ASR Implementation: Techniques for Improving Success

Leslie Turner, Lee Wiseman, W. Kirk Martin, Doug Munch, Glenn Forrest, and Bill Marcous

Aquifer Storage and Recovery (ASR) has become a major component in numerous water resource management initiatives in Florida and other areas around the world. Despite the reliance on this important management tool, there have been challenges in developing ASR in many areas because of a number of factors, mostly involving less-than-anticipated rates of water recovery and the manifestation of undesirable water chemistry changes.

In some cases, failure to achieve a successful ASR system has been the result of inappropriate storage zone selection. While several sources describe the general screening factors for selecting a storage zone, recent applications of a number of specific diagnostic tools and methods have significantly improved probability for developing a successful ASR system. This article discusses some of the most useful tools in ASR implementation and describes how these tools were applied in selecting an ASR storage zone for a project in Central Florida.

An SJRWMD-Sponsored ASR Program

The St. Johns River Water Management District (SJRWMD) identified the need for alternative water supplies, other than fresh groundwater, to meet projected future demands in its 2000 District Water Supply Plan. SJRWMD modeling indicated that increasing groundwater use to meet projected demands could result in undesirable impacts to both water resources and related natural systems.

The water supply plan identified surface water as one of the most cost-effective alternative water supply sources with a significant capacity, but the use of surface water as a reliable supply source requires significant storage because of the seasonal variability of surface water quality and quantity. The SJRWMD believes that the use of ASR technology can be a cost-effective method of storing water and that ASR can provide a means of balancing the supply sources with the temporal aspects of water supply, water demand, and water quality.

For these reasons, the SJRWMD sponsored an ASR Construction and Testing Demonstration Program for higher water-demand areas within the designated priority water resource caution areas of the district. The program aim is to evaluate the effectiveness of ASR in helping store and manage alternative water supplies within the east Central Florida area.

The goal of the ASR Construction and Testing Program is to examine the appropriateness of integrating ASR technology into regional water resource and water supply development projects. The program was divided into the following 10 project tasks:

- ASR Construction and Testing Program Plan
- Project Evaluation and Site Selection (Desktop Feasibility Assessment)
- Cooperator Agreement
- Site-Specific Data Collection and Preliminary System Design (Exploratory Well)
- ASR Pilot Project Design
- Regulatory Permitting
- ASR Facilities Construction, Monitoring, and Testing
- Startup and Training
- Large Cycle Operational Monitoring and Evaluations
- Peer Review of ASR Consultant Team Work

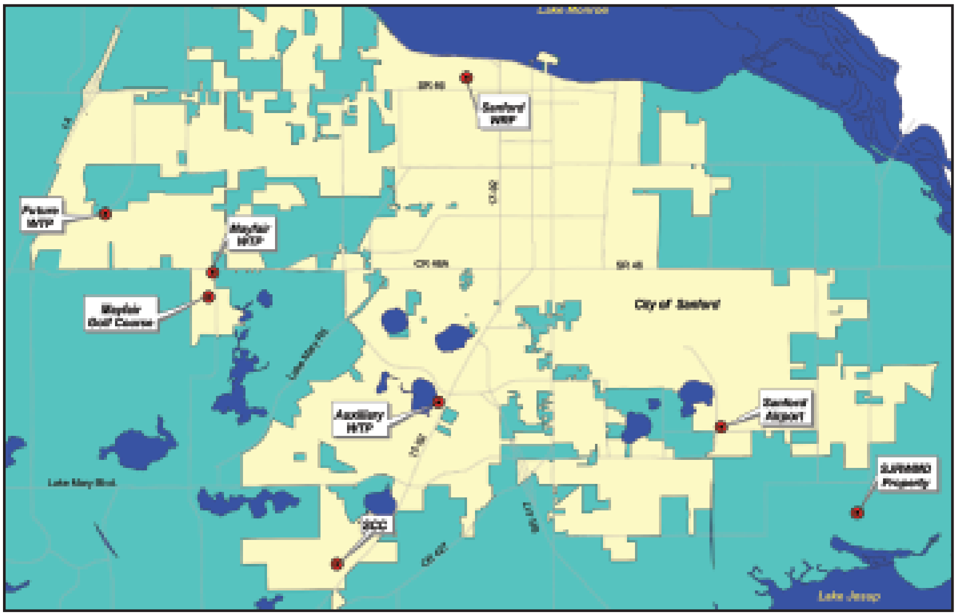

Figure 1: Location Map of Potential ASR Well Sites

Leslie Turner, P.E., is a senior project manager in the Maitland office of the consulting engineering firm CDM. Lee Wiseman, P.E., BCEE, is an associate with CDM, and W. Kirk Martin, P.G., is a vice president with the firm. Doug Munch, P.G., is director of the Division of Groundwater Programs for the St. Johns River Water Management District and Glenn E. Forrest, P.E., is a senior project manager with the district. Bill Marcous is the utility manager for the city of Sanford. This article was presented as a technical paper during the FSAWWA Fall Conference in November 2006.

City of Sanford, Cooperator

Accomplishing the goal of the SJRWMD's ASR Construction and Testing Demonstration Program required interfacing with the governmental entities or private utilities that actively participate, own, operate, or maintain a constructed facility arising out of this program. These entities are referred to as Cooperators. The case study presented in this article consists of an engineering and hydrogeological evaluation of an ASR system for the city of Sanford, one of the Cooperators in the SJRWMD's ASR Program.

Project Evaluation & Site Selection (Desktop Feasibility Assessment)

A desktop evaluation was performed on the feasibility of ASR throughout Sanford. Potential saline water intrusion and wetland drawdown impacts were identified by the SJRWMD as limiting factors for the city's groundwater use allocation. To help meet projected potable water demands, an ASR system could be used to store treated potable water, or surface water treated to drinking standards, from a proposed surface water treatment plant (WTP) that would likely be constructed on the St. Johns River near Lake Monroe. Ultimately, the ASR system would provide storage for potable water from a surface water treatment facility that uses the St. Johns River system as a raw water source.

The required potential capacity of the surface WTP, and thus ASR storage requirements, is unknown at the present time, but ASR systems have a high degree of flexibility in their capacity, since they can be readily expanded to meet increases in storage requirements by the installation of additional wells.

Eight locations were initially evaluated as potential sites for an ASR system in the desktop evaluation (Figure 1):

- Future WTP
- Mayfair Golf Course
- Mayfair WTP
- Auxiliary WTP
- Sanford North Water Reclamation Facility (WRF)
- Sanford Airport
- SJRWMD property near Lake Jesup
- Seminole Community College (SCC)

Based on the available hydrogeologic data, ASR was considered feasible at the first six sites. The last two sites were eliminated because of excessive salinity at the top of the aquifer and because the proposed ASR storage zone was within the middle-confining unit.

