JOURNAL OF ENVIRONMENTAL HYDROLOGY

The Electronic Journal of the International Association for Environmental Hydrology
On the World Wide Web at http://www.hydroweb.com

VOLUME 14 2006

OPERATIONAL CONSIDERATIONS AND RECOMMENDATIONS FOR THE EVERGLADES RESTORATION ASR SCHEME

Christopher J. Brown | U.S. Army Corps of Engineers, Geotechnical Branch, Jacksonville, Florida USA

The purpose of this paper is to evaluate three different water resources operational scenarios for the Comprehensive Everglades Restoration Project (CERP) Aquifer, Storage and Recovery (ASR) scheme. The ASR scheme for the CERP proposes to utilize 333 wells to store up to 6,300,000 cubic meters of freshwater per day into a brackish water carbonate aquifer located in southern Florida, USA. The three different schemes analyzed represent a range of realistic operational plans that could be utilized for the restoration project. The various ASR operational schemes were developed based upon existing research and new numerical modeling efforts. The numerical model developed is capable of simulating the mixing of freshwater and ambient groundwater within the Floridan Aquifer System. The modeling effort determined that each of the three operational schemes tested could represent the optimal plan depending upon the site-specific geology and hydrodynamics. Therefore, care must be taken in matching the best operational scheme to the given geological environment. In addition, the modeling effort demonstrated that the long-term cumulative recovery efficiency assumed for the CERP ASR plan should be feasible and obtainable.

INTRODUCTION

The Everglades Ecosystem, located in southern Florida, is a myriad of wetlands, tidal marshes, cypress domes, estuaries and coral reefs. The Everglades is like no other ecosystem in the world. It is a broad, flat expanse of wetlands inhabited by a plethora of plants and animals. Dubbed the "River of Grass" by Marjorie Stoneman Douglas, the Everglades is in trouble (Douglas, 1947). Water quantity, water quality, water distribution and timing of water deliveries have all been disrupted over time and have all been radically changed over the last 100 years (Davis, 1994).

The Central and Southern Florida Project Comprehensive Review Study (USACE and SFWMD, 1999), developed jointly by the U.S. Army Corps of Engineers (USACE) and the South Florida Water Management District (SFWMD), presents a framework for Everglades restoration. Now known as the Comprehensive Everglades Restoration Project (CERP), this plan contains 68 components, including structural and operational changes to the Central and Southern Florida (C&SF) Project. The overarching 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. It has been theorized that improvements to native flora and fauna, including threatened and endangered species, will occur as a result of the restoration of the hydrologic conditions. One of the technologies being evaluated in support of CERP is the use of Aquifer, Storage and Recovery (ASR) wells. The use of ASR is increasing in the United States and abroad. The CERP relies heavily upon ASR technology to provide additional system storage. Six ASR components currently form the proposed CERP ASR System, which includes a total of 333 ASR wells and related surface facilities in the vicinity of Lake Okeechobee, Florida as well as within Palm Beach County, Florida. All 333 proposed ASR wells have a target capacity of 19,000 cubic meters per day. The scale of the proposed CERP ASR program is unprecedented; therefore, a series of pilot projects and a regional feasibility study are being completed to determine the ultimate potential of the plan. Additional information on these proposed projects is presented in the Final Pilot Project Design Report (USACE and SFWMD, 2004). Figure 1 depicts the proposed location of the 333 ASR wells in south Florida.

ASR FUNDAMENTALS

Recharge to groundwater aquifers is ultimately derived from rainfall that falls on the land. Much of the rainfall that occurs on the land runs off to nearby surface water bodies, evaporates, or is abstracted for various water supply uses. Only a fraction of the total rainfall reaches subsurface aquifers via percolation into the ground. Recharge to a surficial water-table (unconfined) aquifer is generally higher than comparable recharge amounts to deeper, confined, aquifers due to proximity to the land surface. According to the American Society of Civil Engineers (ASCE), recharge is

"the replenishment of ground water by downward infiltration of water from rainfall, streams, surface depressions, and other sources, or by introduction of water directly into an aquifer through wells, galleries, or other means. Recharge can be either natural or artificial." (ASCE, 2001, p. 3)

Modern artificial recharge (AR) is the process of augmenting natural recharge of groundwater aquifers. According to the National Research Council (NRC), AR is:

"a process by which excess surface water is directed into the ground – either by spreading on the surface, by using recharge wells, or by altering natural conditions to increase infiltration – to replenish an aquifer. "(NRC, 1994, p. 1)

