the data sets utilized in the evaluation was five acres for upland parcels. This size would also allow installation of a small ASR well cluster and associated water treatment plant. Therefore, no parcel smaller than five acres was carried forward into secondary screening. In addition, land use was utilized as a pass or fail criterion to select land use categories most compatible with the proposed ASR program. The three criteria used were:

- Distance from Lake Okeechobee or a source water body (keep within three miles of Lake Okeechobee, conveyance canals or major waterways to minimize pumping costs)
- Minimum project size of five acres for ASR well cluster plus water treatment plant (minimum mapping unit is five acres for upland land covers and two acres for wetlands according to GIS metadata supporting Land Use maps)
- Land Use [Based upon FDOT Land use definitions, (FDOT, 1999)]

The land use criterion was applied based upon customized queries of the GIS database. Only a group of acceptable land use categories were carried forward into the secondary screening process. Acceptable land use types are:

- Undeveloped land in urban areas
- Agricultural lands
- Lands occupied by exotic species such as Brazilian pepper
Everglades Aquifer Storage and Restoration  
Brown, Weiss, Verrastro, and Schubert

- Rural lands in transition
- Borrow Areas
- Spoil Areas
- Fill Areas
- Burned Areas
- Canals and Locks
- Electric power transmission lines/right of way
- Water supply plants

Unacceptable land use examples are:
- Urban and commercially developed areas
- Housing sub-divisions and developments
- Lakes, streams and reservoirs
- Wetlands (over two acres), swamps, mangroves, submerged aquatic vegetation
- Coastal habitat areas (mud-flats, beaches, oyster beds)
- Forested or wooded lands
- Sewage treatment plants
- Solid waste disposal facilities (landfills)

Since this effort was conducted as a preliminary site selection procedure, the disposition of forested or wooded lands was debated among the interagency team. ASR proponents argued that since ASR footprints are generally very small compared to other water resource options, the impacts to forest ecology would be small. The interagency biologists argued that in a preliminary analysis, it would be prudent to exclude all lands that could have significant habitat values for wildlife, including Federally listed species. In addition, since the ASR system is planned to support the largest environmental restoration project in the United States, every effort should be made to limit even small environmental impacts. Following the friendly and practical debate, the interagency team agreed to exclude native forest lands from further consideration for the preliminary site selection activity.

After the pass or fail criteria were applied to the GIS maps, the area under consideration for ASR site selection was reduced substantially. Figure 2 shows the area remaining for secondary screening activities along with the locations of primary surface water features and the outline of the United States Geological Survey’s (USGS) 1:24,000 quadrangles. The surface water features and the quadrangle outlines were then utilized to identify 97 ASR site selection polygons. Due to the broad nature of the site selection process, the interagency team opted to conduct further screening at a polygon level.

Along the east coast of Florida, within the urbanized zone of the study area, site selection polygons entrained many small parcels ranging in size from a few acres to hundreds of acres. The final distribution of ASR site selection polygons is shown on Figure 3. Each of the site selection polygons was then ranked against eight secondary screening criteria as follows:

- Ecological Suitability – Based on rarity, sensitivity, and/or value of habitat for plants, fish, and wildlife, and likelihood of presence of Federally threatened or endangered species (Rank 0 to 2; 2
Use and Density Factor – Known Floridan Aquifer System well users (Rank 0 to 2; 2 if no wells are located in a polygon, 1 if 1 to 5 wells within polygon, and 0 if more than 5 wells within polygon)

Water Quality Assessment – Based upon published characterization of source water quality under the FDEP 305b clean water program (Rank 0 to 2; Rank 2 if source water fully meets standards, 1 if source water partially meets standards, and 0 if source water does not meet standards)

Groundwater Quality of UFAS (Rank 0 to 2; Rank 0 if chloride concentration of the upper UFAS groundwater is less than 250 mg/l or greater than 3,000 mg/l., rank 1 if chloride concentration of UFAS is between 1,500 and 3,000 mg/l, and rank 2 if chloride concentration of UFAS is between 250 and 1,500 mg/l.

Road Density (Construction/O&M Access) (Rank 0 to 2; Rank 0 if density of roads are low, 1 if density of roads are medium, and 2 if density is high)

Locate near existing power lines (Rank 0 to 2; Rank 0 if not adjacent to existing power lines, 1 if near small KVA lines (in mostly urban areas), 2 if near major transmission lines)

Pressure induced changes or high dispersive mixing potential, based upon aquifer transmissivity (Rank 0 to 2; Rank 0 if T<5,000 ft²/day or if T>25,000 ft²/day, 2 if T is between 5,000 to 25,000 ft²/day)

Operational Flexibility (Rank 1 to 2; Rank 2 if close to Lake Okeechobee and major canal or
Each criterion was then applied to all 97 site selection polygons and raw scores were developed for each polygon. Figures 4 and 5 depict examples of the scoring basis for groundwater quality of the UFAS and ecological suitability, respectively.

After each polygon was scored against the secondary site selection criterion, the raw scores for each site were multiplied by a weighting factor ascribed to each criterion. The weighting factors were developed through a consensus-driven approach among the interagency team. The weighting factors underwent several iterations of changes during the process. Some of the weighting factors were reduced to account for the size of the ASR project footprints. As ASR project footprints are generally small, avoidance of sensitive habitats could be considered for the ecological suitability criterion. A similar rationale was utilized for the water quality of the source water. The final weighting factors ranged from one to four, with only the most important ASR performance factors weighted at greater than one. Only the ambient groundwater quality criterion garnered a weighting of four since it affects both recoverability of stored water and potential impacts to biota caused by the recovered water. The pressure induced changes and the location of existing users criteria each earned a weight factor of three. Ecological suitability was assigned a weight factor of two. All other selection criteria were assigned a weight factor of one. After the weighting factors were applied, all of the scores were normalized from 0 to 1 and plotted on a final set of GIS map coverages. Figure 6 depicts the final color-coded ASR suitability index map developed for the project. The polygons with the highest
Figure 4. UFAS aquifer chloride water quality - between 250 and 1500 mg/l.

Figure 5. Ecological suitability.
ASR site suitability have an index greater than 0.75. Polygons with an index of 0.25 or less are probably poor candidates for any ASR projects. Figure 6 also depicts the location of the ASR Pilot Projects. The site selection evaluation has also provided confirmation of the pilot locations as good project locations.

CONCLUSIONS AND SUMMARY

As the four pilot ASR projects move forward, it is critical to capture the data from the operations of these ASR wells to define parameters within the Regional ASR model. The refined regional model will be used to simulate the proposed 333 ASR wells as envisioned in the CERP. To this end, the interagency team has narrowed the evaluation of the proposed ASR well systems to areas deemed suitable based on various geological, hydrological, ecological, and infrastructure criteria. By defining pass/fail criteria and developing suitability indices, the team was able to eliminate, score, and select site selection polygons for further study. In addition, the development of an ASR site selection suitability index has advanced the plan formulation efforts for the CERP. The polygons most suitable for ASR development will be the focal point of detailed numerical modeling. Ultimately, the Regional Study will provide the technical basis upon which to evaluate the proposed CERP ASR system. The Regional Study will also aid in the evaluation and planning of operational considerations, as well as define suitability and sustainability within the south Florida environment.

![Figure 6. ASR suitability index.](image)
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REFERENCES


design of aquifer storage and recovery systems”. Florida Water Resources Journal, February 2002, pp. 31-35.


Hydraulic Fracturing of the Floridan Aquifer from Aquifer Storage and Recovery Operations

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Key Terms: Aquifer Storage and Recovery, Hydraulic Fracturing, Rock Mechanics, Floridan Aquifer System, Triaxial Compressive Strength, Unconfined Compressive Strength

ABSTRACT

Potential for hydraulically induced fracturing of the Floridan Aquifer System (FAS) and the overlying Hawthorn Group deposit exists due to operation of seven potential aquifer storage and recovery facilities planned to be developed in south-central Florida to enhance Everglades restoration. The purpose of this study was to determine critical threshold water pressures at which hydraulically induced fracturing of the FAS rock matrix may occur. Several FAS rock matrix samples were collected, tested, and evaluated to define representative mechanical properties, which were then used in relation with in situ stresses to determine critical threshold water pressures. Three hydraulically induced fracturing failure mode evaluation methods based on shear, tensile, and microfracture development were utilized. Microfracture development requires the lowest critical threshold water pressure to induce fracturing, followed by tensile and then shear failure modes. Predictive critical threshold water pressures for tensile and microfracture development failure modes can potentially be achieved during full-scale operation of the planned aquifer storage and recovery facilities; therefore, appropriate design considerations and operational precautions should be taken to minimize water pressures that exceed this operational constraint. If hydraulically induced fractures are developed in the FAS, their propagation into the Hawthorn Group deposit would likely be arrested by or re-directed along the discontinuity zone at the contact of these two deposits. Additionally, the Hawthorn Group deposit exhibits a significantly lower modulus of elasticity than the FAS, which would tend to effectively arrest hydraulically induced fracture propagation.

INTRODUCTION

A portion of the April 1999 Comprehensive Everglades Restoration Plan (CERP) includes a proposed large-scale development of aquifer storage and recovery (ASR) facilities throughout southern Florida to provide additional freshwater storage for Lake Okeechobee, its tributaries, and the Greater Everglades Ecosystem (U.S. Army Corps of Engineers [USACE] and South Florida Water Management District [SFWMD], 1999). As currently proposed, the CERP ASR system includes up to 333 ASR wells and associated surface facilities at multiple sites. During periods when the quantity of surface water is sufficient to meet the environmental needs of the Everglades ecosystem, the wells will be used to inject, or recharge, treated surface water into the Floridan Aquifer System (FAS) for storage, and conversely during low-water conditions, the same wells will be used to recover water from the FAS to replenish surface waters of the ecosystem. Each proposed ASR well has a target recharge capacity of 5 million gallons (1.9 × 10^7 L) of treated water per day and a variable recovery rate depending on surface-water needs.

The USACE and SFWMD are evaluating the feasibility of the proposed CERP ASR system through the construction and testing of pilot ASR wells and surface-water treatment systems, along with the development of a comprehensive regional feasibility study. One component of the feasibility study is to determine the hydraulically induced fracturing potential of the FAS and overlying Hawthorn Group deposit from an anticipated daily ASR recharge or recovery volume of 1.67 billion gallons (6.3 × 10^9 L) of water.

The magnitude of the increase/decrease in hydraulic pressure within the upper portions of the FAS during recharge/recovery ASR operational cycles, respectively, is highly dependent upon a number of factors, such as transmissivity of the FAS, well
spacing, and injection and recovery rates. During ASR operational recharge phases, increases of 100 to 200 feet (ft) (31 to 61 m) in static hydraulic head in the FAS within the areas of the ASR well fields are possible (Brown et al., 2005; Brown, 2007). Conversely, during ASR recovery phases, similar decreases in magnitude of the static hydraulic head are possible. These hydraulic pressure changes will need to be considered during the evaluation of planning and engineering constraints that may limit ASR system design and operation. An effect of large-scale ASR operation is the potential for hydraulically induced fracturing of the limestone rock matrix of the FAS and the overlying Hawthorn Group deposit. Hydraulically induced fracturing of the FAS may locally increase its transmissivity and actually enhance practical ASR operational recharge and recovery rates.

Hydraulic fracturing 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 and deployment, hydraulically induced fracturing was thought to occur when the hydraulic pressure at any specific point in the well reached or just exceeded the pressure due to the weight of the overburden at that point (which is considered to be about 1 pound per square inch [psi] per foot [0.023 MPa/m] of overburden) (Bouwer, 1978; Smith, 1989). Since these early developments, it has been shown through numerous 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 (0.011 MPa/m) of depth in poorly consolidated coastal plain sediments to 1.2 psi/ft (0.027 MPa/m) 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 (0.015 MPa/m to 0.018 MPa/m) of depth. As a rough guide, drilling professionals trying to induce hydraulic fracturing estimate required down-hole injection pressures of 1 psi/ft (0.023 MPa/m) of depth plus an additional 1,500 psi (10.3 MPa) (Sterrett, 2007). Overall, these general hydraulically induced fracturing criteria envelope a wide range of injection pressures that could initiate the onset of fracturing for wide ranges of in situ states of stress and rock matrix types. Therefore, we need to calculate site-specific hydraulic pressures, or water pressures, that may initiate the onset of hydraulically induced fracturing based on FAS rock matrix mechanical properties and in situ stress conditions in order to develop ASR facility design and operational criteria.