No overriding hydrogeologic reason existed to prefer one of the remaining six sites over the rest, but since the ASR target zone for the first three sites would have been the Lower Floridan Aquifer, they were eliminated from consideration as test well sites because of a greater cost for implementation. Other SJRWMD pilot projects were evaluating the feasibility of ASR in the Lower Floridan Aquifer. Although the first three sites were eliminated from further consideration for the testing program, it does not indicate that the sites were unsuitable for future ASR installations.

The ASR storage zone for the Auxiliary WTP site was determined to be the lower part of the Upper Floridan Aquifer, while the Sanford WRF site and the Sanford Airport site were found to have a target ASR zone in the upper portion of the Upper Floridan Aquifer. Estimates of probable capital costs for the conceptual designs were comparable for each of these three sites. The Auxiliary WTP site did exhibit a slight cost advantage because of the presence of onsite pumping, storage, and disinfection facilities. Overall from a cost standpoint, none of the three remaining sites was preferred over the others. Historic land uses and required setbacks at the Sanford WRF severely limited the implementation of potable water ASR at that site.

Considering relevant hydrogeological and site selection factors, the evaluation performed for the desktop assessment indicated that ASR in the city of Sanford was technically feasible. Two alternative sites (Auxiliary WTP and Sanford WRF) were preferred and considered economically and logistically feasible.

In consideration of the SJRWMD ASR program goals and objectives and the city's water management needs, it was recommended that ASR be further investigated at the Auxiliary WTP site. The hydrogeologic characteristics, land area, and existing facilities made the Auxiliary WTP site the preferred location for further site-specific investigation and potable water ASR test well construction and testing.

Definition of an Ideal Storage Zone

In order to obtain sufficient data to accurately design and construct an ASR test well, an exploratory well was recommended for the Auxiliary WTP site. The exploratory well would provide site-specific hydrogeological data that would be used to further evaluate ASR feasibility and would be used to design the pilot ASR system. If the results of the test program were favorable, a recommendation would be made to permit the construction of a one-well pilot ASR system at the site.

The target capacity of the ASR system was a minimum of 0.5 to 1 million gallons per day (mgd) per well. The pilot ASR system would consist of a single ASR recharge and recovery well; two storage-zone monitor wells; a confining-zone monitor well; a wellhead and associated appurtenances; and necessary site facilities such as pipeline, valves, electrical service, and instrumentation and controls.

Selection of an optimum ASR storage zone, where mixing injected potable water with native water is minimized, results in greater local storage capacity and higher recovery efficiency. Ideally, a storage zone for this type of ASR system should have native water chloride concentrations in the 250 to 1,000 mg/L range. The storage zone should have a transmissivity and anticipated ASR well specific capacity that efficiently accepts the target well capacity.

Continued on page 36

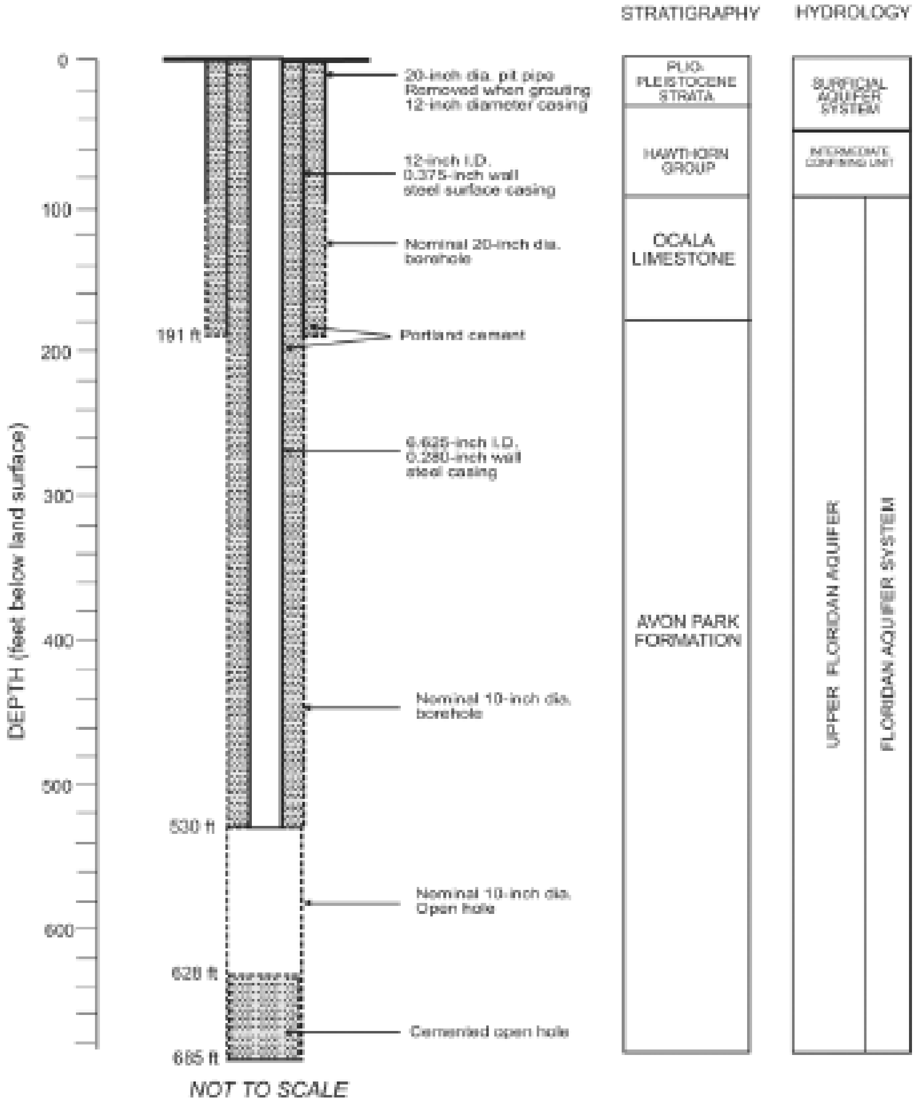

Figure 2: Exploratory Well Construction Diagram

Figure 3: Photograph of Cores

Figure 4: Photograph of the Drilling Equipment

Continued from page 35

Flow into and out of the storage zone should be largely from matrix flow rather than conduit (fracture) flow. Adequate confinement above and below the proposed storage zone is needed to minimize vertical flow into and out of the storage zone. The potential for adverse reactions between the storage zone rock and native water should be carefully considered and minimized as much as possible.