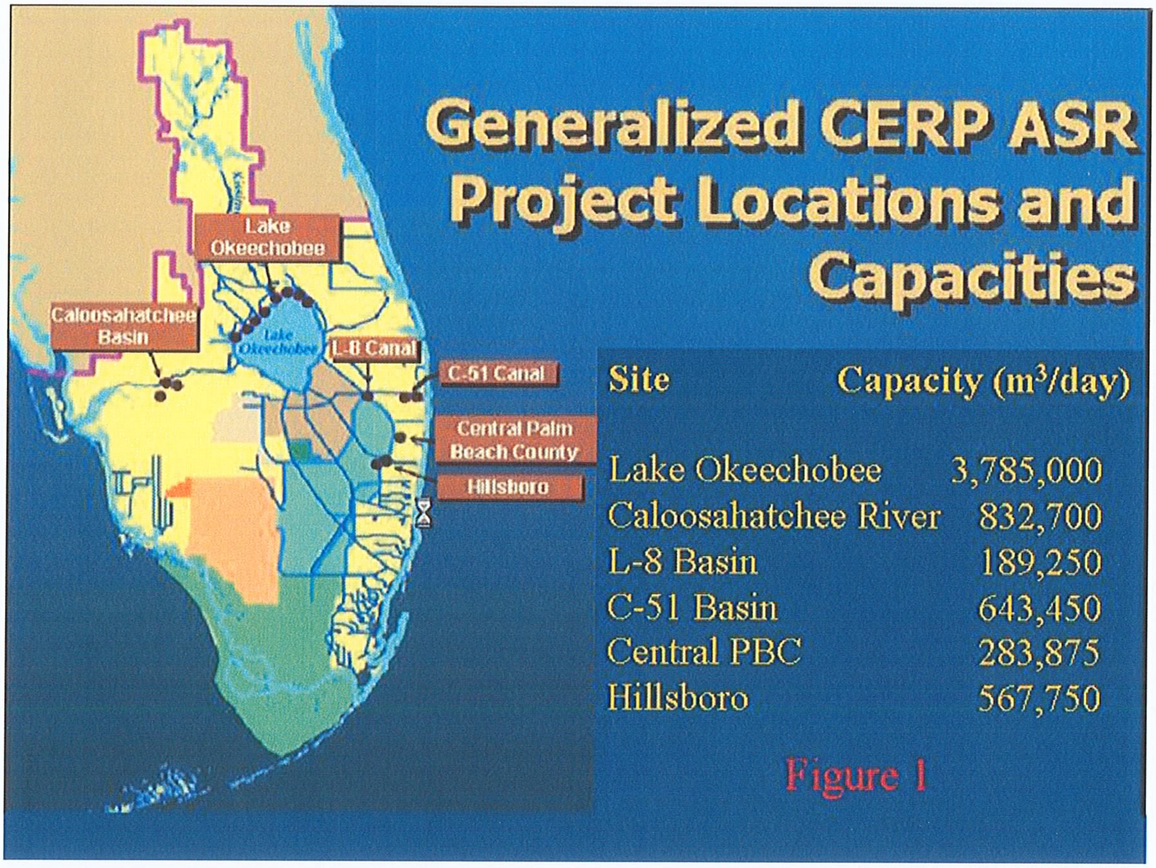

Figure 1. Proposed location of CERP ASR Wells

AR provides a means to store water underground in times of water surplus to meet demand in times of shortage. Water recovered from AR projects can be utilized for a variety of potable and non-potable uses. AR can also be used to control seawater intrusion in coastal aquifers, control land subsidence caused by declining ground water levels, maintain base flow in some streams, and raise water levels to reduce the cost of groundwater pumping (NRC, 1994).

Recharge can be introduced through various surface infiltration methods or through wells. Recharge can be introduced into the saturated or unsaturated portions of an aquifer. Both unconfined and confined aquifers have been used for AR (ASCE, 2001). Surface spreading methods are mainly amenable in unconfined aquifers (Asano, 1985), while wells are utilized to recharge confined aquifers (NRC, 1994).

ASR is a simple concept in which water is stored in subsurface permeable aquifers when water is plentiful and extracted during times of peak demand. According to the British Geological Survey (Jones et al. 1999, p. 3), ASR is a sub-set of AR 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."

ASR projects are utilized in three broad areas to augment water supplies. The largest and most common use of ASR projects is in support of potable water supply projects. The second most common use of ASR projects is in support of agriculture in the form of irrigation water supply. The newest alternative use for ASR is in support of environmental water supply to support in-stream uses, as is the case with the CERP. Each of these categories presents great opportunities to exploit ASR technology, however, each option is subject to many constraints. The primary constraints can be grouped into four general categories including:

- Regulatory
- Recharge and recovered water quality
- Water availability and demand
- Availability of a suitable storage aquifer

Regulatory thresholds usually dictate limitations on the use of the source water and the recovered water based upon its quality. In addition to the required regulatory thresholds, the end use of the water is of particular importance. Although water may meet all regulatory requirements, recovered water use may be constrained by one or more constituents contained within the water. For instance, recovered water containing moderate amounts of sodium or boron may preclude the use of the water for irrigating certain crops (Rhoades et al. 1992). Environmental use of the water could be questionable where recovered water contains low concentrations of heavy metals such as selenium or copper. Potable use may be constrained in cases where disinfection by-products form in-situ due to the presence of residual chlorine in the source water.