The purpose of this study was to determine critical threshold water pressures at which the onset of hydraulically induced fracturing of the FAS rock matrix may occur and their implications for fracturing the Hawthorn Group deposit at each potential ASR site. The evaluation of potential hydraulically induced fracturing of the FAS and Hawthorn Group deposit was accomplished for seven potential ASR sites: Caloosahatchee River, Moorehaven, Kissimmee River, Port Mayaca, Hillsboro, Seminole-Brighton, and Paradise Run (Figure 1).

**HYDROGEOLOGIC SETTING**

There are three principal hydrogeologic systems in south Florida; in descending stratigraphic order, they are: the Surficial Aquifer System (SAS), the Hawthorn Group deposit, and the FAS. Within each of these hydrogeological systems, there are confining units. Additionally, depending on the lithologic makeup of the Hawthorn Group deposit, it may act as an aquifer, termed the Intermediate Aquifer System (IAS), or as a much less permeable deposit acting predominantly as a confining unit effectively separating the SAS and the FAS.

Across the study area, the SAS typically consists of series of deposits that are hydraulically connected unconfined and semi-confined aquifers of Pleistocene and Pliocene age. These deposits are composed of loose, sandy materials; sandy and shelly porous limestone; and sandstone and silts that exhibit a wide range of permeabilities, and that are divided into distinct aquifers separated by less permeable units that serve as semi-confining layers. The individual aquifers that make up the SAS tend to be discontinuous and locally productive, reflecting the overall complex stratigraphic nature of this aquifer system. The thickness of the SAS varies from approximately 32 to 210 ft (10 to 64 m) at the potential ASR sites.

As previously stated, the Hawthorn Group deposit exhibits characteristics of either an aquifer consisting of beds of sand, sandy limestone, limestone and dolostone, silt, and clay, or a confining unit (Fernald and Purdum, 1998). The IAS portion of the Hawthorn Group deposit pinches out in the southern and eastern portions of Florida, including the study...
area, where the clay content of the deposit increases and it acts as a confining unit separating the SAS and FAS. In the study area, the stratigraphic makeup of the Hawthorn Group deposit is complex, exhibiting numerous inter-fingering thin units of fine-grained, low-permeability sediments and some limestone layers (Scott, 2001). Clay units within the Hawthorn Group deposit have been characterized as variable and include both kaolinite and smectite mineral types, which exhibit a deformable nature. The thickness of the Hawthorn Group deposit varies from approximately 396 to 735 ft (121 to 224 m) at the potential ASR sites.

The FAS is a thick sequence of Paleocene- to Miocene-age carbonate units underlying the entire state of Florida. The upper part of the Cedar Keys Formation, Oldsmar Formation, Avon Park Formation, Ocala Limestone, Suwannee Limestone, and the lower portion of the Arcadia Formation are included in the FAS (Miller, 1986; Reese, 2000). Low-permeability anhydrite units in the lower portion of the Cedar Keys Formation constitute the base of the FAS. The FAS, a source for primary water supply and supplemental irrigation water, dips to the south, where it is overlain by clays and silts of the Hawthorn Group deposit. A confining unit is present in the middle of the FAS, effectively dividing it into upper and lower units. The middle confining unit consists of a less permeable carbonate unit relative to the upper and lower units.

In the vicinity of the study area, the potentiometric surface of the FAS rises above land surface to 40 to 55 ft (12 to 17 m) mean sea level (msl), resulting in artesian conditions as wells freely flow up to 2,000 gallons per minute (126 L/s). North of Lake Okeechobee, the FAS yields freshwater, which becomes more mineralized (total dissolved solids >1,000 mg/L) along coastal areas and throughout southern Florida. Although the hydraulic gradient in the FAS contains an upward component, the confining nature of the Hawthorn Group deposit prevents significant upward movement of brackish water from entering the SAS (Fernald and Purdum, 1998).

**METHODOLOGY**

Three primary evaluation methods, termed shear, tensile, and microfracture, 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 FAS. Two additional evaluation methods to determine hydraulically induced fracturing potential were also utilized to check the outcomes of the three primary methods. A typical ASR well will only inject or recover water directly into or out of the FAS, thereby imparting hydraulically induced fracture driving stresses to the FAS. Stress due to the weight of overburden is the primary stress resisting hydraulically induced fracturing, which, within the FAS, exhibits its lowest magnitude at the top of the FAS, rendering this point the most vulnerable to the onset of hydraulically induced fracturing and making it the evaluation point of interest. For the three primary methods, a factor of safety (FS) of 10 percent was applied to the predictive hydraulically induced fracturing results to account for assumptions applied to the evaluations and to define ASR design and operational water-pressure thresholds above which caution should be exercised.
Several other factors may influence FAS rock matrix stability, rendering it more or less susceptible to hydraulically induced fracturing due to installation of a well borehole or ASR operational recharge and recovery phases; these include: (1) resultant stress intensity on the well borehole wall due to decreasing water pressure in the well (Aadnoy, 1996), (2) magnitude redistribution of the pre-drilling in situ principal stress field around the well borehole (Fjar et al., 2008), (3) chemical dissolution or precipitation of FAS rock matrix, and (4) fatigue failure of the well borehole wall due to cyclic ASR operations (Haimson, 1978; Higdon et al., 1985; Singh, 1989; Alehossein and Boland, 2004; and Zhang et al., 2008). The effects, whether positive or negative, of these four factors on the initiation of hydraulically induced fracturing will likely be very minimal and confined to the rock matrix at and very near the well borehole wall and are considered minor limitations of the methodology.

Hydraulically induced fracturing of the Hawthorn Group deposit, if realized, would be the result of vertical upward propagation of fractures initiated within the FAS. Direct hydraulically induced fracturing of the Hawthorn Group deposit due to ASR operation is not possible because water will not be recharged or recovered directly into or out of the Hawthorn Group deposit, thereby eliminating the source of stress that could initiate fracturing of the deposit. To determine potential hydraulically induced fracturing of the Hawthorn Group deposit, a propagation arrest model was applied to the potential ASR sites. The model considers geologic, formation elasticity, and in situ stress factors that influence arrest of propagating hydraulic fractures.

**In Situ State of Stresses**

To understand the potential for and orientation of hydraulically induced fracturing, the in situ state of the regional stress field must be evaluated. In a regional stress field, there exists within a geologic unit a stress point intersected by three orthogonal planes, called principal planes. A stress component is aligned normal to each of these planes: They are termed the maximum ($\sigma_1$), intermediate ($\sigma_2$), and minimum ($\sigma_3$) principal stresses. Under near-horizontal ground that is not subjected to significant tectonic forces, $\sigma_1$ will be oriented in the vertical direction, while $\sigma_2$ and $\sigma_3$ will be oriented in the horizontal direction. These stresses will be compressive in nature simply due to the weight of the overlying geologic materials, confinement, and fluid pressure if fluid is present. Under in situ conditions where the regional stress field is subjected to significant tectonic forces, such as faulting, or influences from significantly uneven topographic ground conditions, $\sigma_1$ and associated $\sigma_2$ and $\sigma_3$ may not be oriented in the vertical and horizontal directions, respectively (Goodman, 1980). A review of the world stress map for the study area indicated that tectonically induced stress does not appear to be prevalent as exhibited by the lack of stress indicators in the study region (Heidbach et al., 2008). However, this lack of tectonic stress indicators may be due to an incomplete stress-indicator data set for the region. All ASR project sites have nearly horizontal ground conditions with no major topographic change and are not subjected to significant tectonic activity; therefore, it is assumed that the in situ states for $\sigma_1$ and associated $\sigma_2$ and $\sigma_3$ are oriented in the near-vertical and horizontal directions, respectively.

In many cases, $\sigma_2$ is near or equal in magnitude to $\sigma_3$, allowing for a two-dimensional stress analysis (Rahn, 1986), which is an acceptable evaluation criterion for the proposed ASR sites based on the directional distribution of the in situ regional stress field. If $\sigma_2$ is significantly greater in magnitude than $\sigma_3$, the use of three-dimensional analysis may be warranted because a two-dimensional analysis may over- or under-predict the effects of applied forces. General conceptual hydrogeologic conditions assumed for the ASR project sites along with a two-dimensional stress element showing the orientations of the principal stresses at the top of the FAS are shown on Figure 2A. In addition to the principal stresses acting on the element, shear and normal stresses are acting on planes oriented at all angles within the stress element as a result of the influence of the principal stresses. Along an internal plane oriented at some angle in the stress element, a shear stress, $\tau_0$, provides a force acting tangential to the plane, while a normal stress, $\sigma_0$, provides a force acting normal to the plane, as shown on Figure 2B. Shear stresses are not associated with planes upon which principal stresses act.

**Shear Method**

The shear method involves an analysis of shear stresses developed as a result of the principal stresses acting at the evaluation point of interest. Ultimately, the shear strength of the FAS 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 FAS rock matrix, the potential for hydraulically induced fracturing along some critical failure plane within the FAS rock matrix exists. Fracturing due to shear may be induced at the well borehole wall or at any
The shear strength, $S_t$ (Force/Length$^2$ [F/L$^2$]), of the FAS rock matrix along some critical failure plane at an evaluation point of interest was determined utilizing the following Mohr-Coulomb equation (Terzaghi and Peck, 1967; Jaeger et al., 2007):

$$S_t = C + (\sigma_0 - P) \tan \Phi$$

(1)

where $C$ is cohesive strength of FAS rock matrix [F/L$^2$], $\sigma_0$ is stress normal to the potential failure plane [F/L$^2$], $P$ is water pressure [F/L$^2$], and $\Phi$ is angle of internal friction of FAS rock matrix (in degrees). The Mohr-Coulomb criterion is a linear function of the rock-failure, or stress, envelope (Goodman, 1980). To determine $P$ at the evaluation point of interest, the following relationships are used:

$$P = \gamma_w \times PH$$

(2)

where $\gamma_w$ is specific weight of water [F/L$^3$], and PH is pressure head [L]. The value of PH for the evaluation point of interest can be determined using the following form of Bernoulli’s equation in terms of hydraulic head:

$$TH = EH + PH + VH$$

(3)

where $TH$ is total head [L], $EH$ is elevation head [L], and $VH$ is velocity head [L]. The $VH$ term is very small relative to the $TH$, $EH$, and $PH$ terms due to the extremely slow rate of groundwater movement and can therefore be considered negligible and removed from the equation. Measurements of $TH$, $EH$, and $PH$ are made from some consistent datum, which will be msl for purposes of this evaluation. Solving Eq. 3 for $PH$ yields:

$$PH = TH - EH$$

(4)

The following Mohr circle formulation can be used to determine the magnitude of $\tau_{\theta}$, a component in Eq. 1, acting on the critical failure plane (Rahn, 1986; American Society for Testing and Materials [ASTM], 2007 [D 7012]):

$$\sigma_{\theta} = \left[\frac{(\sigma_V + \sigma_H)}{2}\right] + \left[\frac{(\sigma_V - \sigma_H)}{2}\right] \cos 2\theta$$

(5)

where $\sigma_V$ is total overburden stress [F/L$^2$], $\sigma_H$ is total horizontal stress [F/L$^2$], and $\theta$ is angle of the critical failure plane ($45^o + \Phi/2$) [in degrees]. Simply based on nomenclature, the principal stresses $\sigma_1$ and $\sigma_3$ are synonymous to $\sigma_V$ and $\sigma_H$, respectively, due to vertical and horizontal orientation. The critical failure plane upon which hydraulically induced fracturing, illustrated in Figure 2B, is likely to occur develops at an angle, $\theta$, of $45^o + \Phi/2$ from $\sigma_H$ (Hubbert and Willis, 1957; Blyth and de Freitas, 1984).