Techniques Used during Exploratory Well for Improving Success

The first phase of the test program for the Sanford ASR site was completed in 2005 and included:

- Specialized drilling and well construction methods
- Detailed geophysical logging analyses
- Field and laboratory testing of aquifer and confinement hydraulics and water quality
- Bench-scale studies of geochemical reactions between aquifer matrix materials and various qualities of injectate
- Hydrologic and chemical modeling

These were all performed in support of the ASR storage zone selection and ASR system design. Figure 2 presents the exploratory well construction diagram.

The project had several unique challenges, including a cavernous strata located above the selected storage zone (530 to 628 feet below land surface), rapidly increasing salinity below the storage zone, and an aquifer matrix consisting mostly of porous dolostone.

The application of key diagnostic methods was critical to the identification of unique site characteristics and the development of specific design considerations. As ASR becomes increasingly utilized in regional and local water management strategies, the use of these tools will become important to ASR system siting, design, operation, and critical go/no-go decision points.

Cuttings & Core Descriptions

Continuous wireline core was obtained from a depth of 191 feet below land surface (ft bls) to a depth of 594 ft bls (Figure 3). Wireline systems collect the core within a sample tube located inside the core barrel. Cores were cut using the HQ coring system manufactured by the Boart Longyear Company. The HQ coring bits collect a 2.5-inch diameter core.

After a core the length of the sample tube has been cut, the tube is unlatched and pulled to the surface using a wireline. The core is then removed and the sample tube lowered and reattached.

The major advantage of wireline coring systems is that they do not require the entire drill string to be removed after each core segment is collected (Figure 4), which greatly expedites the coring process.

The site-specific lithology at the Sanford Auxiliary WTP site was derived from drill cuttings and continuous core samples; it is summarized by the following general descriptions:

- 0-25 ft bls – sand/silty sand, dark brown to grayish brown, mostly very fine to fine grained size quartz sand, undifferentiated Plio-pleistocene surficial deposits.
- 25-45 ft bls – sandy clay/clayey sand, gray, soft, undifferentiated Plio-pleistocene surficial deposits.
- 45-95 ft bls – clay with sand and shell hash, greenish gray, Hawthorn Group.
- 95-188 ft bls – limestone, pale yellow to light gray, Ocala Formation.
- 188-394 ft bls – limestone and limestone laminate, pale yellow, Avon Park Formation
- 394-685 ft bls – dolostone and limestone, laminate, pale yellow to dark grayish brown, Avon Park Formation.

The site-specific hydrostratigraphy at the Sanford Auxiliary WTP site can be summarized by the following general descriptions:

- 0-45 ft bls – Surficial Aquifer System; the water table aquifer consists of undifferentiated plio-pleistocene sands, and the sandy clay.
- 45-95 ft bls – Intermediate Confining Unit; described as the confining clays of the Hawthorn Group.
- 95-685 ft bls – Floridan Aquifer System; the top of the Floridan Aquifer System is placed at approximately 95 ft bls, at which depth there is a downward transition from clay and shell hash (Hawthorn Group) to soft, porous non-phosphatic fossiliferous limestone (Ocala Limestone). The Floridan Aquifer System continues into the limestone and dolostone of the Avon Park

Continued on page 38

Table 1: Summary of Geophysical Logs

Log Date	Log Types	Logged Interval	Comments
9/17/04	Caliper, gamma ray, dual induction, normal resistivity (16- & 64-inch), spontaneous potential, acoustic (sonic) with variable density log (VDL). Static: fluid specific conductance, resistivity, and temperature. Dynamic: fluid specific conductance, resistivity, and temperature. Dynamic flowmeter with interpretation. Borehole video survey.	0 – 598 ft bls	12-inch diameter casing, 10-inch nominal borehole.
9/23/04	Caliper, gamma ray, dual induction, normal resistivity (16- & 64-inch), spontaneous potential, acoustic (sonic) with variable density log (VDL). Static: fluid specific conductance, resistivity, and temperature. Dynamic: fluid specific conductance, resistivity, and temperature. Dynamic flowmeter with interpretation. Borehole video survey.	0-685 ft bls	After drilling deeper

Figure 5: The Geophysical Logging Equipment

Continued from page 36

Formation to the total depth of the boring.

Geophysical Logging

The geophysical logging program was designed to collect information on the hydrogeology of penetrated strata, to gather data on borehole geometry to assist in the setting and cementing of casing strings, to determine packer intervals, and to identify and evaluate potential ASR storage zones and confining strata. Logging activities were completed by Advanced Borehole Services (ABS) and were witnessed by CDM personnel. A summary of all borehole geophysical logs is provided in Table 1.

The caliper log provided information on caverns and fractures. From the caliper log, a cavern was identified at 415 feet bls. The acoustic log provided an insight into the hardness of the rock in the borehole.

The dual induction log provided information on the conductivity found in the borehole. The dual induction log results indicated an overall trend of increasing conductivity to a depth of 553 feet bls. Below 553 feet, the conductivity decreased because of the presence of hard dolostone.

The flowmeter logs showed significant flow from the cavern zone identified in the other geophysical logs, as well as delineating flow from 550 to 580 feet bls. The flowmeter log also indicated that little flow entered the well between 625 and 640 feet bls. The water quality logs indicated that the cavern produced freshwater and that the underlying strata produced mildly brackish water.

Thin Section Petrography

Thin sections were prepared from 21 samples of the exploratory well core and cuttings, at sample depths ranging from 453 to 685 ft bls. The objective of the thin section analyses was to obtain information on the lithology and composition of the main rock types encountered in the core. Of particular interest was the core mineralogy, texture, porosity (abundance and type), and apparent hydraulic conductivity.

The sampled interval included the ASR storage zone and adjoining confining strata. Samples included representatives of the main rock types observed in both the core and cuttings.

The thin sections were prepared by Burnham Petrographics Inc. The samples were impregnated with blue epoxy to highlight pore spaces. The thin section analyses were performed by CDM staff using a Zeiss Incident-Light Photomicroscope with a built-in camera.

The porosity of the samples was visually estimated. Limestones were categorized using the limestone classification scheme of Dunham (1962). The apparent hydraulic conductivity of samples was qualitatively evaluated by the pore size and abundance and by the degree to which pores appeared to be interconnected.