Operational schemes used by most ASR practitioners worldwide include storage of excess water during times of abundance and recovery of stored water during periods of water shortage or during peak demand times. For ASR projects that support potable water supply and irrigation, annual recharge, storage, and recovery cycles are common. For ASR projects that support environmental restoration projects, the recharge, storage, and recovery cycle can be quite variable. For some larger projects, the availability of source water and environmental demand can be sporadic with storage durations over several years possible. For smaller restoration projects, an annual cycle may be appropriate. The CERP requirements represent a hybridized system with both annual and semi-annual availability and demand cycles. CERP ASR wells located along the lower east coast of Florida (e.g., in Palm Beach County) will need to recharge, store, and recover water within the same given year, similar to standard potable projects in their operational scheme. CERP ASR wells located along Lake Okeechobee will need to recharge, store, and recover water over longer periods of time. For instance, previous modeling simulations of the restored Everglades ecosystem (USACE and SFWMD, 1999) revealed that the Lake Okeechobee ASR wells may recharge, store, or recover for periods longer than one year in several instances. In addition, these wells would store vastly more freshwater than comparable ASR wells proposed for Palm Beach County, Florida.

ASR PERFORMANCE FACTORS IN BRACKISH WATER AQUIFERS

The performance of an ASR system is controlled by a complex interaction among many variables. It has been explored through examination of existing site data, development of physical models, through development of simple analytical models, and through development of numerical models. ASR performance factors can be sub-divided into several categories. First, many ASR performance factors are dependent upon the intrinsic physical properties of the aquifer storage zone selected including hydraulic conductivity, porosity, thickness, heterogeneity, strength of aquifer materials, character of aquifer zone, dispersivity, and tortuosity. Another category of ASR performance factors is linked to boundary conditions present at the well site including pre-existing aquifer gradient and density of water in the storage zone. A third category of ASR performance factors is dependent upon site operational considerations including injection rate and volume, quality of the source water, type of source water pre-treatment, storage duration, and well design.

The character and structure of an aquifer may lead to heterogeneity of the intrinsic properties. Many aquifers are not true "ideal" porous media and are subject to nonidealities (Alpay, 1972). Examples of nonidealities given by Alpay include pore size distribution, non-uniform permeability, geologic stratification, and geologic structure (e.g., faults, dip). Brown et al. (2004) discuss pressure induced changes of non-ideal confining units as a result of ASR pumping.

These various factors can also lead to complicated diffusion pathways or enhanced mechanical dispersion (Domenico and Schwartz, 1998). Mechanical dispersion is mixing caused by local variations in velocity. Mechanical dispersion is an "advective" process and is discussed by Anderson (1984) and Sudicky (1986). At field scale, it appears that dispersivities increase with scale up to an asymptotic limit (Gelhar et al. 1992). At any given scale, dispersivities in the longitudinal direction (primary flow direction) can range over two to three orders of magnitude depending on the variability in hydraulic conductivity (Gelhar et al. 1992). Schulze-Makuch (2005) updated Gelhar's work by compiling a larger dispersivity database from various reports and literature. Schulze-Makuch also proposed a relationship between the geologic medium and hydrodynamic dispersion.

Performance at ASR sites is often expressed as a percentage of the water injected versus what is recovered. The most common performance metric for these sites is "recovery efficiency," a concept first presented in the 1970s (Kimbler et al. 1975) and refined in the 1990s (Pyne, 1995). ASR practitioners have utilized the term "recovery efficiency" as the metric of choice to evaluate the feasibility and cost effectiveness of prospective ASR projects. The definition of recovery efficiency utilized by most researchers is the total volume of water recovered (*Vr*) up until the applicable regulatory limit, expressed as a percentage of the volume injected (*Vi*), in a given operational cycle. Equation (1) provides a mathematical representation of this concept:

$$\text{Recovery Efficiency } (RE) = Vr/Vi \times 100\% \qquad (1)$$

For instance, an ASR project that injects 1,000,000 cubic meters of water and then subsequently recovers only 100,000 cubic meters before regulatory discharge limits have been exceeded has a RE of 10%. In most instances, chloride or total dissolved solids (TDS) is the limiting parameter in potable ASR projects. The cumulative recovery efficiency (*CRE*) is a useful metric in evaluating long-term ASR site performance since it tracks the cumulative water volume recovered (*CVr*) versus the cumulative volume injected (*CVi*). The cumulative recovery efficiency as developed by Kimbler et al. (1975) is defined in Equation (2):

$$\text{Cumulative RE } (CRE) = CVr/CVi \times 100\% \qquad (2)$$

In the case of the CERP ASR sites, freshwater derived from excess storm water will be injected into aquifers with brackish groundwater. According to Drever (1997), brackish waters have a TDS of between 1,000 to 20,000 mg/l. During aquifer recharge operations, the injected freshwater mixes with the poorer-quality ambient groundwater. Mixing is due to advection, hydrodynamic dispersion, and buoyancy (density) stratification. During recovery periods, the recovered water is a mix of the injected and ambient water. Typically, the recovery of the water is halted once the water quality surpasses a regulated value. The effect of the various performance factors on RE or CRE has been discussed by Brown (2005). Brown (2005) concluded that the most important ASR performance factors affecting RE or CRE were:

- Hydrodynamic dispersion (as measured by aquifer dispersivity)
- Recharge volume and resulting bubble size
- Recharge water quality
- Ambient water quality
- Density differential between recharge and ambient water

The five key performance variables are listed in order of importance with the last one being least important in cases of slightly brackish aquifer storage zones. Brown (2005) determined that the overall density differential has a less substantial effect upon RE or CRE in brackish water aquifers with ambient TDS of less than 5,000 mg/l and in cases where storage durations were minimized to less than 90 days. In addition, in anisotropic aquifers where the horizontal hydraulic conductivity is much greater than the vertical hydraulic conductivity, density stratification is minimized further (Missimer et al. 2002). Since all proposed CERP aquifer storage zones can be characterized as highly anisotropic and only contain slightly brackish groundwater (less than 4,000 mg/l TDS), density differentials will only be of minor importance to the overall recovery of the stored freshwater. Density differentials will be more important in cases where storage of freshwater is anticipated to be longer than one year. For this paper, density differentials were neglected and numerical model simulations conducted assumed a constant density in the aquifer storage zone. To ensure validity of this assumption during modeling, storage durations were all kept to zero and the aquifer was assumed to have an isotropy ratio of 0.10.

HYDROGEOLOGIC CONCEPTUAL MODELS

The hydrogeology in most of South Florida consists of a layer cake of aquifers and confining units. The three primary aquifers in the study area include the Surficial Aquifer System (SAS) ranging from 30 to 100 meters 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 500 meters. 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 50 and 300 meters below land surface in the study area and is usually synonymous with the Hawthorn Group. The FAS can generally be subdivided into several permeable zones, separated by low-permeability limestones. It is composed of sandstone, sandy limestone, 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 permeable zone", and «Lower Floridan Aquifer" (Miller, 1997). The CERP ASR project proposes to utilize the permeable units within the FAS as storage zones for excess freshwater from Lake Okeechobee and other surface water bodies located in the study area.

Due to the large regional nature of the CERP, the hydrogeology across the study area may vary considerably. It is likely that the geologic character of the proposed CERP ASR storage zones will vary from sandy limestone or sandstone characterized by low to moderate hydrodynamic dispersion and mixing to karst limestone or dolostone zones characterized by conduit flow with high hydrodynamic dispersion and major mixing. Obviously, the geologic character probably frames a continuum from a sandier, low dispersion storage zone to a cavernous, high dispersion storage zone. Within this geologic character continuum, ASR performance will be governed by the four primary performance factors listed above. Depending upon the overall geologic character encountered, different ASR operational models may be warranted. In this paper, numerical model simulations were completed to evaluate three different operational scenarios versus three different geologic conceptual models that may be encountered in the CERP study area.

MODEL SIMULATIONS

A number of investigators have undertaken modeling of ASR systems in order to explore assorted controls on system performance. Khanal (1980), Merritt (1986), Huntley and Bottcher (1997), Wright and Barker (2001), Missimer et al. (2002), and Pavelic et al. (2002), have all developed models of brackish-water ASR projects. Khanal and Pavelic et al. utilized conventional two-dimensional models to explore the expected performance. Streetly (1998) and Anderson & Lowry (2004) have investigated ASR performance in near-potable aquifers using numerical models.

Consistent with previous research efforts, an ASR simulator model was developed to confirm and evaluate ASR performance variables and operational schemes. The models were all originally constructed utilizing the United States Geological Survey (USGS) groundwater flow model code MODFLOW (McDonald and Harbaugh, 1988) and the contaminant transport code MT3DMS (Zheng and Wang, 1999). The model domain was 64 kilometers by 64 kilometers and included 1.5-meter resolution at the well head and within 100 meters of the well head, gradually increasing to 1,000 meters at the model boundary. The model was one layer thick and included only the aquifer storage zone. The thickness of the storage zone was fixed at 61 meters and a horizontal hydraulic conductivity of 15.2 meters/day. The model simulated the confined Upper FAS with an assigned storage coefficient of 1×10^{-4}. A west to east pre-existing gradient was assigned across the model of 0.0001, similar to that which exists in the FAS beneath Palm Beach County, Florida. The TDS of the aquifer storage zone was assigned a value of 4,000 mg/l similar to the FAS beneath Palm Beach County. The TDS of the recharge water was assumed to be 150 mg/l, that is a reasonable approximation for freshwater in the study area. The simulator model was then utilized as a testing laboratory to review various hydrogeologic conceptual models in conjunction with differing operational schemes.

Three different hydrogeologic conceptual models were simulated, including a low dispersion case thought to represent sandy portions of the FAS; a moderate dispersion case thought to represent limestone portions of the FAS; and scale-dependent moderate dispersion case.

- The low dispersion case was assigned a constant dispersivity (α) of 0.30 meters across the entire model domain. For this conceptual model, freshwater transport is dominated by advection through the sand to sandy limestone porous media.