The total overburden stress, $\sigma_V$, is due to the weight of the overburden at the evaluation point of interest and is defined by:

$$\sigma_V = \sum_{i=1}^{n} \gamma_i \times h_i$$

(6)

where $\gamma_i$ is the specific weight of the geologic unit at its natural moisture content [F/L$^3$], and $h_i$ is the
thickness of the geologic unit [L]. The following relationship is used to determine \( \sigma_H \) according to Terzaghi’s effective stress law (Rutqvist and Stephansson, 2003):

\[
\sigma_H = \sigma_{\text{Heff}} + P
\]  

(7)

where \( \sigma_{\text{Heff}} \) is horizontal effective stress [F/L^2]. The stress field component, \( \sigma_{\text{Heff}} \), results from the \( \sigma_H \) force acting upon the FAS rock matrix, while \( P \) (described in Eq. 1 and Eq. 2) is the stress field component of \( \sigma_H \) resulting from the forces acting upon water in the pore spaces of the FAS rock matrix. Utilizing the following relation, \( \sigma_{\text{Heff}} \) can be determined by:

\[
\sigma_{\text{Heff}} = K_0 \times \sigma_{\text{Veff}}
\]  

(8)

where \( \sigma_{\text{Veff}} \) is vertical effective stress [F/L^2], and \( K_0 \) is the coefficient of lateral earth pressure. At the potential ASR sites, a reasonable estimate of \( K_0 \) can be determined by:

\[
K_0 = 1 - \sin \Phi
\]  

(9)

The stress field component \( \sigma_{\text{Veff}} \) results from the \( \sigma_V \) force acting upon the FAS rock matrix, while \( P \) (described in Eq. 1 and Eq. 2) is the stress field component of \( \sigma_V \) resulting from the forces acting upon water in the pore spaces of the FAS rock matrix and can be determined by:

\[
\sigma_{\text{Veff}} = \sigma_V - P
\]  

(10)

To determine the shear stress, \( \tau_0 \) [F/L^2], acting along a critical failure plane at an angle \( \theta \) at a point of interest in the FAS, the following Mohr circle formulation is utilized (Rahn, 1986; ASTM, 2007 [D 7012]):

\[
\tau_0 = \left[ \left( \sigma_V - \sigma_H \right) / 2 \right] \sin 2\theta
\]  

(11)

This method can be used to evaluate an incremental series of shear strengths and shear stresses at corresponding \( P \) values for the FAS evaluation point of interest. By plotting respective shear strengths and shear stresses at corresponding \( P \) values, the \( P \) at which hydraulically induced fracture onset will occur can be determined by identifying the critical threshold shear stress that exceeds the shear strength of the rock.

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 \( \sigma_3 \) by an amount equal to the tensile strength of the rock. After a hydraulic 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).

Theoretically, the 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 (Goodman, 1980; Rahn, 1986; Smith, 1989; Domenico and Schwartz, 1998; and Jaeger et al., 2007). Fracture plane orientation and propagation align generally with the principal stress axes as described previously and thus will align as such relative to the orientation of any principal stress axes (e.g., if \( \sigma_3 \) is aligned vertically, then the fracture plane orientation and propagation will be horizontal). In addition to the vertical propagation alignment of the induced hydraulic fracture (assuming \( \sigma_1 \) and \( \sigma_3 \) axes are in vertical and horizontal alignment, respectively), the fracture will propagate radially from the well. According to Smith (1989), the orientation and propagation of fractures can also be influenced by anisotropy or planar inhomogeneities in the rock (i.e., bedding, schistosity, cleavage, joints, etc.). Fracture orientation and propagation may potentially parallel these types of features. The stress field at the tip of a fracture may influence an adjacent fracture’s stress field tip and thus its propagation path and orientation (Pollard et al., 1982). Jaeger et al. (2007) suggests that the fractures may be irregular and discontinuous in nature; that is, they may not initiate or propagate along the entire length of a fracture plane.

The tensile method, developed by Hubbert and Willis (1957), involves an analysis of a critical stress level respective to some \( P \), acting at the evaluation point of interest, that is required to initiate hydraulically induced fracturing of a well borehole wall as
described already. If, at some evaluation point of interest, the $P$ within the well borehole is equal to or greater than the critical water-pressure stress level for the well borehole wall, the potential for hydraulic fracturing of the well borehole wall and FAS rock matrix exists. The critical water-pressure stress level, $P^f$ [F/L$^2$], at an evaluation point of interest, of the FAS rock matrix at the well borehole wall is determined utilizing the following equation (Hubbert and Willis, 1957):

$$P^f = (\sigma_V \times M) - P_a \times (M - 1) \quad (12)$$

where $P_a$ is ambient pre-fracture water pressure [F/L$^2$]. Equation 6 is used to determine $\sigma_V$, and $M$ is the ratio of horizontal to vertical stress, which is equivalent to $K_o$ and is determined using Eq. 9. Actual values of $P$ within the well borehole at the evaluation point of interest are determined using Eq. 2 for various incremental head changes. By plotting a series of values representing incremental $P$ values within the well borehole at the evaluation point of interest and comparing them to $P^f$, the $P$ at which hydraulic-fracture onset will occur can be determined when $P$ equals $P^f$.

**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 $P$ 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 $P$, 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 $\sigma_1$ and $\sigma_2$ principal stress axes and perpendicular to the $\sigma_3$ stress axis; 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 $P$ that initiated the dilatancy effect tends to be relieved (Keith and Rimstidt, 1985). However, if $P$ 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).

After the macrofracture planes are developed, failure will likely occur and may be initiated at the well borehole wall or at any point within the FAS that exhibits appropriate dilatancy conditions.

To evaluate the microfracture failure criterion at the evaluation point of interest, the following empirical relations are used (Handin et al., 1963):

$$\text{HDR} = \frac{P}{\sigma_H} \quad (13)$$

where HDR is Handin Dilatancy Ratio (HDR), and $P$ and $\sigma_H$ are determined using Eq. 2 and Eq. 7, respectively. The HDR at which dilatancy is initiated, resulting in the onset of microfracturing, differs for various rock types. For sedimentary rocks, such as those of the FAS, dilatancy is observed when HDR is approximately 0.8 (Handin et al., 1963). Therefore, for the purposes of this microfracturing failure criterion, 0.8 will be considered the critical level for HDR at which the onset of dilatancy and microfracture development will occur and be termed the Limiting Handin Dilatancy Ratio (LHDR). It should be noted that this microfracture failure criterion is supported by actual FAS laboratory rock testing stress-strain results. By plotting a series of HDR values at associated $P$ values and comparing them to the LHDR, the $P$ at which microfracture onset will occur can be determined.

**Check Methods**

Goodman (1980) presented a method based on the Mohr-Coulomb linear failure criterion in terms of principal stresses at peak load condition to determine the $P$ in pores and fissures required to initiate fracture of intact rock. Calculation of $P$ is based on an initial state of stresses, defined by $\sigma_V$ and $\sigma_H$ at some evaluation point of interest. The hydraulic fracture-inducing $P$ can be determined using the following equation:

$$P = \sigma_H - \left\{[(\sigma_V - \sigma_H) - qu]/[\tan^2 (45^\circ + \Phi/2) - 1]\right\} \quad (14)$$

where $qu$ is unconfined compressive strength [F/L$^2$] of the intact rock matrix. The mechanical property $qu$ is determined through testing FAS rock matrix samples in an unconfined manner. Resultant fracture-inducing $P$ values calculated by this check method can be compared to ensure that predictive $P$ values calculated by the shear method are not grossly over- or under-represented.

A second check method considers initiation of hydraulically induced fracturing, either at a well borehole wall or within the FAS, when the fluid pressure at the evaluation point of interest is equal to
50 to 67 percent of $\sigma_V$ (Bouwer, 1978). To determine the critical fluid pressure required to initiate hydraulic fracturing, Eq. 6 is used to calculate $\sigma_V$ at 100 percent, which is then multiplied by the desired fluid pressure percentage factor, resulting in $\sigma_V \times \%$. The following relation is used to determine the height of fluid column, $h_f$ [L], required to equal $\sigma_V \times \%$.

$$h_f = \frac{\sigma_V \times \%}{\gamma_f} \quad (15)$$

where $\gamma_f$ is the specific weight of the fluid [F/L]. The resultant $h_f$ values calculated using this check method can be converted to like terms and compared with the hydraulically induced fracturing predictive $p^f$ and TH values determined using the tensile and microfracture methods, respectively, assuring results are not grossly over- or under-represented.

Hydraulically Induced Fracture Propagation Arrest Model

A criterion of ASR design and operation is to minimize the potential to hydraulically induce fracturing of the Hawthorn Group deposit. Hydraulically induced fracturing of the Hawthorn Group deposit may allow uncontrolled recharge distribution and be detrimental to the recovery phase efficiency of ASR operations. Hydraulically induced fracturing of the Hawthorn Group deposit, if realized, would be the result of vertical propagation of fractures initiated within the FAS. Gudmundsson and Brenner (2001) present a model of hydraulically induced fracture propagation arrest. According to their model, arrest of hydraulically induced fracture propagation is 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 ability to redistribute the fracture-promoting hydraulically induced stress field at the tip of a propagating fracture. It is the redistribution of the stress field intensity that allows the hydraulically induced fracture to 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 become arrested or propagate some distance along the plane of the discontinuity rather than continue across the discontinuity.

A laboratory testing or field-derived value, $E$, describes the amount of axially applied stress that is required to achieve a given amount of axial elastic shortening of a core of rock, acting as a measure of the stiffness of the rock. The greater the stiffness of the deposit, the greater is the value of $E$. 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). When a hydraulic fracture encounters a deposit exhibiting a substantially lower $E$ than the fracture host deposit, the hydraulic fracture tip stress tends to dissipate in the lower $E$ deposit to levels not conducive for continued fracture propagation and thus becomes arrested.

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). In the case of a compressive stress barrier, the hydraulic fracture tip stress is dissipated in such a manner that it penetrates only a short distance within the rock mass hosting the compressive stress barrier. Hydraulic fracture tip stress is dissipated in much the same manner in a tension stress barrier as it is in a compressive stress barrier. This redistribution of hydraulic fracture tip stress allows for a very limited distance of fracture propagation into the rock mass hosting the compressive or tension stress barrier, followed by arrest. An exception may be a tension stress barrier arresting fracture propagation due to shear.

LABORATORY TESTING AND RESULTS

Mechanical and elastic properties of the rock matrix that are used in the hydraulically induced fracturing evaluation methods include $\Phi$, $C$, and $E$. The methodology used to determine $\Phi$ and $C$ was through the development and evaluation of Mohr envelopes from various sets of laboratory rock strength testing results. In order to develop the Mohr stress envelopes, $qu$ and triaxial compressive strength (TCS) laboratory testing results of FAS rock matrix specimens were utilized, and if available, tensile strength laboratory results were also incorporated into the evaluation. Additionally, during $qu$ and TCS 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 in the field through core-drilling techniques. Rock specimens for testing were obtained from the field samples by coring in the laboratory and exhibited a typical diameter of 2.2 inches (5.6 cm). The lithology of the rock specimens tested was consistent and consisted of
intact, fine-grained, slightly muddy limestone with very few defects such as 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, 2008a). Unconfined and triaxial compression testing of rock specimens giving qu and TCS, respectively, were completed by ASTM method D 7012 (ASTM, 2007) or earlier versions of this standard of practice congruent to the testing time frame. A single splitting tensile test was performed under compliance with ASTM method D 3967 (ASTM, 2008b). Stress-strain curves for select rock specimens were developed, from which values of E were obtained following ASTM method D 7012 (ASTM, 2007) or earlier versions of this standard of practice.