The examined samples included both limestones and dolostones. The examined limestone samples were from 546 ft bls and above. The dolostones were all formed by the replacement of limestone precursors, which were compositionally and texturally similar to the preserved limestones. The main rock types observed in the examined thin sections are described as follows:

- Laminated limestones are characterized by the presence of alternating laminae that vary mainly by the abundance of fossils. The laminations reflect variations in current energy during deposition. The limestones consist of peloid fossil mudstones to grainstones, using the Dunham (1962) classification system. A photomicrograph of laminated limestone from 453 ft bls is shown in Figure 6. The laminated limestones have low macroporosity (visible porosity) but have relatively high microporosity. Microporosity consists of micron-sized pore spaces, which are evident by the absorption of the blue epoxy in the thin sections. Microporous limestones may have high total porosities, as measured by core plug analyses and geophysical logs, but they typically have low permeabilities. Iron sulfide minerals (likely pyrite) are concentrated along some organic-rich laminae but are present overall in only trace quantities.
- A calcarenitic limestone is essentially cemented carbonate sand. A photomicrograph of a calcarenitic limestone from 546 ft bls is shown in Figure 7. The calcarenites are classified as peloid (intraclast) bioclast grainstones using the Dunham (1962) system. Calcarenites are deposited under relatively high current energy conditions, resulting in the winnowing out of carbonate mud matrix. In general, calcarenites have high porosities (and also hydraulic conductivities) at the time of deposition, but porosity may be greatly reduced by compaction and calcite cementation. The calcarenite samples from 474 and 546 ft bls, however, have minimal calcite cementation, thus retaining high porosities, and are likely have a high hydraulic conductivity.

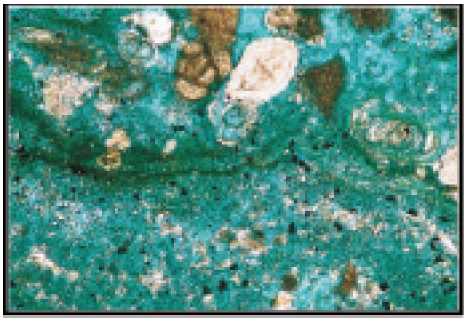

Figure 6: Thin-Section Photomicrograph (Laminated Limestone at 453 ft bls)

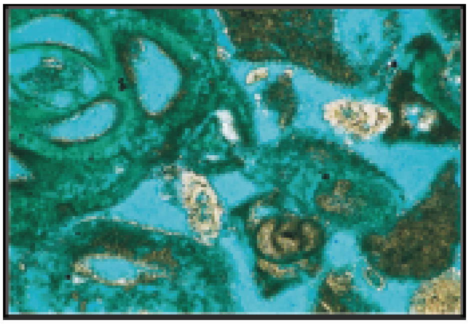

Figure 7: Thin-Section Photomicrograph (Calcarenitic limestone at 546 ft bls)

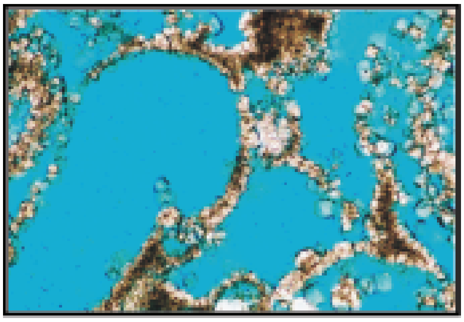

Figure 8: Thin-Section Photomicrograph (Moldic Dolostone at 600 ft bls)

- Dolostone with common to abundant moldic porosity is the most common rock type encountered in the exploratory well, particularly below 490 ft bls. The molds tend to have a rounded subequant, or less commonly elongate "shell" shape, and appear to have been formed by the dissolution of calcium carbonate grains, mostly fossils. The moldic dolostones appear to have been deposited as either calcarenites

Continued on page 40

Table 2: Summary of X-Ray Diffraction Analyses

Mineral Constituent	Sample (ft bls)				
	524 Limestone (mudstone-wackestone)	540 Dolostone (mimetic)	584 Dolostone (moldic)	593 Dolostone (moldic)	685 Dolostone (laminated)
	Relative abundance (%)				
Quartz	Trace	Trace	Not detected	Not detected	Trace
Calcite	99	1	1	1	1
Dolomite	Trace	99	99	99	99
Clay minerals	1	Not detected	Trace	Trace	1

Continued from page 38

(bioclast grainstone and packstones) or as carbonate mud-rich deposits. The crystal size of the dolomite crystals that constitute the matrix of the molds is highly variable between samples, ranging mostly from approximately 4 to 200 µm in diameter. A key variable in the moldic dolostone samples is the degree of interconnection of the moldic pores. Where the dolomite matrix between the dolomite crystals has a loose fabric, the sample likely has a very high hydraulic conductivity. Conversely, if the matrix between the molds is tight, the sample may have a low hydraulic conductivity, despite a relatively high porosity. Some moldic dolostone cuttings from 600 ft bls have extraordinarily high porosities, well in excess of 50 percent, as illustrated in Figure 8. The dolomitized calcarenite (bioclast grainstone) retains both high moldic and intergranular porosities. The 600 ft bls samples are likely have a high hydraulic conductivity. At the other extreme are the moldic dolostone samples in which the space between moldic pores consists of tightly packed, interlocking dolomite crystals in which there is virtually no effective porosity. These tight-matrix dolostone samples are a classic example of rock with a high total porosity but low effective porosity, and thus also with very low hydraulic conductivities. Impurities (inclusions), including minerals such as iron sulfide, tend to be encapsulated within the cores of dolomite crystals.

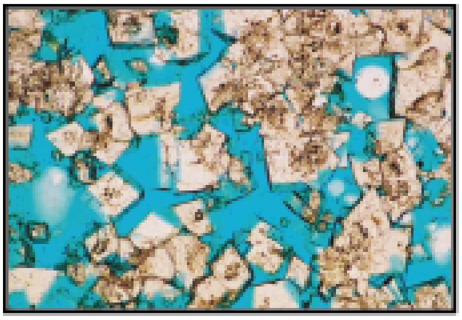

Figure 9: Thin-Section Photomicrograph (Sucrosic Dolostone at 588 ft bls)

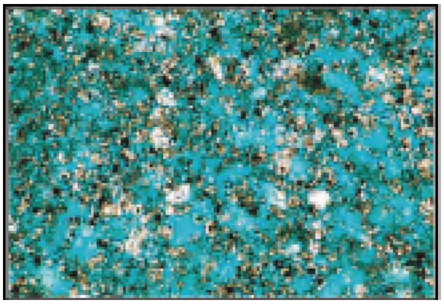

Figure 10: Thin-Section Photomicrograph (Laminated Dolostone at 685 ft bls)

