

Aquifer Storage and Recovery Issue Team Assessment Report and Comprehensive Strategy

A Report to the South Florida Ecosystem Restoration

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Aquifer Storage and Recovery Issue Team

Background and Issue Identification

The Aquifer Storage and Recovery Issue Team was formed by the South Florida Ecosystem Restoration Working Group in September, 1998. The Team's purpose is to develop an action plan and identify projects to address the surface water, hydrogeological and geochemical uncertainties associated with regional aquifer storage and recovery (ASR) facilities. The plan will address the uncertainties through the creation of a list of projects or actions with their appropriate costs that should be undertaken to test the feasibility of ASR facilities as proposed in the Central and Southern Florida Project Comprehensive Review Study.

ASR is generally defined as "the storage of water in a suitable aquifer through a well during times when water is available, and recovery of the water from the same well during times when it is needed" (Pyne, 1995). ASR facilities have been in operation in the United States for about thirty years. In essence, the technology allows aquifers to be used as underground water storage reservoirs. The first ASR facility in Florida was permitted in 1982 and the State currently has six operational ASR facilities, with an additional twelve under construction as of February, 1998. Many of these facilities have multiple wells, with the largest currently operating systems (Peace River/Manasota Regional Water Supply Authority; City of Cocoa) able to recover about 8 million gallons/day or about 25 acre feet/day (GCSSF, 1996b). These facilities utilize either treated surface water or treated groundwater as their supply source. However, the FDEP has recently issued two construction permits, received another construction application and held two pre-application meetings with several utilities interested in using reclaimed water as an ASR source water. See Attachment 1 for a list of ASR facilities in Florida.

Some of the twenty-two potential uses identified for ASR (Pyne, 1995) that may be applicable for South Florida, include:

Seasonal Storage - Storage during wet months for recovery during dry months or when needed.

Long-term Storage - Storage during wet years for recovery during drought years.

Restore Ground Water Levels - Reverse groundwater level declines by incorporating ASR systems.

Agricultural water supplies - Provide seasonal storage of water for agricultural purposes.

Enhance Wellfield Production - Wellfields are usually designed to operate within their long-term safe, sustained yield. When these same wellfields are converted to ASR mode, it is often possible to produce water at higher rates during peak demand months, counting on artificial recharge during off-peak months to restore water levels before the next peak demand season.

Compensate for surface salinity barrier leakage losses - In South Florida, salinity barriers are located on major drainage channels discharging to saltwater. With ASR, wells could be located adjacent to these barriers, recharging water into deep brackish aquifers during wet months. Stored water would be recovered during drought months to compensate for leakage losses.

Reclaimed water for reuse - High quality reclaimed water may be stored seasonally in brackish aquifers for recovery to meet irrigation demands, eliminating the need for expensive aboveground storage.

The use of ASR is increasing nationally since, with appropriate quality of the injected water, it creates few environmental impacts, is less expensive than many other water storage options, and can efficiently store water for later retrieval. However, the use of large-scale ASR for supplying the huge amounts of water in regional water storage

facilities like those proposed in the Restudy (i.e., a total of 1,775 MGD or 5,100 acre feet/day) has never been attempted, and therefore is currently unproven as a reliable large-scale technology. This uncertainty is a major concern for water users, such as in the Everglades Agricultural Area (EAA) and by the Miami-Dade, Palm Beach and Lee County utility interests, who in the Restudy proposal will use regional ASR storage to augment their local water supply resource. This uncertainty prompted the Governor's Commission for a Sustainable South Florida, in its Conceptual Plan, to recommend that "ASR technology should be investigated to determine its feasibility at a regional scale" (GCSSF, 1996b; p. 47).

Treated surface water or groundwater ASR have been identified as an important water storage component for all alternatives being evaluated in the Central and Southern Florida Project Comprehensive Review Study. Under the Study, ASR facilities have been proposed to provide environmental benefits such as environmental water supply deliveries, flood water attenuation, and improved Lake Okeechobee stages. In addition, ASR could also augment urban and agricultural water supplies.