All specimens met preparation criteria established in ASTM method D 4543 (ASTM, 2008a), with the exception of three specimens that minimally failed the length-to-diameter ratio criterion. In addition to adhering to ASTM standard practices, several criteria were also considered to ensure that acceptable testing results were obtained. Just prior to testing, the specimens were cored in the laboratory from existing FAS rock matrix samples that had been collected 4 months to 9 years earlier. As noted in several studies, rock specimens will undergo simultaneous hardening and mechanical fatigue as soon as they are removed from the ground (Kowalski, 1994). Upon its collection, a rock specimen will expand due to the relaxation of in situ stresses. During this expansion period, the rock specimen will harden, resulting in increased strength. The degree of this hardening phenomenon is specific to the type of rock and time lapse after its collection, as the specimen will exhibit increasing hardness with time until it reaches a maximum strength. Mechanical fatigue of a rock specimen is primarily a result of changes of atmospheric agents such as temperature, moisture, and pressure, which will impart fatigue on a rock specimen until it is disintegrated. Typically, an ongoing hardening process will impart a greater influence in increasing the strength of a rock specimen than mechanical fatigue will impart in weakening the strength of the specimen, thereby resulting in an overall net increase in strength seen during the hardening process. At completion of the hardening process, mechanical fatigue continues to slowly act and decreases the strength of the rock specimen until it is disintegrated. A discernible trend of slightly decreasing rock specimen strength is seen that is attributable to the sample collection and laboratory testing time lapse; however, any significant strength differences are likely largely due to natural strength variations that would be expected in the FAS rock matrix.

Wet rock specimens tend to fail at lower axial loads, providing a more realistic interpretation of in situ rock strength for such conditions; however, this effect of decreasing strength with increasing moisture content is small, and for most engineering applications it can be disregarded (Obert and Duvall, 1967). However, Shakoor and Barefield (2009) indicated that an amplification in the reduction in strength, to a substantial level, with an increasing degree of saturation can be seen for various rock types. Also, the reduction in strength primarily occurred at moisture contents between 0 percent and 33 percent of fully saturated rock specimen conditions. Because the FAS rock core testing was completed under undrained and less than 50 percent specimen saturation conditions, excessive pore pressure likely did not accumulate during testing, as increasing pore pressure may increase the apparent strength of the rock specimen. With the specimens being wet during testing, however, any appropriate reduction in apparent strength would closely approximate in situ conditions. Confining pressures applied during triaxial testing of the rock specimens ranged from 60 to 400 psi (0.41 to 2.76 MPa) based on an estimated average horizontal effective stress likely seen during ASR operational conditions. The temperature of a rock specimen can also be adjusted to mimic the in situ temperature condition resulting from a natural geothermal gradient or other heat sources. At high temperatures, rock specimens will exhibit enhanced ductility, depressed yield strength, and a lower ultimate strength than those at lower temperatures (Handin et al., 1963; Davis, 1984). However, the in situ temperatures noted at the ASR sites are sufficiently low, as exhibited by the temperature of water extracted from the FAS, that temperature adjustment during rock specimen testing was not required. Based on these testing criteria, testing was performed to approximate in situ stress and temperature conditions encountered during ASR operational recharge and recovery phases.

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. Additionally, the apparent strength of a rock specimen can be influenced by the rate of strain, as a rock specimen will exhibit greater strength as the
rate of strain is increased. Another indicator of valid testing is the failure modes of the rock specimens. Rock specimens tested under unconfined conditions primarily exhibited longitudinal failure, along with some specimens exhibiting shear failure. Rock specimens tested under triaxial conditions primarily exhibited shear and multiple shear failure modes and to a lesser extent longitudinal failure. The rock specimen tested under the splitting tensile test failed by a single fracture splitting the specimen into two near equal-sized halves. These are typical failure modes indicating acceptable testing procedures were completed.

Testing procedures and results appear to be valid and exhibit minimal data-use uncertainty based on adherence to rock specimen preparation criteria prescribed in ASTM method D 4543 (ASTM, 2008a). Slightly lower \( qu \) results were seen for specimens exhibiting a significant time lapse between sample collection and testing when compared to results for those exhibiting a minimal time lapse. The lower \( qu \) values slightly reduce the arithmetic mean values for \( qu \) and \( C \), which will result in less calculated resistance to hydraulically induced fracturing. Rock testing and mechanical property results are summarized in Table 1. Arithmetic mean values of 998 psi (6.9 MPa), 28.9°, and 332 psi (2.3 MPa) were determined for \( qu \), \( \Phi \), and \( C \), respectively, to be used in the hydraulically induced fracturing evaluation methods. Arithmetic mean values for TCS and \( E \) were not determined because their magnitudes can be influenced by the confining pressure applied during testing, and substantial amounts of tests were not conducted at various confining pressures. At confining pressures ranging from 60 to 400 psi (0.41 to 2.8 MPa), the TCS of 28 specimens ranged from 350 to 11,930 psi (2.4 to 82.3 MPa). Testing results of 18 samples for the tangent modulus \( E \) ranged from 0.33 to 17.4 \( \times 10^6 \) psi (2,275 to 119,969 MPa) at confining pressures ranging from 0 to 210 psi (0 to 1.5 MPa).

### DISCUSSION OF RESULTS

#### Primary Methods

The predictive maximum allowable TH values and well-head pressures initiating hydraulically induced fracturing utilizing the primary methods of evaluation for each potential ASR site are shown in Table 2. Hydraulically induced fracturing, under the primary methods, can be initiated at the well borehole wall or anywhere within the FAS when the TH critical threshold level is reached at any point in the hydraulic

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**Table 1. Laboratory testing results for Floridan Aquifer System rock matrix specimens.**

<table>
<thead>
<tr>
<th>ASR Site</th>
<th>Boring Number</th>
<th>Depth* (ft bgs)</th>
<th>Time Lapse** (yr/mo)</th>
<th>Laboratory Test</th>
<th>( qu ) (psi)</th>
<th>( \Phi ) (°)</th>
<th>( C ) (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caloosahatchee River</td>
<td>CCBRY</td>
<td>653</td>
<td>0/7</td>
<td>U/T</td>
<td>1,110</td>
<td>34.0</td>
<td>330</td>
</tr>
<tr>
<td>Caloosahatchee River</td>
<td>CCBRY</td>
<td>740</td>
<td>0/7</td>
<td>T</td>
<td>NR</td>
<td>36.5</td>
<td>760</td>
</tr>
<tr>
<td>Caloosahatchee River</td>
<td>CCBRY</td>
<td>910</td>
<td>0/7</td>
<td>U/T</td>
<td>415/650</td>
<td>34.5</td>
<td>450</td>
</tr>
<tr>
<td>Caloosahatchee River</td>
<td>CCBRY</td>
<td>952</td>
<td>0/7</td>
<td>U/T</td>
<td>1,145</td>
<td>34.0</td>
<td>360</td>
</tr>
<tr>
<td>Caloosahatchee River***</td>
<td>Various</td>
<td>932–1,324</td>
<td>2/0</td>
<td>U</td>
<td>NR</td>
<td>NR</td>
<td>443</td>
</tr>
<tr>
<td>Caloosahatchee River</td>
<td>CCBRY</td>
<td>733</td>
<td>0/4</td>
<td>U</td>
<td>486</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Caloosahatchee River</td>
<td>CCBRY</td>
<td>851</td>
<td>0/4</td>
<td>U</td>
<td>1,652</td>
<td>NR</td>
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<td>Caloosahatchee River</td>
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<td>897</td>
<td>0/4</td>
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<td>1,145</td>
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<td>2/0</td>
<td>U</td>
<td>1,301</td>
<td>NR</td>
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<td>Hillsboro</td>
<td>W-17986</td>
<td>1,134</td>
<td>9/0</td>
<td>U/T</td>
<td>330</td>
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<tr>
<td>Moorehaven</td>
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<td>875</td>
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<td>U/T</td>
<td>460</td>
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<td>ST/U/T</td>
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<td>400</td>
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<tr>
<td>Kissimmee River</td>
<td>W-18776</td>
<td>656</td>
<td>7/0</td>
<td>U/T</td>
<td>430</td>
<td>13.5</td>
<td>175</td>
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<td>Kissimmee River</td>
<td>W-18776</td>
<td>803</td>
<td>7/0</td>
<td>U/T</td>
<td>520</td>
<td>23.5</td>
<td>180</td>
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<tr>
<td>Seminole-Brighton</td>
<td>W-18811</td>
<td>693</td>
<td>1/6</td>
<td>U/T</td>
<td>870/1,100</td>
<td>36.0</td>
<td>265</td>
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<td>932</td>
<td>1/6</td>
<td>U/T</td>
<td>560</td>
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<tr>
<td>Paradise Run</td>
<td>W-18814</td>
<td>797</td>
<td>1/0</td>
<td>U/T</td>
<td>2,090</td>
<td>38.5</td>
<td>275</td>
</tr>
</tbody>
</table>

*bgs = below ground surface; \( qu \) = unconfined compressive strength; psi = pounds per square inch; \( \Phi \) = angle of internal friction; \( C \) = cohesion; U = unconfined compressive; T = triaxial compressive; ST = splitting tensile; NR = not recorded. 1 ft = 0.3048 m; 1 psi = 0.006895 MPa.

*Specimens for laboratory testing typically retained within 10 ft of listed depth.

**Time lapse between sample collection and laboratory testing.

***Arithmetic mean values reported by Brown et al. (2005) for various borings to include Port Mayaca site.
Fracturing the Floridan Aquifer

Table 2. Predictive water-pressure thresholds above which hydraulic fracturing at the top of the Floridan Aquifer System may be induced.

<table>
<thead>
<tr>
<th>ASR Site</th>
<th>Shear Method</th>
<th>Tensile Method</th>
<th>Microfracture Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FS/No FS</td>
<td>FS/No FS</td>
<td>FS/No FS</td>
</tr>
<tr>
<td></td>
<td>TH (ft NGVD)</td>
<td>TH (ft NGVD)</td>
<td>TH (ft NGVD)</td>
</tr>
<tr>
<td></td>
<td>Pressure (psi)</td>
<td>Pressure (psi)</td>
<td>Pressure (psi)</td>
</tr>
<tr>
<td>Caloosahatchee River</td>
<td>&gt;&gt;400</td>
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<td>343</td>
</tr>
<tr>
<td></td>
<td>&gt;&gt;164</td>
<td>125</td>
<td>139</td>
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<tr>
<td>Moorehaven</td>
<td>&gt;&gt;400</td>
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<td>505</td>
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<tr>
<td></td>
<td>&gt;&gt;167</td>
<td>190</td>
<td>212</td>
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<td>Kissimme River</td>
<td>&gt;&gt;400</td>
<td>301</td>
<td>334</td>
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<tr>
<td></td>
<td>&gt;&gt;168</td>
<td>125</td>
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<tr>
<td>Port Mayaca</td>
<td>&gt;&gt;400</td>
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<tr>
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<td>&gt;&gt;164</td>
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<td>Hillsboro</td>
<td>&gt;&gt;400</td>
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<td>&gt;&gt;168</td>
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<td>Seminole-Brighton</td>
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<td>Paradise Run</td>
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<td>&gt;&gt;165</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>97</td>
</tr>
</tbody>
</table>

TH = total head; NGVD = National Geodetic Vertical Datum, 1929; FAS = Floridan Aquifer System; FS = factor of safety applied at 10 percent; >> = significantly greater than. 1 ft = 0.3048 m; 1 psi = 0.006895 MPa.

pressure field. However, the mechanics of hydraulically induced fracturing under the tensile method require that the TH 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 TH 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 TH below the critical threshold level. To reach the TH critical threshold level, injection of water into the FAS is required; however, fracture initiation and propagation can still occur during recovery if the TH remains at or above the TH critical threshold level.

The shear method evaluation results indicate that it is highly unlikely that hydraulically induced fracturing due to shear failure will occur under any probable ASR operational condition, either of the well borehole wall or within the FAS (Table 2). The tensile method evaluation results indicate that hydraulically induced fracturing due to failure of the well borehole wall is possible if ASR operations increase the TH to the predictive critical threshold levels (Table 2). Likewise, the microfracture method evaluation results indicate that hydraulically induced fracturing due to microfracture development is possible if ASR operations increase the TH to the predictive critical threshold levels (Table 2).

It should be remembered that the resultant predicted TH values shown in Table 2 are for the evaluation point of interest at the top of the FAS. The stratigraphic zone of the FAS below the evaluation point of interest requires TH values greater than those shown in Table 2 to initiate hydraulically induced fracturing, assuming the FAS rock matrix exhibits similar or greater fracture-resistant mechanical properties to those used in the evaluations. For all potential ASR sites, check method results are consistent with predictive TH values as determined using the primary methods.