- Sucrosic dolostones consists of loosely packed, rhombohedral dolomite crystals and with their resultant ‘sugary’ texture. An example of a sucrosic dolostone from 588 ft bls is illustrated in Figure 9. Sucrosic dolostones typically have high intercrystalline porosities, in addition to a variable moldic porosity. Sucrosic dolostones would be expected to have high hydraulic conductivities. There is a gradation between sucrosic dolostones with abundant intercrystalline porosities to tight moldic dolostones. For example, some cuttings from 610 ft bls consist of rhombohedral dolomite crystals that have partially coalesced into dense mosaics.
- Laminated dolostones are essentially laminated limestones that have been replaced by finely crystalline dolomite. A photomicrograph of a laminated dolostone from 685 ft bls is shown in Figure 10. The illustrated laminated dolostones consist mostly of dolomitized fossil mudstones to wackestones. The dolomitic matrix has a high microporosity, probably in excess of 25 percent. The hydraulic conductivity of laminated dolostones is likely low because of the fine pore size. Trace iron sulfide minerals (likely pyrite) are present and often become concentrated in what were organic-rich laminae or burrows.

X-Ray Diffraction Analyses

Another specific diagnostic tool used was X-ray diffraction (XRD) analyses. XRD analyses were performed on four bulk rock samples to confirm the mineralogical characterization made by thin section petrography. The samples analyzed were from 524, 540, 584, 593, and 685 ft bls, and the analyses were performed by Mineralogy Inc.

For each sample, a representative 1.5-gram sample split was milled to an approximate mean particle diameter of 30-40 micrometers using a high Cr-steel milling apparatus. Each sample was packed into an aluminum XRD sample holder. The bulk powder specimen was then analyzed with a Philips XRG-3100 automated x-ray diffraction unit (typical scan range 3-50 degrees 2-Theta, 0.02 degrees/second, 35kV, 30mA).

This procedure provided the raw digital data (scan intensity vs. degrees 2-Theta) used to graph the x-ray diffractogram for the solid. The resulting spectra were subsequently analyzed with the aid of Philips search/match (“TADD”) software and the J CPDS x-ray diffraction database. The results of the XRD analyses are summarized in Table 2.

The XRD results were fully consistent with the thin section petrography results. The dolostone samples were all composed almost entirely of dolomite. The minor amount of calcite detected occurred largely as inclusions within the center of dolomite crystals. The concentrations of iron sulfide minerals were below the XRD detection limit.

Core Sample Elemental Analyses

Whole-rock elemental analyses were performed on six core samples and one duplicate sample by Activation Laboratories under contract with the Florida Geological Survey (FGS). These analyses were performed using inductively coupled optical emission spectrometry (ICP-OES), trace element fusion inductively coupled plasma mass spectrome-

Table 3: Summary of Core Sample Elemental Analyses

Constituent	Sample (ft bls)						
	541-542	549-550	559.1-560	569-570	569-570 (Dupl.)	588-589	630-660
$CaCO_3$ (Wt %)	58.40	97.30	64.04	57.41	57.36	57.58	57.45
$MgCO_3$ (Wt %)	40.35	2.07	35.45	41.17	41.12	41.94	42.36
Fe_2O_3 (Wt %)	0.09	0.09	0.05	0.07	0.06	0.04	0.04
As (ppm)	2	<1	3	3	-	1	1
U (ppm)	2.43	1.77	3.08	3.40	3.33	2.36	2.92

Table 4: Summary of Reverse-Air Discharge Water Quality Data

Date	Sample depth (ft bls)	pH	Specific Conductance (µmhos/cm)	Chloride (mg/L)	Comments
Nominal 12-inch diameter borehole for 6.625-inch casing.					
08/31/04	215	8.09	343	34	
08/31/04	235	8.12	468	56	
08/31/04	255	8.18	406	45	
08/31/04	275	8.19	605	54	
09/01/04	295	8.11	430	53	
09/01/04	315	8.07	485	67	
09/01/04	335	8.10	543	83	
09/01/04	355	8.09	536	87	
09/01/04	375	8.10	542	95	
09/01/04	395	8.11	568	93	
09/01/04	415	8.10	398	53	
09/01/04	435	8.15	394	40	
09/01/04	455	8.06	406	54	
09/02/04	475	8.06	413	47	
09/02/04	495	8.07	422	48	
09/08/04	515	8.08	480	64	
09/08/04	535	8.08	472	52	
09/08/04	555	8.10	485	61	
09/09/04	575	8.11	522	78	
09/10/04	595	8.11	556	92	
09/10/04	598	8.11	558	86	Water sample collected after 1 hr of development.
9/22/04	615	8.33	707	123	
9/22/04	635	8.21	823	154	
9/22/04	655	8.19	1076	232	
9/22/04	675	8.18	1354	313	
9/22/04	685	8.18	1367	320	

try (ICP-MS), instrumental neutron activation analysis (INAA), and x-ray fluorescence spectrometry (XRF). Also, carbon and sulfur were analyzed using an automated LECO CS-344 analyzer with a solid-state detector. The analytical package included 47 elements, along with organic and total carbon. The results are summarized in Table 3.

The core sample average arsenic concentration of less than 2 parts per million (ppm) is less than the average value of 3 ppm for 36 carbonate samples from the Floridan Aquifer System in Southwest Florida. The sample levels are less than the global average of 2.5 ppm for limestones in general (Arthur et al., 2002).

The core sample average uranium concentration of 2.49 ppm is less than the average value of 5 ppm for 36 carbonate samples from the Floridan Aquifer System in Southwest Florida, but the sample uranium concentration is higher than the global average of 2 ppm for limestones in general (Arthur et al., 2002).

The core sample elemental analyses data does not suggest the Sanford storage zone rock has a high susceptibility to arsenic and uranium leaching, but the relationship between limestone and dolostone whole-rock trace element composition and metals leaching during ASR storage has not been fully determined.

Discharge Water Quality Data

Samples of the discharge water from the reverse-air circulation system were collected during the drilling of the nominal 12-inch diameter borehole, for the 6.625-inch diameter casing to 530 ft bls and for the reaming of the core hole to total depth. Water samples were analyzed in the field for pH, specific conductance, and chloride concentration.

In general, the reverse-air discharge water can provide some semi-quantitative insights into changes in aquifer water quality with depth. The limitation of the reverse-air discharge data is that the analyzed samples are a mixture of water produced from the entire open bore, rather than from discrete interval samples.