- The moderate dispersion case utilized a constant α of 7.6 meters across the entire model domain. For this conceptual model, freshwater transport is a combination of advection and hydrodynamic dispersion through slightly vuggy limestone porous media. It is important to note that most numerical models completed to date evaluating ASR performance have all assumed constant α.

- The last hydrogeologic conceptual model introduces scale effects into the model through assignment of radially increasing α.

Schulze-Makuch (2005) extended research on scale dependent hydrodynamic dispersion originally completed by Gelhar et al. (1992) by correlating geologic character and project scale. Brown (2005) further extended this concept by adapting dispersion correlation equations to ASR projects. Brown also proposed further sub-divisions of the carbonate geological character category introduced by Schulze-Makuch. Schulze-Makuch's research determined a power law relationship relating geologic character and project scale to dispersivity. Equation 3 provides the general relationship determined by the research:

$$\alpha = cL^m \tag{3}$$

where c is a characteristic parameter of a geologic medium; L is the flow distance or problem scale; and m is a scaling exponent related to the geologic medium. In order to account for ASR scale effects, Brown (2005) substituted the radius of a theoretical ASR bubble, Rm, for L to form Equation (4):

$$\alpha = c(Rm)^m \tag{4}$$

This equation provided a means to estimate and assign a realistic radially-increasing α to the model domain. However, based upon cautionary words from Gelhar et al. (1992), the α probably approaches an asymptote at values greater than 35 meters. Therefore, the maximum α assigned to the model domain was 35 meters. Based upon the characteristics of a vuggy limestone as presented in Brown (2005, Table 3-31), c was assigned a value of 0.405 while the exponent m was assigned a value of 0.81. Therefore, the assigned model a ranged from 2.6 meters at 10 meter scale to 9.6 meters at 50 meter scale to 23.4 meters at 150 meter scale. At radial distances greater than 250 meters, the α value was assumed to be constant at 35 meters.

A review of the ASR case studies indicates that two general operational strategies have been employed to maximize RE. First, the traditional approach is to develop the ASR storage zone through multiple recharge and recovery cycles. Optimally, a similar size recharge volume is used every cycle to continually buffer the ambient water quality with freshwater recharge. This is a "pore volume" approach consistent with experiments performed by Haggerty et al. (1998). The second approach is establishing a "target storage volume" (TSV) by recharging large quantities of freshwater for the first few cycles to ensure that a target recovery volume can be achieved as soon as possible by reconditioning of the aquifer water quality. The TSV approach has been discussed previously by Pyne (1995). Various size TSVs have been experimented with but the optimum size has not yet been determined. For this paper, three separate operational scenarios or schemes were tested with the ASR simulator model. First, a typical pore volume approach was simulated using six separate 30-day recharge and recovery cycles. Second, a TSV approach was simulated using a moderate size TSV prior to starting a typical pore volume approach with six 30-day recharge and recovery cycles. Last, an aquifer "flushing" approach utilizing a massive single cycle volume was tested with 180 days of recharge followed by 180 days of recovery. All three schemes utilized the same cumulative total of freshwater recharge over a 360-day period (e.g., almost one full year of testing). The amount of recovery during each period was constrained by the applicable water quality limit of 500 mg/l TDS. Once this value was exceeded during recovery, the next subsequent recharge cycle was started.

Each operational approach included cumulative recharge of 3,420,000 m^3 of freshwater over the 360-day simulation period with the exception of the TSV cases where the cumulative recharge volume included an additional 383,000 m^3 of freshwater to build the initial target storage volume. Each operational approach was tested using all of the three hydrogeologic conceptual models discussed earlier in this paper. Table 1 presents the simulation matrix for the study.

Table 1. Simulation matrix with simulation name assigned.

	Hydrogeologic Conceptual Model		
Operational Scheme	Low Dispersion (geology dependent constant α)	Moderate Dispersion (geology dependent constant α)	Moderate Dispersion (geology and scale dependent α)
Pore Volume	A	D	G
Moderate TSV	B	E	H
Aquifer Flushing	C	F	I

RESULTS AND DISCUSSION

Table 2 displays the results of the model simulations over the one-year period. The table lists the individual first and last cycle recovery efficiency, the first and last cumulative recovery efficiency, the first and last cycle recovery volume, and the cumulative recovery volume for the entire simulation. Table 3 displays a theoretical "benefit to cost ratio" (B/C ratio) assuming that the value of the water recovered is the same as the cost of the water recharged. The B/C ratio is calculated after one year of model simulations.

Table 2. Model simulation results with key performance metrics.