Fracture gradients were developed as another alternative to illustrate and compare the P values required to initiate the onset of hydraulically induced fracturing. A fracture gradient is P in psi per foot of depth below ground surface at which the onset of hydraulically induced fracturing will be initiated. Fracture gradients were calculated by determining the P values at which the initiation of hydraulically induced fracturing is realized at the evaluation points of interest and dividing it by the thickness of strata above those points. Fracture gradients for the shear method are substantially greater than 0.73 psi/ft (0.017 MPa/m) for both no applied FS and applied FS. Fracture gradients for the tensile and microfracture methods are 0.69 and 0.61 psi/ft (0.016 and 0.014 MPa/m) for no applied FS and 0.66 and 0.59 psi/ft (0.015 and 0.013 MPa/m) for an applied FS of 10 percent, respectively. These fracture gradients were found to be consistent between all potential ASR sites. In addition, the fracture gradients estimated using the primary methods are consistent with those suggested by Ehlig-Economides and Economides (2010).

Hydraulically Induced Fracture Propagation Arrest

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

Values of $E$ were calculated from the rock testing program results for the FAS rock matrix; however, testing of Hawthorn Group deposit materials was not completed, and therefore values of $E$ were not obtained. Values of $E$ for the FAS rock matrix ranged from $0.33 \times 10^6$ to $17.4 \times 10^6$ psi ($2,275$ to $119,969$ MPa). The range of values of $E$ for the Hawthorn Group deposit materials is expected to be significantly lower than those of the FAS due to the different types of materials found in each deposit. For clay and silt materials such as those found in the Hawthorn Group deposit, typical values of $E$ are in the range of 300 to 15,000 psi (2.1 to 103.4 MPa) (Converse, 1962; Hallam et al., 1978; Das, 1984; Hunt, 1986; Cernica, 1995; and Bowles, 1997). Modulus of elasticity values estimated for the Hawthorn Group deposit from down-hole seismic velocity data at a project site north of Lake Okeechobee (Golder Associates Incorporated, 2009) suggest values ranging from 28,000 to 42,000 psi (193.1 to 289.6 MPa) for clay- and silt-dominated samples.

Due to the Hawthorn Group deposit being significantly less stiff than the FAS, the fracture tip stress of a vertically propagating hydraulically induced fracture initiated in the FAS is likely to be effectively redistributed and dissipated in the Hawthorn Group deposit. Dissipation of the tip stress in the Hawthorn Group deposit would occur at such a level that the propagation of the hydraulic fracture would be arrested at the FAS and Hawthorn Group deposit contact, in keeping with the arrest model presented by Gudmundsson and Brenner (2001).

On the basis of the little evidence that exists about the ability of geological or anthropogenic sources to create differential stress patterns, it is considered that zones or entire stratigraphic units of the FAS and Hawthorn Group deposit are not subjected to compressive or tension stresses at quite different magnitudes. Therefore, a stress barrier or barriers that would arrest vertical propagation of a hydraulic fracture initiated in the FAS from entering the Hawthorn Group deposit is not likely.

**APPLICATION EXAMPLE**

The primary methods to evaluate hydraulically induced fracturing were applied to the potential Caloosahatchee River ASR site to illustrate development of predictive maximum allowable TH values and well-head pressure hydraulically induced fracturing thresholds. The conceptual hydrogeological model used for the evaluation of this potential ASR site consists of 32 ft (10 m) of SAS and 518 ft (158 m) of the Hawthorn Group deposit, each exhibiting an approximate specific unit weight of 130 pounds per cubic foot (2,082 kg/m$^3$) at their natural moisture content. The evaluation point of interest is the top of the FAS (i.e., 550 ft [168 m] below ground surface).

Predictive stress and head relations under recharge and recovery ASR operational phases using the shear method are shown on Figures 3 and 4, respectively. Hydraulically induced fracturing due to shear would be initiated when the magnitude of the shear stress component applied to the FAS rock matrix is equal in

![Figure 3](image-url) Predictive relation of stress in pounds per square inch (psi) and total head in feet (ft), based on the 1929 National Geodetic Vertical Datum (NGVD), for operational recharge phase using the shear method for the critical failure plane of 59°. 1 ft = 0.3048 m; 1 psi = 0.006895 MPa.

![Figure 4](image-url) Predictive relation of stress in pounds per square inch (psi) and total head in feet (ft), based on the 1929 National Geodetic Vertical Datum (NGVD), for operational recovery phase using the shear method for the critical failure plane of 59°. 1 ft = 0.3048 m; 1 psi = 0.006895 MPa.
magnitude to the shear strength component of the FAS rock matrix (i.e., on Figures 3 and 4, the shear stress line would intercept the shear strength line). As illustrated on Figures 3 and 4, respectively, the shear trend lines will converge at very high TH values under the recharge phase, while they diverge under the recovery phase. These trends show that it is extremely unlikely that ASR operational recharge and recovery conditions will be met to initiate the onset of hydraulically induced fracturing within the well bore and/or FAS. If hydraulically induced fracturing due to shear were to occur, the critical shear failure plane would likely align at a $\theta$ angle of 59.5° measured from the horizontal.

The predictive stress and head relations under the ASR operational recharge phase using the tensile method are shown on Figure 5. Hydraulically induced fracturing of the well borehole wall would initiate when the magnitude of the $P$ stress component in the well borehole equals the magnitude of the critical stress level (i.e., on Figure 5, the intercept of the water-pressure stress line and the critical stress level). It can be determined from Figure 5 that hydraulic fracturing may be initiated and propagated when the TH value within the well borehole reaches or exceeds approximately 343 ft (105 m) National Geodetic Vertical Datum (NGVD). However, hydraulic fracturing is not a concern at levels under this TH.

Predictive HDR and head relations under the recharge phase derived from the microfracture method are shown on Figure 6. Hydraulically induced microfracturing of the FAS rock matrix would be initiated and maintained when the ratio of the $P$ stress component to the total horizontal stress component, the HDR, is equal to and greater than the LHDR, set at 0.8 (i.e., on Figure 6, the HDR line would intercept and project above the LHDR line). It can be determined from this figure that hydraulically induced microfracturing will potentially be initiated and maintained under the ASR operational recharge phase when the TH within the well bore and/or FAS reaches and exceeds approximately 244 ft (74 m) NGVD. However, microfracture initiation is not a concern at levels under this TH.

**CONCLUSIONS**

Three primary methods, termed shear, tensile, and microfracture, based on relationships of FAS rock matrix mechanical properties and in situ stresses were applied to determine the $P$ values that would induce hydraulic fracturing at the top of the FAS. Shear method results indicate that an extremely high $P$ in the FAS 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 by tensile splitting of the well borehole wall. Microfracture method results indicate that a moderately low $P$ is required to initiate fracturing by tensile splitting of the well borehole wall. More likely, moderately low $P$ values causing microfracture initiation may be achieved within practical ASR operational limits (Table 2). Two additional hydraulically induced fracturing methods were applied and produced results consistent with the three primary methods, providing for increased assurance of the predictive $P$ 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 $P$ 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.

Potential for hydraulically induced fracturing of the Hawthorn Group deposit, due to vertically upward propagating fractures initiated in the FAS, is very unlikely. These type of 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 deposit. If the fracture were able to propagate through the discontinuity and into the Hawthorn Group deposit, the softer nature of the Hawthorn Group deposit would arrest its propagation. It is likely that significant stress barriers are not present in the FAS and Hawthorn Group deposit, therefore stress barriers do not provide an arrest mechanism for hydraulically induced fracture propagation.

ACKNOWLEDGMENTS

We thank June Mirecki and Orlando Ramos-Gines of the U.S. Army Corps of Engineers, Jacksonville District, and Robert Verrastra and Emily Richardson of the South Florida Water Management District, for their support and reviews, which greatly enhanced this manuscript. Also, we would like to thank the three anonymous Environmental & Engineering Geoscience reviewers for their valuable comments that significantly improved this manuscript.

REFERENCES

Fracturing the Floridan Aquifer


Arsenic Control During Aquifer Storage Recovery Cycle Tests in the Floridan Aquifer
by June E. Mirecki, Michael W. Bennett, and Marie C. López-Baláez

Abstract
Implementation of aquifer storage recovery (ASR) for water resource management in Florida is impeded by arsenic mobilization. Arsenic, released by pyrite oxidation during the recharge phase, sometimes results in groundwater concentrations that exceed the 10 μg/L criterion defined in the Safe Drinking Water Act. ASR was proposed as a major storage component for the Comprehensive Everglades Restoration Plan (CERP), in which excess surface water is stored during the wet season, and then distributed during the dry season for ecosystem restoration. To evaluate ASR system performance for CERP goals, three cycle tests were conducted, with extensive water-quality monitoring in the Upper Floridan Aquifer (UFA) at the Kissimmee River ASR (KRASR) pilot system. During each cycle test, redox evolution from sub-oxic to sulfate-reducing conditions occurs in the UFA storage zone, as indicated by decreasing Fe²⁺/H₂S mass ratios. Arsenic, released by pyrite oxidation during recharge, is sequestered during storage and recovery by co-precipitation with iron sulfide. Mineral saturation indices indicate that amorphous iron oxide (a sorption surface for arsenic) is stable only during oxic and sub-oxic conditions of the recharge phase, but iron sulfide (which co-precipitates arsenic) is stable during the sulfate-reducing conditions of the storage and recovery phases. Resultant arsenic concentrations in recovered water are below the 10 μg/L regulatory criterion during cycle tests 2 and 3. The arsenic sequestration process is appropriate for other ASR systems that recharge treated surface water into a sulfate-reducing aquifer.

Introduction
Aquifer storage recovery (ASR) systems are important components of water resource management plans for regions that have appropriate subsurface permeability (Bloetscher et al. 2005; Dillon et al. 2005; Pyne 2005; National Academy of Sciences 2008; Maliva and Missimer 2010). In Florida, permitted ASR systems store treated surface (potable) water (Reese 2002; Mirecki 2004; Reese and Alvarez-Zarikian 2007) or reclaimed water (Clinton 2007) in the Floridan Aquifer during the wet season, for distribution back to surface water in the dry season. ASR serves as the largest component of new storage in the Comprehensive Everglades Restoration Plan (CERP; National Academy of Sciences 2001, 2002). Regional implementation of CERP ASR could capture approximately 1.6 billion gal/d (6056 megaliters/d) of surface water currently lost to tide directly through the St. Lucie Canal and Caloosahatchee River.

Arsenic mobilization during ASR cycle testing presents a significant challenge to expanded use of potable and reclaimed water ASR in Florida. The source and mechanism of arsenic mobilization during cycle testing in carbonate aquifers are well known through controlled laboratory leaching and column experiments (Fischler and Arthur 2010; Onstott et al. 2011), mineralogical characterization of aquifer matrix (Price and Pichler 2006; Pichler et al. 2011), and modeling studies (Mirecki 2006; Jones 2004; Reese and Alvarez-Zarikian 2007).
and Pichler 2007) at Floridan Aquifer ASR systems, and also from extensive field studies at Australian reclaimed water ASR systems (Herczeg et al. 2004; Dillon et al. 2005, 2008; Vanderzalm et al. 2010, 2011). Arsenic is released during oxidation of pyrite by dissolved oxygen as recharge water flows through permeable zones in the carbonate aquifer (Jones and Pichler 2007; Fischler and Arthur 2010). Resultant arsenic concentrations measured in groundwater during ASR cycle testing can exceed the Federal and state maximum contaminant level (10 μg/L). Once released into the aquifer, arsenic can: (1) be sequestered by sorption to iron oxyhydroxide phases that are stable under oxic or sub-oxic aquifer redox conditions (Vanderzalm et al. 2011); or (2) be transported as the dissolved complex arsenate (As(V)) or arsenite (As(III)) under oxic to sub-oxic, iron-poor conditions (e.g. Höhn et al. 2006); or (3) co-precipitate as an iron sulfide phase under sulfate-reducing, iron-rich conditions. The third condition has not been documented at any ASR system, and has important implications for arsenic attenuation and also regulatory compliance during ASR cycle tests in the Floridan Aquifer.