The value of the reverse-air discharge data is further compromised in the Sanford Auxiliary WTP ASR exploratory well because of the presence of the open core hole, which was a conduit for the upward migration of the deeper, more saline waters during reaming operations. Subsequently, the reverse-air discharge water quality testing was not qualified as a significant data source for the Sanford Auxiliary WTP ASR exploratory well.

Packer tests were run to provide superior depth-specific water quality data. Regardless, the data were still useful to demonstrate that increases in discharge water salinity usually correlated with increases in native groundwater salinity. The reverse-air data from the Sanford Auxiliary WTP ASR exploratory well are compiled in Table 4.

The increase in specific conductance and chloride concentrations between the 215 and 685 ft bls samples reflect the fact that the water quality in the reamed hole was being impacted by the open core hole. Salinity changes with depth are most evident below 598 ft bls. The change shows a moderate increase between the 615 and 685 ft bls, which approximately correlates with the decrease in formation resistivity recorded on the geophysical logs. The reverse-air discharge data suggests the chloride concentration in the lower part of the Upper Floridan Aquifer is in the 150 to 300 mg/L range.

Packer Testing

A total of eight packer tests were performed on the reamed hole in order to obtain site-specific information on water quality and aquifer hydraulics. Five of the tests consisted of single packer tests, while three of the tests were performed using a dual straddle packer assembly with a 25-foot spacing between elements.

A submersible pump with a capacity of

Continued on page 42

Table 5: Summary of Packer Test Results

No.	Depth (ft bls)	Pumping rate (gpm)	Drawdown (feet)	Estimated average hydraulic conductivity (ft/day)	Chloride (mg/L)	Specific Conductance (µmhos/cm)
1	550 – 598	87	6.3	76.9	248	1,113
2	500 – 598	84.5	6.3	36.6	249	1,100
3	658 – 685	81	8.3	97	530	2,050
4	618 – 685	81	8.1	39.9	430	1,853
5	530 – 685	81	8.1	17.3	407	1,750
6	635 – 660	81	9.5	90.9	451	1,865
7	590 - 615	82	9.8	89.8	330	1,328
8	530 - 555	20	17.7	11.8	294	1,278

Table 6: Summary of Step-Drawdown Test Results

Step	Pumping rate (gpm)	Drawdown (feet)	Specific Capacity (gpm/ft)	Estimated Transmissivity (gpd/ft)
1	100	1.9	52.6	105,200
2	205	6.4	32.0	64,063
3	425	28.4	14.9	29,800

Continued from page 41

100 gpm was installed in the 4½-inch inner diameter drill pipe. Water levels were measured within the drill pipe and annulus between the drill pipe and well casing using pressure transducers and a Hermit™ datalogger. The test intervals were chosen in areas where, based on borehole video examination, the borehole was near circular, of uniform diameter, relatively smooth (compared to nearby boreholes), and where proper packer seating could be expected.

The tests consisted of a three-hour pumping period and a recovery period until the water returned to static level. In general, water quality (field parameters) stabilized very quickly during development and test pumping. At the end of each packer test, a water sample was collected and transported by PC&B Laboratories for analysis for chloride, total dissolved solids (TDS), sulfate, and sodium. The results of the straddle packer tests are summarized in Table 5.

Several of the tests had drawdowns of six to nine feet at a pumping rate of approximately 80 gpm. A large part of the measured drawdown was likely due to the head loss within the drill pipe and screen within the straddle packer. The head loss from the friction within the drill pipe alone would be on the order of five to seven feet. The relatively low measured drawdowns may have been due to either the tested interval having a high transmissivity or to leakage around the packer.

The tested intervals consisted predominantly of dolostone, which typically has a rough, often fractured, borehole wall because of its tendency to deform in a brittle manner. The borehole roughness may have allowed some leakage around packers to occur, even though the packer was properly set. Alternatively, flow may have bypassed packer elements through fractures.

All the tests appeared to have had a good packer seal, especially Packer Test No. 8 (530 – 555 ft bls), as evidenced by the 17.7 feet of drawdown at a lower pumping rate of 20 gpm.

The time-drawdown plots of the recovery data for each test were completed. The recovery data for most tests showed an oscillation in water level with peaks above static water level. The oscillatory recovery pattern is indicative of a strong casing effect in the data, which precludes standard interpretation of the data.

The average hydraulic conductivity of the packer test intervals (included in Table 5) were estimated by multiplying the specific capacity by 2,000 to obtain an estimated transmissivity (Driscoll, 1986, Appendix 16.D.), and then dividing the transmissivity by the thickness of the tested interval.

Core Sample Hydraulic Analyses

A total of 25 core samples were chosen for the analysis of porosity and hydraulic conductivity (both vertical and horizontal). The analyses were performed by the FGS. Porosity was calculated from measured sample volume and weight using a sample density estimated from mineralogy. Hydraulic conductivity measurements were performed using a falling head permeameter.

The average horizontal hydraulic conductivity was 4.50×10^{-2} ft/day, and the maximum measured value was 3.34×10^{-1} ft/day. The core plug horizontal hydraulic conductivities were two or more orders of magnitude less than the average hydraulic conductivity values estimated from the packer test data. The difference between the hydraulic conductivities from the core plug and packer test data indicates that much of the proposed ASR storage zone strata is unproductive. Flow is likely focused in relatively infrequent, highly conductive beds and may possibly also be from fractures.

Aquifer Pumping Test

The pumping test selected for the Sanford Auxiliary WTP ASR exploratory well was a step-drawdown test performed on the completed well. The objectives of the test were (1) to evaluate potential ASR well yields, (2) to obtain an estimated transmissivity for the ASR storage zone, and (3) to obtain aquifer water quality data on the ASR storage zone.

The test was performed on October 15, 2004, and consisted of three steps, each lasting two hours, at pumping rates of 100, 205, and 425 gpm. The results are presented in Table 6. Transmissivity was estimated as 2,000 times specific capacity (Driscoll, 1986, Appendix 16.D.).

As indicated in Table 6, the transmissivity of the Upper Floridan Aquifer ranges from 29,000 to 105,200 gallons per day per foot (gpd/ft). From the SJRWMD's MODLOW model of East-Central Florida (McGurk and Presley, 2002), the transmissivity of the lower zone of the Upper Floridan Aquifer in the vicinity of the auxiliary plant ranges from 120,000 gpd/ft to 800,000 gpd/ft. The transmissivity values from the step-drawdown test are lower than the regional values.

The test results indicate that the proposed ASR storage zone (530 to 628 ft bls) is adequately productive for an ASR system with a capacity of 1 MGD. The drawdown at a 1 MGD pumping rate would be 47 feet using the Step 3 specific capacity of 14.9 gpm/ft.