Simulation	RE C1 %	RE C6 %	CRE C1 %	CRE C6 %	Vol C1 (m^3)	Vol C6 (m^3)	Cum Volume Recovered (m^3)
A	78.30	97.50	78.33	92.78	446,500	555,750	3,173,019
B	100.0	100.0	60.00	90.00	570,000	570,000	3,420,000
C	90.00	NA	90.00	NA	3,103,448	NA	3,103,448
D	32.50	80.83	32.50	66.25	185,250	460,750	2,265,750
E	61.67	81.00	37.00	65.57	351,500	461,700	2,491,698
F	72.77	NA	72.77	NA	2,489,000	NA	2,489,000
G	25.83	64.17	25.83	51.25	147,250	365,750	1,752,750
H	45.00	65.00	27.00	50.63	256,410	370,370	1,923,750
I	31.11	NA	31.11	NA	1,064,000	NA	1,064,000

Note: C1 refers to Cycle 1; Vol refers to volume; Cum refers to cumulative; NA refers to not applicable

Table 3. Model simulation B/C Ratios.

Simulation	B/C Ratio
A	0.93
B	0.90
C	0.90
D	0.66
E	0.66
F	0.73
G	0.51
H	0.51
I	0.31

Tables 2 and 3 provide a wealth of information regarding the various combinations of operational scheme and hydrogeologic conceptual model. First, a comparison of the three operational schemes tested in a constant low hydrodynamic dispersion environment (Simulations A, B, and C) reveals that the TSV approach results in the highest RE values cycle to cycle but the lowest CRE values, while the aquifer flushing approach assures the largest volume of water available after one cycle. The TSV approach ensures that the initial recovery volume would be at least 570,000 m^3. If a benefit to cost ratio is compared as in Table 3, the pore volume approach appears to be the most cost effective. Technically, it is reasoned this occurs due to the translation of the freshwater bubble due to pre-existing aquifer gradient. With low hydrodynamic dispersion, advection is the dominant mixing and transport process. Scenarios B and C involve recharge of larger volumes of water during the initial cycle, some of which becomes unrecoverable due to the bubble translation. Since the pore volume approach involves lower recharge volumes, less water becomes unrecoverable. Therefore, depending upon the goals and objectives of the project, under low hydrodynamic dispersion conditions the pore volume approach is recommended. In regards to the CERP, low hydrodynamic dispersion conditions are not expected for a majority of potential locations, however, if one is discovered within Palm Beach County, the pore volume approach would be recommended to the extent practical since the approach would also be consistent with the expected availability of freshwater in the study area. In a practical sense, however, the difference in performance among the three operational schemes is minor and after many years of repetitive ASR cycles, any of the three schemes should result in superior performance.

Second, a comparison of the three operational schemes tested in a constant moderate hydrodynamic dispersion environment (Simulations D, E, and F) reveals that the aquifer flushing approach results in the highest RE values cycle to cycle and the highest CRE values, while it also assures the largest volume of water available after one cycle. If a benefit to cost ratio is compared as in Table 3, the aquifer flushing approach appears to be the most cost effective. The TSV approach succeeds in recovering the largest cumulative volume of freshwater but at an investment 10% higher than the other two options. It also appears that the initial effectiveness of the TSV dissipates by the sixth recharge and recovery cycle since the CRE value is approximately the same as the corresponding pore volume approach. Technically, it is reasoned this occurs because the cumulative unrecovered freshwater buffer eventually equals out after six cycles. Similar reasoning explains the success of the aquifer flushing approach where the overall buffer volume approaches an asymptote. Therefore, depending upon the goals and objectives of the project, under moderate hydrodynamic dispersion conditions the aquifer flushing approach is recommended. In regards to the CERP, the operation of the ASR system north of Lake Okeechobee is heavily dependent upon the availability of excess freshwater not currently allocated to an existing water demand. The freshwater availability is expected to be discontinuous with massive volumes available for some periods of time and moderate volumes for others. In addition, constant moderate dispersion conditions are not expected for a majority of the potential Lake Okeechobee locations, however, if some are discovered in the area north of Lake Okeechobee, the aquifer flushing approach would be recommended to the extent practical since the approach would also be consistent with the expected availability of freshwater in the study area. In essence, a larger volume of freshwater available would lend itself to the aquifer flushing approach.

Third, a comparison of the three operational schemes tested in a scale dependent moderate hydrodynamic dispersion environment (Simulations G, H, and I) reveals that the TSV approach results in the highest RE values cycle to cycle and the second highest CRE values, while it also ensures the availability of at least 250,000 m^3 of freshwater can be utilized immediately. If a benefit to cost ratio is compared as in Table 3, the TSV or the Pore Volume approach appear to be cost effective. The TSV approach also succeeds in recovering the largest cumulative volume of freshwater but at an investment 10% higher than the other two options. It also appears that the initial effectiveness of the TSV dissipates by the sixth recharge and recovery cycle since the CRE value is approximately the same as the corresponding pore volume approach. Technically, it is reasoned this occurs because the cumulative unrecovered freshwater buffer eventually equals out after six cycles. Therefore, depending upon the goals and objectives of the project, under scale dependent moderate hydrodynamic dispersion conditions the TSV approach is recommended. In regards to the CERP ASR program, these last three cases represent the most likely hydrogeologic conceptual model. The model simulations suggest that for ASR projects in Palm Beach County where more frequent, moderately-sized ASR cycles are expected, the TSV approach would be the best operational scheme. For the ASR wells north of Lake Okeechobee, massive volumes of freshwater are likely to be available sporadically, pointing to the aquifer flushing approach, even though the performance may not be as good as the TSV approach. It may be possible to develop a hybrid operational scheme north of Lake Okeechobee also. When moderate freshwater volumes present themselves, the TSV approach should be considered instead of the pure aquifer flushing scheme. Unfortunately, the model simulations indicate that the flushing approach may result in dampened system performance.