Characterization and controls on arsenic transport and fate during ASR cycle testing have been impeded in the United States by the lack of extensive sampling. Most ASR system investigations are performed by water utilities at potable water ASR systems (Florida Department of Environmental Protection [FDEP] 2007). Water-quality datasets at utility ASR systems usually are limited to analytes required for permit compliance rather than geochemical characterization. Consequently, little is known of the magnitude and duration of arsenic mobilization, and factors that control arsenic transport and fate in the Floridan Aquifer. Without better assurance that ASR systems can perform in regulatory compliance, the future of ASR implementation is uncertain.

The overall objective of CERP ASR pilot system operations is to evaluate ASR feasibility at representative locations in south Florida. ASR feasibility is demonstrated by several factors including: (1) percent recovery of recharged surface water; (2) regulatory compliance with all state and Federal water-quality criteria; and (3) cost-effective subsurface storage. At the Kissimmee River ASR (KRASR) pilot system, three cycle tests have been completed with a groundwater monitoring program objective to evaluate water-quality changes.

Arsenic mobilization and subsequent attenuation are shown during three successive cycle tests at KRASR. In this report, the geochemical controls on arsenic transport and fate during ASR cycle testing in the Upper Floridan Aquifer (UFA) are defined. Our hypothesis is that arsenic, released by oxidation of pyrite during early portions of the recharge phase, is subsequently attenuated by co-precipitation in a stable iron sulfide phase during late recharge, storage, and recovery. The native UFA sulfate-reducing redox condition is disrupted only temporarily by dissolved oxygen introduced during recharge. Addition of dissolved (probably colloidal) iron and organic carbon in recharge (surface) water, mixing with sulfate-rich groundwater, provides abundant electron acceptors to re-establish microbe-mediated sulfate reduction, iron sulfide precipitation, and consequently arsenic attenuation. The result is that arsenic concentrations are nearly always below 10 μg/L in all well samples collected weekly during the storage and recovery phases of successive cycles at KRASR.

Hydrogeologic Setting

At KRASR, the artesian UFA occurs within a thick sequence of interlayered marine calcareous and dolomitic limestones of Eocene and Oligocene age (Figure 1), and serves as the storage zone for ASR cycle tests. The UFA is confined by the overlying Intermediate Confining Unit, which consists of approximately 400 feet (122 m) of Hawthorn Group interlayered clays, silts, and fine sands (Scott 1988). Lower confinement of the UFA is provided by the Middle Confining Unit, which consists of 400 to 500 feet (122 to 152 m) of dolomitic limestone, dolomite, and dolostone (Reese and Richardson 2008). Hydrostratigraphic and lithostratigraphic characteristics are defined using geophysical logs, lithologic descriptions, and limited coring during construction of the ASR and monitoring wells (CH2MHill 2004; Golder Associates 2007; Entrix 2010).

Water is stored in the UFA at depths between −543 and −856 feet (−166 and −261 meters, m) below the National Geodetic Vertical Datum of 1929 (NGVD29). However, permeability is not uniform with depth in the storage zone. Water will flow preferentially through zones of higher permeability that develop at or near unconformable formation contacts, and to a lesser extent, bedding planes. Permeability in the UFA is interpreted from geophysical logs in boreholes for the ASR and all storage zone monitor wells (SZMWs), and aquifer performance testing during construction of the ASR well. Static and dynamic flow logs were corrected for variations in borehole diameter from caliper logs, and interpreted to quantify the percent contribution of individual zones to total flow in the borehole that became the ASR well. Geophysical flow log interpretations indicate that 80% of flow occurs at the top of the storage zone, at depths between −546 and −609 feet (−166 and −186 m) NGVD29 (Figure 1). This preferential flow zone is consistent with an unconformable contact between the Arcadia Formation (lower part of the Hawthorn Group) sediments and the Ocala Limestone, and has been observed at a similar depth in all KRASR SZMWs, and commonly in UFA boreholes surrounding Lake Okeechobee (Reese and Richardson 2008). A smaller component of flow (12%) occurs below the base of the storage zone between −880 and −930 feet NGVD29. This preferential flow zone may occur near the formation contact between the Ocala Limestone and Avon Park Formation. An aquifer performance test of the entire storage interval at the ASR borehole resulted in a transmissivity value of 36,765 ft²/d (CH2MHill 2004).

A chloride-based conservative mixing model confirms extensive transport of recharge water along this
Figure 1. Hydrogeologic cross-section and plan view of the Kissimmee River ASR system. SZMW, storage zone monitor well; T, transmissivity. The 1100 feet SZMW is a dual zone well, but only upper zone sample data are presented. Horizontal axis in cross-section is not to scale. All distances are relative to the ASR well. Length conversions are: 350 feet (107 m); 1100 feet (335 m); 2350 feet (716 m); 4200 feet (1280 m).

upper preferential flow zone to the 1100 feet SZMW (Figure 2). Mixing fractions were calculated following the method of Herczeg et al. (2004) to show how the percentage of recharge water component changes throughout cycles 2 and 3 (Table S1, Supporting Information). After 1 or 2 months of recharge during cycles 2 and 3 (respectively), samples from the 1100 feet (335 m) SZMW consist of 90% or greater recharge water. This monitor well has a short open-interval (−544 to −583 feet; 166 to 178 m NGVD29) that intersects the preferential flow zone of the UFA. Interpretations of geophysical flow logs and the conservative mixing model support a conceptual hydrogeologic model in which most of the groundwater flow occurs in the a preferential flow zone of the uppermost UFA across the ASR wellfield.

The Kissimmee River ASR System and Cycle Testing History

The KRASR system is located on the eastern bank of the Kissimmee River near its confluence with Lake Okeechobee, Florida (Figure 1). The ASR system was designed for minimal pre-treatment of Kissimmee River source water prior to recharge into the UFA storage zone. Pre-treatment consists of pressurized media filtration and ultraviolet disinfection at a recharge rate of 5 million gal/d (MGD; 18.9 megaliters/d, MLD).

Groundwater is recovered at a rate of 5 MGD, with diversion of the first 0.3 million gallons (MG; 1.1 megaliters, ML) of turbid water to on-site storage ponds. When turbidity, pH, and specific conductance criteria are achieved, recovered water is re-oxygenated over a cascade aerator and returned to the Kissimmee River. More detailed information about system design and operation are found at US Army Corps of Engineers (USACE 2004, 2012).

Each ASR cycle test consists of recharge, storage, and recovery phases. Three cycle tests were completed at KRASR between 2009 and 2011 (Table 1). Each successive cycle test increased in duration and volume stored. Recovery exceeded 100% of the recharged volume during cycle 1 so that aquifer arsenic concentrations were returned to initial values (below 10 μg/L) prior to cycle 2. Interpretations are based primarily on data acquired during cycles 2 and 3 because these cycles represent intended ASR system operations.

Data Collection Effort

A single ASR well is surrounded by four SZMWs (Figure 1), designated by their lateral distances from the
Table 1
Recharge, Storage, and Recovery Pumping Rate, Durations, and Volumes During KRASR Cycle Tests

<table>
<thead>
<tr>
<th>Phase</th>
<th>Start Date</th>
<th>End Date</th>
<th>No. of Days</th>
<th>Avg. Pumping Rate, in MGD (MLD)</th>
<th>Volume, in MG (ML)</th>
<th>Percent Volume Recovered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge</td>
<td>January 12, 2009</td>
<td>February 9, 2009</td>
<td>28</td>
<td>4.7 (17.8)</td>
<td>128.5 (486.4)</td>
<td>—</td>
</tr>
<tr>
<td>Storage</td>
<td>February 9, 2009</td>
<td>March 9, 2009</td>
<td>28</td>
<td>4.8 (18.2)</td>
<td>183.8 (695.7)</td>
<td>143%</td>
</tr>
<tr>
<td>Recovery</td>
<td>March 9, 2009</td>
<td>April 17, 2009</td>
<td>39</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge</td>
<td>May 11, 2009</td>
<td>August 28, 2009</td>
<td>109</td>
<td>3.8 (14.4)</td>
<td>334.23 (1.27)</td>
<td>—</td>
</tr>
<tr>
<td>Storage</td>
<td>August 28, 2009</td>
<td>October 28, 2009</td>
<td>61</td>
<td></td>
<td></td>
<td>—</td>
</tr>
<tr>
<td>Recovery</td>
<td>October 28, 2009</td>
<td>January 2, 2010</td>
<td>66</td>
<td>4.0 (15.1)</td>
<td>331.5 (1255)</td>
<td>99%</td>
</tr>
<tr>
<td>Cycle 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge</td>
<td>January 19, 2010</td>
<td>July 9, 2010</td>
<td>171</td>
<td>4.9 (18.5)</td>
<td>793.1 (3002)</td>
<td>—</td>
</tr>
<tr>
<td>Storage</td>
<td>July 9, 2010</td>
<td>January 4, 2011</td>
<td>178</td>
<td></td>
<td></td>
<td>—</td>
</tr>
<tr>
<td>Recovery</td>
<td>January 4, 2011</td>
<td>June 17, 2011</td>
<td>164</td>
<td>4.98 (18.9)</td>
<td>805.5 (3049)</td>
<td>102%</td>
</tr>
</tbody>
</table>

ASR well: 350 feet (107 m), 1100 feet (335 m), 2350 feet (716 m), and 4200 feet (1,280 m). Each monitor well has an open interval identical to that of the ASR well, between −543 and −856 feet (−166 and −261 m) NGVD29. Two SZMWs located farthest from the ASR well were constructed during cycle 2, so data were obtained at these distal wells only during cycle 3. All wells were sampled weekly at the wellhead for field parameters, major and trace inorganic constituents, nutrients, and microbes for the entire testing duration, using standard methods for groundwater sampling, laboratory analyses, and quality control (FDEP 2008). All analyses were performed at laboratories certified by the National Environmental Laboratory Accreditation Program. In addition to wellhead samples, the 350 feet SZMW is instrumented with a SeaCat 19plusV2Profiler, (Sea-Bird Electronics Inc., Bellevue, Washington), which is suspended downhole in the UFA preferential flow zone at −588 feet (−186 m) NGVD29. The SeaCat 19plusV2Profiler provided hourly in-situ measurements of pH, temperature, specific conductance, dissolved oxygen (DO), oxidation–reduction potential (ORP), and pressure through each cycle test. Because DO is the primary electron acceptor during pyrite oxidation, in-situ DO measurements at a location 350 feet away from the ASR well are particularly important to quantify proximal redox conditions in the storage zone. The SeaCat Profiler measures DO using a Clark polarographic membrane with a gold cathode, which is more stable and is not affected by dissolved hydrogen sulfide compared to sensors with a silver cathode (Sea-Bird Electronics Inc. 2012). The SeaCat Profiler was installed on January 25, 2009 (cycle 1 recharge), and checked during monthly data downloads. The DO sensor began to fail sometime during August 2009, so Cycle 2 DO values are not presented. Power supply issues caused interruption to the continuous record from this probe between 30 March and 22 August 2010. The SeaCat Profiler was recalibrated at the manufacturer between 13 February and 30 March 2010 (cycle 2) and between 1 June and 9 July 2011 (cycle 3).

Source Water and Native Floridan Aquifer Water Quality

The Kissimmee River is the source of recharge water, and water-quality data reflect dry and wet season conditions through the cycle tests (Table 2). Recharge water quality is characterized using samples from the ASR wellhead during the recharge phase of all cycle tests. Recharge water is oxic, and has neutral pH, low carbonate alkalinity, low total dissolved solids (TDS) concentrations, and relatively high concentrations of total and dissolved organic carbon, iron and manganese (Table 2).

The native UFA at this location is relatively fresh as indicated by low chloride and TDS concentrations and specific conductance values (Table 2). Native UFA groundwater at KRASR is characterized as sulfate-reducing and has slightly alkaline pH, moderate carbonate alkalinity and sulfate concentrations, and low concentrations of metals including iron. Arsenic concentrations generally are less than 3 μg/L.