Laboratory Evaluations

At the end of the step-drawdown test, water samples were collected from the ASR exploratory well to be analyzed for primary and secondary drinking water standards, major and minor cations and anions, and field parameters. A sample of potable water from the Sanford utilities system was collected the day of the step-drawdown test for analysis for the same suite of parameters. The samples were transported to PC&B Environmental Laboratories Inc. for analysis.

The storage zone water samples had chloride, sodium, and TDS concentrations of 280 mg/L, 105 mg/L, and 690 mg/L, respectively. Color, chlorides, and TDS were detected in the storage zone sample at concentrations above their secondary drinking water standards.

Trace Metal Analysis

Iron was detected above the secondary drinking water standard of 300 µg/L (490 µg/L). No other metals were detected above either the primary or secondary drinking water standards in the storage zone sample. No metals were detected above either the primary or secondary drinking water standards in the potable water sample.

Florida Geological Survey Leachability Analysis

The FGS was subcontracted to perform bench-scale experiments to evaluate the leachability of core samples from the proposed ASR storage zone for arsenic and uranium. The methods and results of leachability experiments are documented in the FGS report entitled *Bench-Scale Geochemical Assessment of Water-Rock Interaction Sanford Aquifer Storage and Recovery Facility.* The experiments were performed on six rock (core cuttings) samples, whose whole-composition was first determined, as reported above.

A new bench-scale leaching procedure was implemented that used nitrogen gas to lower the dissolved oxygen concentration in order to simulate anoxic conditions. For each experiment, 300 grams of sample were placed in a reaction vessel with 1,000 mL of either source or deionized water.

Some leaching experiments utilize only enough core to yield detectable metals in solution. In this experiment, however, a very high ratio of core chip to water was used in an attempt to approximate aquifer porosity conditions.

The experiments were run for five days under low oxygen conditions, followed by 41 days under high dissolved oxygen conditions, followed by a return to low dissolved oxygen conditions. Periodically, 20-mL samples from the reaction vessel solution were collected and analyzed for 67 elements by Activation Laboratories using ICP-MS and ICP-OES. The solution was also monitored for physical parameters (dissolved oxygen, temperature, pH, and conductivity).

The results of leachability testing show a relatively rapid increase in arsenic concentrations for the first five days of the experiments, followed by a much slower increase over time. Dissolved oxygen concentrations did not appear to have a significant affect on arsenic leachability. Reported arsenic concentrations at the end of the experiments ranged from 1.35 μg/L to 34.90 μg/L, with a mean of 14.35 μg/L. The laboratory arsenic concentrations exceed the new MCL of 10 μg/L. All measured uranium concentrations were less than 4.5 μg/L and were well below the new USEPA MCL of 30 μg/L.

It must be emphasized that the leaching experiments were performed under conservative laboratory conditions. The arsenic concentrations measured under the low and high dissolved oxygen experimental conditions were not representative of the concentrations that might occur in the actual ASR storage zone. A lower oxidation-reduction potential (ORP) and reduced fluid flow and mixing (much higher water-rock ratio) would be expected to result in lower arsenic concentrations in ASR and monitor well samples. The data do not indicate that stored water will exceed the 10 _g/L arsenic MCL.

Table 7: Fluid-Mixing Modeling Results

	Solutions (% storage zone and source waters)				
Storage Zone	100	0	90	50	10
Source	0	100	10	50	90
Mineral	**Saturation Index (SI)**				
Calcite	0.35	-0.49	0.24	-0.14	-0.42
Aragonite	0.21	-0.64	0.09	-0.28	-0.57
Dolomite	0.56	-1.41	0.32	-0.49	-1.21
Gypsum	-1.79	-2.87	-1.84	-2.09	-2.60
Anhydrite	-2.01	-3.10	-2.06	-2.32	-2.82
Celestite	-1.69	-3.30	-1.75	-2.10	-2.86
Strontianite	-0.80	-2.17	-0.93	-1.40	-1.94
Rhodochrosite	-1.26	-2.06	-1.36	-1.71	-1.99
Barite	-0.49	-1.62	-0.54	-0.80	-1.33
Quartz	-0.14	-2.38	-0.18	-0.43	-1.10
$Fe(OH)_3$	-1.01	-0.22	-0.81	-0.44	-0.26
Goethite	4.88	5.67	5.08	5.46	5.63
Hematite	11.74	13.26	12.14	12.87	13.20
Manganite	-10.22	-8.53	-9.99	-9.47	-8.91
Pyrolusite	-19.75	-15.03	-6.85	-17.44	-7.99
Pyrite	-34.06	-79.34	-40.10	-56.42	-71.76

Recharge Water Quality & Fluid Mixing Analysis

The potential for mineral dissolution and precipitation as the result of recharge of potable water into the lower portion of the Upper Floridan Aquifer storage zone was evaluated using PHREEQC, a computer program developed by the U.S. Geological Survey for speciation, reaction-path, advective transport, and inverse geochemical calculations (Parkhurst, 1995). The AquaChem software package, developed by Waterloo Hydrogeologic, was used for pre-processing the water chemistry data.

The saturation state of the end-member solutions (potable water and native storage zone water) with respect to mineral phases of concern are summarized in Table 7. Saturation state is expressed as the saturation index (SI), defined as:

$$SI = Log (IAP/K_{sp})$$

Where: IAP is the ion activity production of the solution and K_{sp} = the solubility product of a mineral. Solutions undersaturated with respect to a mineral have an SI of less than 0. Supersaturated solutions have an SI of greater than 0. The saturation indices of mixed solutions with 10 percent, 50 percent, and 90 percent source water are also summarized in Table 7.

A key point concerning calculation of mineral saturation states is that values for carbonate minerals depend on formation water pH and on pE (or Eh) for iron minerals. Obtaining accurate values for the latter, in particular, is notoriously difficult. Caution must be exercised in the quantitative interpretation of the data.

The modeling results indicated that the native storage zone water is close to saturation with respect to calcite, which would be expected in a carbonate aquifer. Typically, pore waters in carbonate aquifers equilibrate with the most soluble carbonate mineral present.

The recharge (potable) water is undersaturated with respect to calcite and dolomite, so the introduction of potable water into the storage zone may result in some dissolution of the aquifer rock, which may increase the hardness of the recovered water. The dissolution of carbonate minerals may also have a beneficial effect by increasing the permeability of the aquifer rock.