Implementation of the planned ASR facilities is expected to take up to 20 or more years. The first stage will be a pilot program to test the ASR feasibility in specific location(s) such as around Lake Okeechobee. As a result of the pilot program and future modeling results, the decision to either develop more ASR wells or end the development will be made. If the decision is to continue the development of more ASR wells, periodic evaluations will be made as the program progresses. If the decision is to discontinue ASR development, other options (having about the same cost) will be evaluated as substitutions for ASR to help make-up for performance reductions. Potential features may include additional storage in above ground reservoirs (by using equivalent costs to better manage seepage), develop desalinization features, or develop water reuse features. Until pilot programs and more intensive studies are completed, the need (if any) for substituted features can not be evaluated.

In the Recommended Plan for the Restudy, about 300 ASR wells were included. The level of recovery was modeled at 70 percent efficiency. Modeling was also conducted assuming lesser efficiencies to evaluate performance reductions of the Plan.

In most cases, the environmental performance suffers the most. For a detailed analysis of the ASR sensitivity, please refer to Appendix B of the Restudy Report or the web site at [HYPERLINK http://www.restudy.org](http://www.restudy.org). As the evaluations show, the overall performance of the plan is reduced but not severely diminished. For example, use of ASR wells around Lake Okeechobee is intended to allow for more natural fluctuations in Lake stage. If ASR around the lake falls short of expectations, alternate storage means will need to be provided to maintain a range in lake levels consistent with a healthy lake and to avoid large freshwater discharges to the estuaries. Water supply is affected to a lesser extent by ASR not performing to expectations. As another example, if the ASR wells along C-51 were not included, then the natural system flows would be reduced by about 26,000 acre-feet per year and the equivalent amount would be lost to tide. ASR wells, without associated land storage, represents about 8 percent of the resources generated in the Restudy plan. However, the ASR water would be delivered during extended dry periods and have very

beneficial effects on the natural system. If some water users feel they do not need the potential benefit of the ASR water supply, then some ASR wells could be eliminated without any adverse impact to the system.

Seven issues associated with the implementation of regional scale ASR facilities were identified during the June, 1998 ASR Workshop and are listed below. However, not all of the issues carry the same level of concern. The Team believes that issues 1, 2, 4, 5 and 7 are the most important. However, all of the issues will be addressed during the feasibility phase of pilot ASR well construction and operation. The remainder of the assessment provides a technical analysis of the issues and strategies to address them.

1. Characterization of the quality of prospective source waters, spatial and temporal variability
2. Characterization of Regional Hydrogeology of the Upper Floridan Aquifer: Hydraulic Properties and Water Quality
3. Analysis of critical pressure for rock fracturing
4. Analysis of Site and Regional Changes in Head and Patterns of Flow
5. Analysis of water quality changes during movement and storage in the aquifer
6. Aquifer Storage and Recovery Potential Effects on Mercury Bioaccumulation for Ecosystem Restoration Projects
7. Relationship between ASR storage interval properties and recovery rates and recharge volume

ISSUE 1

Characterization/Suitability of the quality of prospective source waters, spatial and temporal variability

Description of the issue

Technical feasibility aside, there are regulatory issues that must be resolved before regional, large scale ASR projects using untreated, or partially treated surface water or ground water can be used extensively without either major costs being incurred because of treatment required prior to injection, or from having to obtain regulatory relief.

The Underground Injection Control (UIC) program and regulations are designed to protect underground sources of drinking water (USDW). A USDW is any ground water in an aquifer which contains a total dissolved solids (TDS) concentration of less than 10,000 mg/L. Under the UIC regulations all USDWs are protected equally regardless of whether

the ground water is expected to be used as a drinking water source or not. In addition, the UIC regulations do not distinguish between injection that is for beneficial purposes (e.g., aquifer remediation or ASR) and injection that is only for disposal purposes. Under the UIC regulations all injection wells are treated as if the fluids will always remain in the subsurface. No "credit" is given for systems such as ASR where (at least a portion) of the injected fluid will be recovered.