Geochemical Calculations

Geochemical characterization was performed using public domain codes developed by the U.S. Geological Survey. The aquifer redox condition was evaluated using the Redox Processes Workbook by Jurgens et al. (2009). Mineral saturation indices and charge balance errors for each complete water quality analysis was performed using PHREEQC, version 2.17 with the Wateq4f database (Parkhurst and Appelo 1999), with data entry facilitated with the Excel interface NetpathXL (Parkhurst and Charlton 2008). The choice of controlling redox couple in PHREEQC will determine mineral stabilities. In each water sample, if DO concentration is greater than 0.05 mg/L (the field detection limit), the dissolved oxygen (O−2/O0) couple is used; if DO is below
### Table 2
Recharge Water Quality and Native Floridan Aquifer Water Quality

<table>
<thead>
<tr>
<th>Constituent or Parameter</th>
<th>Unit</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Median</th>
<th>( N )</th>
<th>ASR WELL</th>
<th>1100 feet SZMW</th>
<th>2350 feet SZMW</th>
<th>4200 feet SZMW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>25.3</td>
<td>6.0</td>
<td>28.3</td>
<td>46</td>
<td>25.5</td>
<td>25.2</td>
<td>24.3</td>
<td>24.9</td>
</tr>
<tr>
<td>Specific conductance</td>
<td>μS/cm</td>
<td>227</td>
<td>46</td>
<td>204</td>
<td>46</td>
<td>1347</td>
<td>1300</td>
<td>983</td>
<td>1404</td>
</tr>
<tr>
<td>pH</td>
<td>std. units</td>
<td>6.7</td>
<td>0.4</td>
<td>6.6</td>
<td>46</td>
<td>7.80</td>
<td>7.97</td>
<td>7.95</td>
<td>8.05</td>
</tr>
<tr>
<td>Oxidation–reduction potential</td>
<td>mV</td>
<td>130</td>
<td>59</td>
<td>114</td>
<td>46</td>
<td>–283</td>
<td>–179</td>
<td>–430</td>
<td>–249</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>mg/L</td>
<td>4.5</td>
<td>2.5</td>
<td>3.5</td>
<td>46</td>
<td>0.3</td>
<td>0.02</td>
<td>0.52</td>
<td>0.82</td>
</tr>
<tr>
<td>Color</td>
<td>PCU</td>
<td>91</td>
<td>32</td>
<td>90</td>
<td>44</td>
<td>5.0</td>
<td>10</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Calcium</td>
<td>mg/L</td>
<td>19.2</td>
<td>4.9</td>
<td>17.0</td>
<td>44</td>
<td>51.5</td>
<td>47</td>
<td>28</td>
<td>27</td>
</tr>
<tr>
<td>Magnesium</td>
<td>mg/L</td>
<td>4.8</td>
<td>0.9</td>
<td>4.7</td>
<td>44</td>
<td>38.7</td>
<td>33</td>
<td>30</td>
<td>33</td>
</tr>
<tr>
<td>Sodium</td>
<td>mg/L</td>
<td>16.1</td>
<td>3.8</td>
<td>14.0</td>
<td>45</td>
<td>152</td>
<td>150</td>
<td>59</td>
<td>110</td>
</tr>
<tr>
<td>Potassium</td>
<td>mg/L</td>
<td>4.0</td>
<td>0.6</td>
<td>4.1</td>
<td>44</td>
<td>8.3</td>
<td>7.2</td>
<td>4.7</td>
<td>8.3</td>
</tr>
<tr>
<td>Sulfate</td>
<td>mg/L</td>
<td>15.6</td>
<td>6.5</td>
<td>14.0</td>
<td>45</td>
<td>198</td>
<td>150</td>
<td>170</td>
<td>200</td>
</tr>
<tr>
<td>Sulfide</td>
<td>mg/L</td>
<td>0.1</td>
<td>0.3</td>
<td>0.01</td>
<td>44</td>
<td>0.8</td>
<td>&lt;1.0</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Chloride</td>
<td>mg/L</td>
<td>31.1</td>
<td>7.5</td>
<td>28.0</td>
<td>45</td>
<td>242</td>
<td>260</td>
<td>140</td>
<td>160</td>
</tr>
<tr>
<td>Total alkalinity as CaCO(_3)</td>
<td>mg/L</td>
<td>50</td>
<td>51</td>
<td>36</td>
<td>45</td>
<td>91</td>
<td>84</td>
<td>80</td>
<td>87</td>
</tr>
<tr>
<td>Dissolved organic carbon</td>
<td>mg/L</td>
<td>15.3</td>
<td>1.5</td>
<td>15.5</td>
<td>14</td>
<td>—</td>
<td>1.2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Total organic carbon</td>
<td>mg/L</td>
<td>16.3</td>
<td>1.0</td>
<td>17.0</td>
<td>13</td>
<td>&lt;1.0</td>
<td>1.3</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Arsenic</td>
<td>μg/L</td>
<td>0.9</td>
<td>0.5</td>
<td>0.8</td>
<td>45</td>
<td>&lt;2.6</td>
<td>1.6</td>
<td>0.81</td>
<td>1.2</td>
</tr>
<tr>
<td>Iron</td>
<td>μg/L</td>
<td>226</td>
<td>68</td>
<td>230</td>
<td>45</td>
<td>28</td>
<td>65</td>
<td>23</td>
<td>&lt;2.4</td>
</tr>
<tr>
<td>Manganese</td>
<td>μg/L</td>
<td>4.5</td>
<td>2.8</td>
<td>3.6</td>
<td>45</td>
<td>&lt;3.8</td>
<td>4.3</td>
<td>1.1</td>
<td>0.57</td>
</tr>
<tr>
<td>Nitrate</td>
<td>mg/L</td>
<td>0.142</td>
<td>0.101</td>
<td>0.100</td>
<td>29</td>
<td>0.100</td>
<td>&lt;0.025</td>
<td>&lt;0.003</td>
<td>&lt;0.003</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>μg/L</td>
<td>64</td>
<td>32</td>
<td>54</td>
<td>43</td>
<td>0.010</td>
<td>&lt;0.008</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Note: Concentrations reported as “less than” are below the method detection limit. Recharge water data are measured at the ASR wellhead. Native UFA data are from single samples obtained prior to cycle testing. \( N \) is number of samples.

Results

Redox Environment of the Native Floridan Aquifer System

The sulfate-reducing redox environment is the native condition of the KRASR storage zone as interpreted from groundwater redox couple concentrations. Chapelle et al. (2009) proposed geochemical criteria to distinguish iron-reducing from sulfate-reducing conditions in groundwater using the \( \text{Fe}^{2+}/\text{H}_2\text{S} \) mass ratio, when dissolved oxygen, nitrate, and manganese are absent. The native redox environment in the UFA storage zone at KRASR is sulfate-reducing on the following bases: (1) that low to non-detectable concentrations of dissolved oxygen, nitrate, and manganese are absent. The native redox environment in the UFA storage zone at KRASR is sulfate-reducing on the following bases: (1) that low to non-detectable concentrations of dissolved oxygen, nitrate, and manganese species do not contribute significantly to redox condition; and (2) that the \( \text{Fe}^{2+}/\text{H}_2\text{S} \) mass ratio in native UFA samples collected at the KRASR system is \(<0.3 \) (Table 3).

Redox Evolution During ASR Cycle Tests

Redox evolution in the UFA during cycle testing is defined in space and time. The spatial component is defined by reactions along the flowpath from the point of recharge (ASR well) to the 350 feet SZMW and the 1100 feet SZMW. No water-quality changes were detected at distal SZMWs (2350 and 4200 feet; Tables S3 and S4) during cycles 2 and 3, so data from these SZMWs serve as background (Table 3). The temporal component is defined through time-series presentation of groundwater data at a single monitor well through recharge, storage, and recovery phases during cycle tests 2 and 3. Interpretations will show redox evolution in both space and time.

Redox evolution in the UFA during cycle tests 2 and 3 is interpreted similarly to that of the native UFA, using (1) \( \text{Fe}^{2+}/\text{H}_2\text{S} \) mass ratios from ASR well and SZMW samples (Figure 3); and (2) wellhead and SeaCat Profiler measurements of DO and ORP at depth in the 350 feet SZMW (Figure 4).

The recharge phase of an ASR cycle test introduces DO, organic carbon, and ferric iron into the UFA, which shows low native concentrations of these solutes (Table 2). Source water (Kissimmee River, as measured during recharge at the ASR well) concentrations of redox-sensitive species vary seasonally: DO ranges from 1.6 to 8.8 mg/L; organic carbon ranges from 12 to 18 mg/L; and total iron ranges from 0.060 to 0.360 mg/L (Table 2; Tables S2 through S4). Ferric iron probably is complexed to organic carbon in source water rather than as a particulate phase, as recharge water is highly colored and shows total suspended solids concentrations typically less than the detection limit at 5.0 mg/L. ASR well clogging...
Table 3
Characterization of Sulfate-Reducing Redox Environment in the Native UFA (mg/L)

<table>
<thead>
<tr>
<th>Well</th>
<th>ORP</th>
<th>Nitrate</th>
<th>Manganese</th>
<th>Iron</th>
<th>Sulfate</th>
<th>Sulfide</th>
<th>Fe²⁺/H₂S</th>
<th>Arsenic</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapelle et al. (2009)</td>
<td></td>
<td>&lt;0.5</td>
<td>&lt;0.05</td>
<td>≥0.1</td>
<td>&gt;0.5</td>
<td>—</td>
<td>&lt;0.3</td>
<td>0.010²</td>
<td>—</td>
</tr>
<tr>
<td>criteria¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASR Well (May 5, 2004)</td>
<td>−283</td>
<td>0.10</td>
<td>&lt;0.0038</td>
<td>0.028</td>
<td>200</td>
<td>0.8</td>
<td>0.035</td>
<td>&lt;0.026</td>
<td>KRASR</td>
</tr>
<tr>
<td>(January 6, 2010)</td>
<td>−430</td>
<td>&lt;0.0030</td>
<td>0.0011</td>
<td>0.028</td>
<td>170</td>
<td>1.1</td>
<td>0.025</td>
<td>0.0008</td>
<td>KRASR</td>
</tr>
<tr>
<td>2350 feet SZMW (January 6, 2010)</td>
<td>−249</td>
<td>&lt;0.0030</td>
<td>&lt;0.001</td>
<td>0.024</td>
<td>200</td>
<td>1.2</td>
<td>0.020</td>
<td>0.0012</td>
<td>KRASR</td>
</tr>
<tr>
<td>OKF-101 (November 18, 2010)³</td>
<td>−146</td>
<td>&lt;0.015</td>
<td>0.0025</td>
<td>0.060</td>
<td>230</td>
<td>1.8</td>
<td>0.033</td>
<td>0.0047</td>
<td>5 mi. east of KRASR</td>
</tr>
<tr>
<td>HIF-42 (April 4, 2008)³</td>
<td></td>
<td>0.11</td>
<td>0.0024</td>
<td>0.036</td>
<td>200</td>
<td>0.38</td>
<td>0.095</td>
<td>&lt;0.005</td>
<td>5 mi. north of KRASR</td>
</tr>
</tbody>
</table>

¹Criterion for sulfate-reducing redox environment. All values are in mg/L.
²Arsenic criterion is the Maximum Contaminant Level from the Safe Drinking Water Act.
³Nearby background UFA monitor wells of the South Florida Water Management District.

During cycles 2 and 3 recharge, SZMW samples show Fe²⁺/H₂S values greater than 0.3 (Figure 3A and 3B), indicating that the aquifer redox environment is sub-oxic, and is characterized by both ferric iron- and sulfate-reduction reactions. These reactions likely are coupled to oxidation of organic carbon by native and recharge water microbes (Vanderzalm et al. 2006). Native sulfate-reducing conditions in the storage zone are perturbed temporarily, resulting from iron, organic carbon, and DO transport through a sulfate-reducing UFA redox environment. Farther from the ASR well at both 350 and 1100 feet SZMWs, Fe²⁺/H₂S values decrease, indicating that mixed ferric iron- and sulfate-reduction redox couples dominate as DO is depleted along the flowpath.