The storage zone native water has a relatively high ORP (oxidation reduction potential) for a confined aquifer of -276 mV, which is equivalent to an Eh of approximately -76 mV. The measured DO concentration was 0.12 mg/L. The PHREEQC calculations indicate that the storage zone water is supersaturated with respect to some iron oxide and hydroxide minerals and is greatly undersaturated with respect to iron sulfide minerals. The presence of iron sulfide minerals in the aquifer and dissolved sulfide (0.28 mg/L) in the water sample suggest that the native formation water is more reducing than indicated by the field ORP and DO readings.

The potable recharge water is undersaturated with respect to all the evaluated minerals except for some iron oxides and hydroxides.

The introduction of potable water with a high Pe/Eh would cause the precipitation of dissolved (ferrous) iron in the storage zone water. Iron would likely precipitate as an iron hydroxide, which precipitates more readily than the less-soluble iron oxide minerals. Inasmuch as the dissolved iron concentration of the storage zone water is low (0.49 mg/L), iron hydroxide precipitation would be volumetrically minor.

The introduction of oxygenated water into the storage zone aquifer may also result in the oxidation of iron sulfide minerals exposed at pore surfaces. In much of the dolostones in the storage zone, impurities such as iron sulfide minerals are encapsulated within the center of the dolomite crystals and will therefore be largely isolated from oxygen-poor waters.

Continued on page 44

Continued from page 43

The results of the geochemical modeling indicate no evidence of likely adverse fluid-rock interactions that could result from the introduction of potable water into the proposed ASR storage zone, other than the potential for the oxidation of trace iron minerals. Oxidation of iron sulfide minerals is believed to be the source of arsenic enrichment in stored water, but it must be emphasized that fluid-mixing and fluid-rock interaction modeling give insights only into what reactions are thermodynamically favorable to occur. They do not indicate the degree to which reactions will occur within any given time frame.

Whether or not arsenic leaching will be a significant process in an ASR system depends upon several factors: the concentration of iron sulfide minerals, their location within the aquifer rock, the concentration of arsenic in the minerals, and the kinetics of the alteration reaction, in addition to water chemistry.

What Tools Were Found to Be Most Valuable

While the use of ASR for seasonal demand management is becoming more common, several factors—including technical feasibility, cost, an available water source, and permittability—determine whether ASR is practical for a given location or application. Even when ASR is determined to be practical, one of the primary reasons for failure of ASR projects is improper selection of the storage zone, which results in poor recovery efficiency. The city of Sanford's ASR project is considered a success because of the presence of a good target storage zone. Several tools were used to aid in the storage zone selection for this project.

The tools we found to be the most valuable were the continuous wireline coring, the geophysical/video logging, packer testing, and the FGS leachability study. The wireline coring allowed us to collect rock samples from the lower part of the Upper Floridan Aquifer. The core samples provided the opportunity to visually observe continuous stratigraphy, observing general rock types, physical characteristics, depositional environment, and digenesis. These observations provided the basis for further evaluations.

Once the cores were collected, CDM performed geochemical analysis of the rock from selected representative core samples of the general rock types. Cores were tested for permeability and porosity. Also, the FGS performed a leachability study to evaluate the potential for arsenic and uranium leaching from the rock matrix to the stored and recovered water.

The use of these specialized tools to evaluate the nature of the subsurface was invaluable in determining the feasibility and anticipated reactivity of the proposed storage area.

The geophysical logging provided needed data on changes in lithology, downhole water quality, fractures and potential flow zones, and confinement above and below the proposed storage zone. A major void was identified at a depth of 415 feet bls, which is now located above the target storage zone.

Also, the flowmeter log indicated that little flow entered the well between 625 and 640 feet bls, which is just below our target storage zone. The video log provided a continuous picture of the subsurface conditions along the borehole. This tool also exposed the physical conditions (porosity) in the subsurface and clarified many issues and concerns.

Single and double packer testing provided conformation of flow zones determined from the geophysical logs. CDM was able to determine that the very large void at 415 feet bls was not connected in terms of flow to the lower formations. Also, packer testing was used to estimate the yield of the target storage zone.

Altogether, the data collected from these tools, performed sequentially, were invaluable in selecting a storage zone for the Sanford ASR project.

The design and permitting of the one-well pilot ASR system has been completed. Construction of the system began in January 2007. As of August, the ASR well and associated monitoring wells were installed at the site. The testing completed on the ASR well mirrored the results obtained from the exploratory well. Construction of the surface facilities and associated piping is anticipated to be complete in early 2008, with cycle testing to follow.

References

- Arthur, J.D., Dabous, A.A. and C. Fischler, 2006. Bench-Scale Geochemical Assessment of Water-Rock Interactions: City of Sanford Aquifer Storage and Recovery Facility. Prepared by the Florida Geological Survey for CDM and the St. Johns River Water Management District.
- Arthur, J.D., Dabous, A.A., and Cowart, J.B., 2002. Mobilization of Arsenic and other Trace Elements During Aquifer Storage and Recovery, Southwest Florida, in, Aiken, G.R., and Kuniansky, E.L., eds., U.S. Geological Survey Artificial Recharge Workshop Proceedings, Sacramento, California: Geological Survey Open-File Report 02-89, p. 47-50.
- CDM, 2005. Exploratory Well Project Report for the City of Sanford Florida. Prepared for the St. Johns River Water Management District.
- CDM, 2003. City of Sanford Desktop Assessment of Aquifer Storage and Recovery. Prepared for the St. Johns River Water Management District.
- CH2M Hill, 1997a. Water Supply Needs and Sources Assessment Alternative Water Supply Strategies Investigation, a Tool for Assessing the Feasibility of Aquifer Storage and Recovery: St. Johns River Water Management District Special Publication SJ97-SP4, 143 pp.
- Driscoll, F.G., 1986, Groundwater and Wells: Johnson Filtrations Systems, 1089 pp.
- Dunham, R.J., 1962. Classification of Carbonate Rocks According to Depositional Texture, in Ham, W.E. (eds.) Classification of Carbonate Rocks: American Association of Petroleum Geologists Memoir 1, p. 108-121.
- McGurk, P.G., Brian and Paula Fischl Presley, P.G., 2002. Simulation of the Effects of Groundwater Withdrawals on the Floridan Aquifer System in East-Central Florida: Model Expansion and Revision. St. Johns River Water Management District Technical Publication SJ2002-3, 196 pp.
- Parkhurst, D.L., 1995, User's Guide to PHREEQC – A Computer Program for Speciation, Reaction-Path, Advective Transport, and Inverse Geochemical Calculations: U.S. Geological Survey, Water-Resources Investigations Report 95-4227, 143 pp.