At the center of the regulatory concern over ASR is the definition of "endangerment" as it applies to the UIC regulatory program and the federal regulatory language at 40 CFR 144.12(a) which forms the basis for all state and federal regulations for injection activity.

"Endangerment" is defined in the Safe Drinking Water Act (SDWA) as follows:

Underground injection endangers drinking water sources if such injection may result in the presence in underground water which supplies or can reasonably be expected to supply any public water system of any contaminant, and if the presence of such contaminant may result in such system's not complying with any national primary drinking water regulation or may otherwise adversely affect the health of persons.

However, the "endangerment" language under the federal regulations at 40 CFR 144.12(a) states the following which seems to be somewhat more stringent than that in the SDWA:

No owner or operator shall construct, operate, maintain, convert, plug, abandon, or conduct any other injection activity in a manner that allows the movement of fluid containing any contaminant into underground sources of drinking water, if the presence of that contaminant may cause a violation of any primary drinking water regulation under 40 CFR part 142 or may otherwise adversely affect the health of persons. The applicant for a permit shall have the burden of showing that the requirements of this paragraph are met.

The "endangerment" requirements under the federal regulations at 40 CFR 144.12(a) have been interpreted in many ways ranging from that the primary drinking water standards must be met in the tap water (not prior to injection) so that the fluids injected must be of such high quality that they meet primary drinking water standards and may not otherwise adversely affect the health of persons prior to injection.

The Environmental Protection Agency (EPA) has traditionally taken the position that all primary drinking water quality standards must be met prior to injection. Since the State UIC rules can be no less stringent than Federal regulations, Rule 62-528.605(3), F.A.C., was revised in 1995 as follows:

Class V wells shall be constructed so that their intended use does not violate the water quality standards of Chapter 62-520, F.A.C., at the point of discharge, except where specifically exempted in Rule 62-522.300(2),

F.A.C., provided that the drinking water standards of 40 C.F.R. pt. 142 (1994) are met at the point of discharge. Migration or mixing of fluids from aquifers of substantively different water quality (through the construction or use of a Class V well) shall be prevented by preserving the integrity of confining beds between these aquifers through cementing or other method acceptable to the Department.

For reference, Rule 62-522.300(2), F.A.C., states the following:

No zone of discharge shall be allowed under any of the following circumstances:

Discharges through wells or sinkholes that allow direct contact with Class G-I and Class G-II ground water, except for projects designed to recharge aquifers with surface water of comparable quality, or projects designed to transfer water across or between aquifers of comparable quality for the purpose of storage or conservation.

If the water that is to be injected in the ASR projects associated with the Restudy alternatives will not meet primary drinking water quality standards prior to injection without treatment, under the interpretation above injection can not be permitted unless regulatory relief is provided, or the water is treated to drinking water standards prior to injection. Under the UIC regulations the only relief mechanism available is an aquifer exemption.

An aquifer exemption may be difficult to obtain because the applicant must demonstrate that the ground water in the injection (storage) zone is not currently being used as a drinking water supply, nor is it reasonably expected to be used in the future as a drinking water supply. In addition, the ultimate control over issuing an aquifer exemption is with EPA, not the State.

Since the primary issue of concern is the presence of coliform bacteria in the source water, approximately two years ago, EPA proposed what has been termed the "limited" aquifer exemption. Unlike the standard aquifer exemption, which actually exempts a portion of an aquifer from regulation as a USDW, the "limited" aquifer exemption is parameter specific. That is, the applicant requests the exemption only for those constituents (coliform, etc.) that are in the water that is to be injected which will cause that water not to meet primary drinking water quality standards.

The requirements to obtain a "limited" aquifer exemption are identical to those for obtaining a standard aquifer exemption. However, since the exemption is parameter specific there may be less public concern for issuing the exemption since another discharger could not easily use the exemption to allow discharge of waste. Although EPA first suggested the "limited" aquifer exemption, there have been questions concerning whether one can legally be issued. However, FDEP is proceeding with the processing of the two "limited" aquifer exemptions.