SeaCat Profiler data and wellhead sample data from the 350 feet SZMW show redox evolution in the UFA at a proximal position away from the ASR well (Figure 4A and 4B). In particular, these data quantify DO transport and fate during recharge because the SeaCat Profiler is deployed directly in the upper preferential flow zone of the UFA at ~588 feet NGVD29. Pyrite oxidation will continue as long, and as far away from the ASR well, as DO persists. As recharge water flows away from the ASR well, DO concentrations diminish from a range of 2 to 8 mg/L at the ASR wellhead, to 0.01 to 1.5 mg/L at the 350 feet SZMW, and <0.25 mg/L at the 1100 feet SZMW (Tables S3 and S4). DO and positive ORP values are detected in 350 feet SZMW wellhead samples approximately 2 weeks after the onset of recharge in cycles 1 and 3, resulting in an apparent horizontal flow velocity of 25 ft/d to the east. During later recharge, DO concentrations and ORP values in all SZMW wellhead samples decrease to <0.06 mg/L and ~−100 mV respectively. Iron and organic carbon concentrations also decline along the flowpath during recharge (Tables S3 and S4).

SeaCat Profiler and wellhead sample data obtained during cycle 1 at the 350 feet SZMW show that from mineral precipitation was not observed during three cycle tests. Recharge water also dilutes and displaces native UFA sulfate concentrations (Table 2).
perturbation of the aquifer redox environment during recharge is temporary (Figure 4). During recharge, DO is detected in-situ at higher concentrations (1.5 to 2.5 mg/L) compared to wellhead samples (0.01 to 1.5 mg/L). Upwelling of deeper, low DO water during well purging and sampling results in lower wellhead DO concentrations (Figure 4). Similarly, SeaCat Profiler ORP values also are slightly more positive than wellhead values. SeaCat Profiler data clearly show the rapid decay of DO at a single location once recharge ends. DO declines from an average concentration of 1.6 mg/L (n = 384 readings) during cycle 1 recharge, to below detection (0.05 mg/L) within 5 d. A conservative half-life \((t_{1/2})\) calculated for DO reduction is 25 h.

A few weeks after initiating cycles 2 and 3 recharge, redox conditions in the storage zone evolve from suboxic to mixed iron- and sulfate-reducing redox conditions (Figure 3). \(\text{Fe}^{2+}/\text{H}_2\text{S} \) values continue to decline below 0.3 at all SZMWs during late recharge and storage of cycles 2 and 3. The native UFA is iron-poor in this area (<24 \(\mu\)g/L; see 2350 and 4200 feet SZMW “background” data in Table S4), so ferric iron reduction does not contribute significantly to native UFA redox equilibria. Introduction of iron-rich recharge water into the sulfate-reducing UFA allows a new redox couple to react in the storage zone.

During storage and recovery, DO is depleted, and the aquifer redox environment continues to evolve such that sulfate reduction becomes the dominant redox reaction. \(\text{Fe}^{2+}/\text{H}_2\text{S} \) values decline below 0.3 in all SZMWs, and equilibrate during the first two months of cycles 2 and 3 storage (Figure 3). SeaCat Profiler ORP values are very negative (−400 to −500 mV; Figure 4), more so than wellhead samples (−280 to −300 mV). This disparity may result from a pressure effect on dissolved hydrogen gas equilibrium.

**Arsenic Trends During ASR Cycle Tests**

Arsenic concentration trends through three cycle tests show several common characteristics when data from all wellhead samples are compared (Figure 5). Maximum arsenic concentrations were measured during cycle 1 in all wells, when the initial exposure of the aquifer to DO occurred. Subsequent cycles show arsenic concentration maxima occurring in SZMW wellhead samples during recharge or early storage, then declining through late storage and recovery. This pattern reflects reactive transport (during recharge) and reactions (during storage) of iron and arsenic as the aquifer redox environment evolves from a sub-oxic to sulfate-reducing condition. Arsenic concentration maxima, and concentrations that exceed the 10 \(\mu\)g/L regulatory criterion, coincide with mixed ferric iron- and sulfate-reduction redox environment in the UFA (Figure 5 and Tables S3 and S4). The duration that arsenic exceeds the MCL in the aquifer is approximately 150 d (cycle 2: 3-month recharge, 241-d cycle), and 290 d (cycle 3: 6-month recharge, 513-d cycle), and these exceedances only occur during recharge and early storage phases.

Arsenic concentration trends observed during the static conditions of storage result primarily from geochemical reactions, rather than reactive transport. Declining arsenic concentrations measured at the 350 and 1100 feet SZMWs during cycle 3 storage (Figure 5) suggest that in-situ geochemical reactions are sequestering arsenic in a solid phase, coincident with sulfate-reducing conditions. During cycle tests 2 and 3 storage, arsenic concentrations declined below the 10 \(\mu\)g/L regulatory criterion, prior to the onset of the recovery phase. Consequently, with the exception of one sample in cycle 3 (Figure 5A), all recovered water is in compliance with the Safe Drinking Water Act arsenic criterion. Arsenic exceedances are temporary in the UFA, occurring only during late recharge and storage.

The chloride-based conservative mixing model (Figure 2) supports the geochemical sequestration interpretation. There is little to no change in the fraction of recharge water (>90%) at the 1100 feet SZMW through cycle test 2 and 3 storage, concurrent with declining arsenic concentration. Under static (non-pumping) conditions of storage, groundwater flow in the UFA does not cause significant mixing of native and recharge water over the durations of cycle tests 2 and 3 (at least in proximal positions in the wellfield), so that concentration trends are not affected by advective transport.
Discussion

Iron Mineral Stabilities During ASR Cycle Tests

Mineral saturation indices (SI) were calculated for each wellhead sample collected during cycle tests 2 and 3. Because both cycle tests show identical trends, only SI values from cycle 3 are presented (Figure 6). Two mineral phases are considered: amorphous iron oxyhydroxide (FeOH₃(a)), which is stable under oxic and sub-oxic conditions; and amorphous iron sulfide (FeS), which is the initial iron sulfide phase to precipitation under sulfate-reducing conditions (Schoonen 2004). Mineral stabilities are interpreted at two locations in the storage zone away from the ASR well: the 1100 feet SZMW that is affected by recharge, and the 2350 feet SZMW that represents native UFA conditions. Saturation indices do not change throughout the cycle at the 2350 feet SZMW, confirming that recharge water has not been transported to this distal location in the UFA. Calculated SI values are tabulated in Table S5 for all samples.

The recharge portion of a cycle test shows the greatest change in native mineral stabilities (Figure 6). In the presence of DO in the storage zone, amorphous iron oxyhydroxide is stable as a solid as shown by positive SI values. Iron sulfide is not stable, as shown by negative SI values. During late storage and recovery, the UFA redox environment shifts from sub-oxic, to mixed iron- and sulfate-reduction, and ultimately pure sulfate-reducing conditions. Amorphous iron oxyhydroxide is lost through reductive dissolution under sulfate-reducing conditions. Negative SI for values for iron oxyhydroxide appear late in recharge and continue through the end of the cycle. Simultaneously, amorphous iron sulfide SI values become positive, indicating stability through the end of the cycle, as native sulfate-reducing redox conditions are re-established.

Arsenic Sequestration During KRASR Cycle Tests

Iron mineral stabilities control the appearance, transport, and fate of arsenic in an aquifer. The testable hypothesis for arsenic sequestration during KRASR cycle tests is: if geochemical concentrations and redox conditions that favor precipitation of a stable iron sulfide phase are established during storage and recovery, then dissolved arsenic will be sequestered in the iron sulfide phases. Arsenic sequestration in iron sulfide phase is preferable to that of iron oxyhydroxide, because the
former more closely represents native UFA mineralogy in which arsenic occurs at concentrations generally <3 μg/L.

During recharge, iron-rich recharge water plus iron released during pyrite oxidation can precipitate as amorphous iron oxyhydroxide (Fe(OH)₃(a)). Iron oxyhydroxide is stable under oxic to sub-oxic redox conditions that characterize the storage zone during early recharge. Dissolved arsenic is released during pyrite oxidation, and subsequently can be sequestered by co-precipitation, sorption, or complexation to the iron oxyhydroxide surface (Waychunas et al. 1993; Dixit and Hering 2003). Unfortunately, arsenic sequestration by iron oxyhydroxide surfaces is only temporary, occurring during the oxic redox conditions of recharge of each cycle test.

During late recharge and early storage, the storage zone evolves to sub-oxic and mixed ferric iron- and sulfate-reducing conditions. Iron oxyhydroxide undergoes reductive dissolution by dissolved sulfide, and sorbed arsenic is released again into groundwater (O’Day et al. 2004; Poulton et al. 2004; Onstott et al. 2011). Ferrous iron (Fe²⁺) is released into groundwater where it is transported during late recharge along with arsenic. Thus, in sub-oxic aquifer redox environments, or in the presence of nitrate (a competing electron acceptor with ferric iron), arsenic will remain in solution. A sequence of arsenic sequestration and release under sub-oxic redox conditions (in the presence of nitrate) was demonstrated during cycle tests at the Bolivar reclaimed water ASR system (Vanderzalm et al. 2011).

During storage, sulfate-reducing conditions are re-established in the UFA storage zone, which favors the stability of iron sulfide minerals. Sufficient dissolved iron, sulfide, and the absence of nitrate and manganese are required for iron sulfide precipitation to proceed (Wilkin and Barnes 1997; Butler and Rickard 2000). Concomitant co-precipitation of arsenic in the new iron sulfide phase has been documented in other aquifers (Rittle et al. 1995; Kirk et al. 2004; Root et al. 2009), but has not been documented at any other ASR system to date.

At KRASR, arsenic sequestration is demonstrated by the synchronous evolution of sulfate-reducing redox conditions in the storage zone, accompanied by decreasing arsenic concentrations in all SZMWs during storage and recovery of cycle tests 2 and 3. As each cycle test proceeds from recharge to recovery, arsenic concentrations and Fe²⁺/H₂S mass ratios decline. The simultaneous decline in these geochemical characteristics in all SZMW samples supports the arsenic sequestration hypothesis at KRASR wellfield.

Conclusions

Arsenic mobilization at Florida ASR systems has slowed implementation of subsurface storage because water managers are hesitant to invest in facilities that may not operate in regulatory compliance. Extensive water-quality monitoring at the Kissimmee River ASR system during three cycle tests shows that arsenic mobilization is a temporary process. Arsenic is transported primarily when the aquifer redox environment is characterized by sub-oxic or mixed iron- and sulfate-reducing conditions during recharge, concomitant with Fe²⁺/H₂S values >0.3. Arsenic concentrations can exceed the Safe Drinking Water Act regulatory standard (10 μg/L) under these aquifer redox conditions. As a cycle test proceeds through storage and recovery phases, the redox environment of the UFA is re-established as the native, sulfate-reducing condition (Fe²⁺/H₂S <0.3) that favors arsenic sequestration in iron sulfide solids. Amorphous iron sulfide mineral stability is indicated by positive mineral saturation indices in SZMWs during storage and recovery. Co-precipitation of arsenic with iron sulfide in recovered water during cycles 2 and 3 results in arsenic concentrations that are in compliance with the Safe Drinking Water Act regulatory standard (<10 μg/L).

The mechanism for arsenic sequestration defined here is appropriate for ASR systems having the following characteristics: (1) recharge water that has sufficient iron and organic carbon to stimulate aquifer microbes; (2) recharge water that has negligible concentrations of other electron acceptors (manganese and nitrate) that inhibit sulfate reduction; and (3) a native sulfate-reducing aquifer redox environment.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

- **Table S1.** Mixing Model
- **Table S2.** Cycle Test 1
- **Table S3.** Cycle Test 2
- **Table S4.** Cycle Test 3
- **Table S5.** Mineral Saturation Indices Cycle Test 3

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References


Florida Department of Environmental Protection. 2008. Standard operating procedures for ground water sampling (FS 2200); quality control (FQ 1000); laboratory quality control (LQ 1000). http://www.dep.state.fl.us/water/sas/sop/sops.htm (accessed October 7 2012).