The model simulations conducted for this paper assumed an ambient groundwater TDS value of 4,000 mg/l along with various hydrogeologic conceptual models. The TDS value across the CERP study area is variable with values increasing in a general north to south direction. The TDS values expected north of Lake Okeechobee should be less than half those simulated for this study; therefore, performance of the ultimate system should be better than presented in this study. However, even under "worse-case" water quality conditions, the CRE values after one year ranged from 31 to 93%. These values would be expected to improve considerably in subsequent operational years so that a long-term average CRE of 70% should be feasible. In areas north of Lake Okeechobee, lower TDS ambient groundwater should permit CRE values in excess of 70%. Meeting or exceeding the 70% value is important since the overall ASR performance assumed for the CERP is 70%.

In conclusion, operational schemes selected for ASR projects should give due consideration to the hydrogeologic environment present at the site. Depending upon the hydrogeologic conceptual model for a given site and the objectives of the project, alternate operational schemes may be optimal. This paper has evaluated nine combinations of hydrogeology and operational schemes to determine optimum performance. The paper also discusses these findings relative to the expected operations required for the CERP ASR project. Lastly, the conclusions from this paper could be bolstered through additional model simulations using different initial values of ambient groundwater TDS and possibly the inclusion of density-dependency. A density dependent model would be especially useful in cases of ambient TDS greater than 5,000 mg/l and where ASR storage durations are exceedingly long.

ACKNOWLEDGEMENTS

Valuable input for this study was provided by R. David Pyne of ASR Systems Inc., Dr. Kirk Hatfield of the University of Florida, Dr. Louis Motz of the University of Florida, and Mike Fies of the U.S. Army Corps of Engineers.

This paper has been reviewed by Drs. Greg Whittle and Samir Itani of the U.S. Army Corps of Engineers. Their thorough review has significantly improved the manuscript for publication.

REFERENCES

Alpay, O.A. 1972. A Practical Approach to Defining Reservoir Heterogeneity. Journal of Petroleum Technology, 20(7):841-848.

American Society of Civil Engineers (ASCE). 2001. Standard Guidelines for Artificial Recharge, EWRI/ASCE 34-01. ASCE, New York, New York.

Anderson, M.P. 1984. Movement of Contaminants in Groundwater: Groundwater Transport-advection and Dispersion. In: Groundwater Contamination, National Research Council Studies in Geophysics, NRC (Editor), National Academy Press, Washington, D.C., pp. 37-45.

Anderson, M.P. and C.S. Lowry. 2004. An Assessment of Aquifer Storage &Recovery for Selected Representative Hydrogeologic Settings in Wisconsin. University of Wisconsin-Madison Groundwater Research Report # WR03R005, Madison, Wisconsin, 15 p.

Asano, Takashi. 1985. Artificial Recharge of Groundwater. Butterworth Publications, Toronto, Canada, 198 p.

Brown, Christopher J. 2005. Planning Decision Framework for Brackish Water Aquifer, Storage and Recovery (ASR) Projects, Ph.D. Dissertation, University of Florida, Gainesville, Florida, 415 p.

Brown, C., S. Itani, and M. Zhang. 2004. Final Draft Report, ASR Regional Study: A Scientific Evaluation of Potential Pressure Induced Constraints and Changes in the Floridan Aquifer System and the Hawthorn Group, U.S. Army Corps of Engineers, Jacksonville, Florida, 64 p.

Davis, S.M. 1994. Phosphorus Inputs and Vegetation Sensitivity in the Everglades. In: Everglades The Ecosystem and Its Restoration, Davis, S.M. and J.C. Ogden, (Editors). St. Lucie Press, Delray Beach, Florida, pp. 357-378.

Domenico, P.A. and F.W. Schwartz. 1998. Physical and Chemical Hydrogeology. John Wiley and Sons, Inc., New York, New York.

Douglas, M.S. 1947. Everglades: River of Grass. Rhinehart Press, New York, New York.

Drever, James I. 1997. The Geochemistry of Natural Waters, Surface and Groundwater Environments. Prentice Hall, Upper Saddle River, New Jersey.

Gelhar, L.W., C. Welty, and K.R. Rehfeldt. 1992. A Critical Review of Data on Field-scale Dispersion in Aquifers. Water Resources Research, 28(7):1955-1974.

Haggerty, R., Schroth, M.H. and J.D. Istok. 1998. Simplified method of "push-pull" test data analysis for determining in situ reaction rate coefficients. Ground Water, 29(2):314-324.

Huntley, D. and R.S. Bottcher. 1997. Effect of vertical aquifer heterogeneity on the efficiency of aquifer storage and recovery projects. In: Proceedings, Conjunctive Use of Water Resources: Aquifer Storage and Recovery, American Water Resources Association, October 1997, pp. 211-220.

Jones, H.K., I. Gaus, A.T. Williams, P. Shand, and I.N. Gale. 1999. ASR – UK. A Review of the Status of Research and Investigations. British Geological Survey Technical Report WD/99/54. British Geological Survey, London, United Kingdom, 44 p.

Khanal, N.N. 1980. Advanced Water Supply Alternative for the Upper East Coast Planning Area; Part I – Feasibility of Cyclic Storage of Freshwater in a Brackish Aquifer, and Part II – Desalinization Alternative. South Florida Water Management District Technical Publication no. 80-6, West Palm Beach, FL, 75 p.

Kimbler, O.K., R.G. Kaymann, and W.R. Whitehead. 1975. Cyclic Storage of Freshwater in Saline Aquifers: Louisiana Water Resources Research Institute Bulletin # 10, Baton Rouge, Louisiana, 78 pp.

McDonald, M. G., and A.W. Harbaugh. 1988. A Modular Three-dimensional Finite-Difference Ground Water Flow Model: Techniques of Water-Resources Investigation Report, v. 06-A1.

Merritt, Michael L. 1986. Recovering Fresh Water Stored in Saline Limestone Aquifers. Ground Water 24(4):516-

529.

Miller, J.A. 1997. Hydrogeology of Florida. In: The Geology of Florida, Chapter 6, Randazzo, A.F. and D.S. Jones, (Editors). Univeristy of Florida Press, Gainesville, FL, pp. 69-88.

Missimer, T.M., W. Guo, C.W. Walker, and R.G. Maliva. 2002. Hydraulic and density considerations in the design of aquifer storage and recovery systems. Florida Water Resources Journal, February 2002, pp. 31-35.

National Research Council (NRC). 1994. Ground Water Recharge Using Waters of Impaired Quality. Washington D.C., The National Academies Press, 279 p.

Pavelic, P., P.J. Dillon, and C.T. Simmons. 2002. Lumped Parameter Estimation of Initial Recovery Efficiency During Aquifer Storage and Recovery. In: Management of Aquifer Recharge for Sustainability, P.J. Dillon (Editor) Proceedings of the 4th International Symposium on Artificial Recharge (ISAR4), Adelaide Sept 22-26, 2002, Swets & Zeitlinger, Lisse, Netherlands ISBN. 90 5809 527 4, pp.285-290.

Pyne, R.D.G. 1995. Groundwater Recharge and Wells: A Guide to Aquifer Storage Recovery. Lewis Publishers, Boca Raton, Florida, 375 p.

Rhoades E., A. Kandiah, and M. Mashali. 1992. The Use of Saline Waters for Crop Production – FAO Irrigation and Drainage Paper 48. The United Nations Food and Agricultural Organization, Rome, Italy, 210 p.

USACE & SFWMD. 1999. Central and Southern Florida Project Comprehensive Review Study, Final Integrated Feasibility Report and Programmatic Environmental Impact Statement, USACE & SFWMD, April 1999.

USACE & SFWMD. 2004. Final Pilot Project Design Report/Environmental Impact Statement, Lake Okeechobee ASR Pilot Project, Hillsboro ASR Pilot Project and Caloosahatchee River ASR Pilot Project, U.S. Army Corps of Engineers, Jacksonville, Florida, September 2004, 400 p.

Wright, T.E.J. and J. A. Barker. 2001. Calibration of a Double-Porosity Solute Transport Model Using Short and Long Term Tracer Tests. In: Proceedings IAH XXXI Congress: "New Approaches to Characterising Groundwater Flow", K.P. Seiler and S. Wohnlich (Editors), Swets & Zeitlinger Lisse, Netherlands ISBN 902 651 848 X, pp.683-688.

Schulze-Makuch, Dirk. 2005. Longitudinal Dispersivity Data and Implications for Scaling Behavior. Ground Water, 43(3):443-457.

Sudicky, E.A. 1986. A Natural Gradient Experiment on Solute Transport in a Sand Aquifer: Spatial variability of Hydraulic Conductivity and its Role in the Dispersion Process. Water Resources Research, 22(13):2069-2082.

Streetly, M.J. 1998. The use of modelling to predict the behavior of ASR systems. In: Artificial Recharge of Groundwater, J.H. Peters (editor) A.A. Balkema, Rotterdam, ISBN 90 5809 017 5, pp. 263-267.

Zheng, C. and P. P. Wang. 1999, MT3DMS: A Modular Three-Dimensional Multi-Species Model for Simulation of Advection, Dispersion and Chemical Reactions of Contaminants in Groundwater Systems: Documentation and User's guide, SERDP-99-1: U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

ADDRESS FOR CORRESPONDENCE
Christopher J. Brown
Geotechnical Branch
U.S. Army Corps of Engineers
Jacksonville, Florida 32241
USA

Email: Christopher.j.brown@usace.army.mil