Recently, EPA proposed a policy change concerning coliform bacteria that could significantly improve the regulatory permitability of proposed regional scale ASR facilities in the south Florida area. Based on the water quality information from Lake Okeechobee and the surficial ground water in southeast Florida reviewed thus far, coliform bacteria appears to be the sole parameter that is present at levels which exceed the federal primary drinking water standard. In a drinking water system, the mere presence of coliform bacteria may constitute a violation. Although coliform bacteria are naturally occurring microorganisms found in surface waters such as ponds, lakes, and rivers, they should not be found in a drinking water system and their presence would indicate a potential threat to human health and would be a violation of the primary drinking water standard. Because these microorganisms should not present a health threat when water containing them is stored underground in a brackish aquifer, EPA will evaluate their presence in ASR source water from more of a risk based approach rather than a standard permitting approach based on meeting drinking water standards prior to injection.

The policy currently being evaluated by EPA is based on the following assumptions:

1. Coliform is the only primary drinking water standard at issue.
2. The storage aquifer is brackish or saline. (a total dissolved solids concentration of greater than 1500 mg/L)
3. The development of the ASR project will result in a significant environmental benefit.
4. The storage aquifer is not being used as a drinking water supply in the area of the ASR.
5. The treatment process needed to render the ambient water in the storage zone fit for drinking would also remove Coliform.

Strategy

In order to improve confidence that the water quality of potential ASR source waters has been adequately characterized, additional water quality sampling of these sources for primary and secondary drinking water standards, and microbiological, and other contaminants reasonably expected to be found in the source water should be undertaken as soon as possible. Two proposed ASR pilot projects along the Hillsboro Canal in southern Palm Beach County and around northern Lake Okeechobee are anticipated to be constructed to provide operational information regarding large scale ASR using "raw" surface water and "raw" ground water as sources. Water quality data collection is an important part of determination of the specific sites for these pilot ASR well facilities. In order to maximize efficiency and avoid duplication of effort, EPA and FDEP should participate in developing the water quality parameters, the number of samples to be collected, the collection frequency and the specific locations of data collection.

ISSUE 2

Characterization of the Regional Hydrogeology of the Upper Floridan Aquifer: Hydraulic Properties and Water Quality

Description of the issue

In order to assess the viability of implementing ASR at the proposed scale and in the places proposed, detailed information on the vertical distribution of potential injection zones, their regional extent, their hydraulic properties, and the quality of the native water is needed.

This information on the Upper Floridan aquifer is very limited throughout most of South Florida, especially within inland areas where most of the ASR activity is proposed. Without this information, it is not possible to evaluate factors such as hydraulic interactions between injection sites, recovery efficiencies, and overall hydraulic impact. Optimization of injection rates/recovery volumes depends on knowing the hydraulic properties and water quality of the native water. Knowledge of hydraulic interaction between sites (mutual well interference) is needed to decide on appropriate well spacing and to evaluate the overall changes to the potentiometric surface of the Upper Floridan aquifer. The pilot ASR installations discussed under issue 7 can provide the needed information for their proposed sites, but because of the greater cost of the ASR wells, only limited sites most likely will be tested over the next several years. The needed regional data can only be obtained through a well designed and conducted test drilling program run simultaneously with the installation of the pilot ASR facilities. Such a program would cost on the order of several million dollars and require a few years to complete.

Strategy

The first step in designing the test drilling program is to assemble all of the currently available data on the hydrogeology of the Upper Floridan aquifer and evaluate its shortcomings, if any, relative to the proposed ASR needs. This should take about six (6) months, and cost about \$75,000. From this evaluation, the number and locations of test wells needed to provide hydrogeologic data in areas lacking data can be determined. Site selection should be based on the likely proximity of ASR well locations to source waters and discharge points. These exploration/test wells will provide detailed information on the potential injection target zones available. The exploration/test wells can later serve as monitor wells for ASR well operation.

The primary focus of the test drilling program should be to identify potential injection target intervals for evaluation. Ideally, the following various hydrogeologic conditions should be evaluated, however test wells should address conditions encountered at each site.

- 1) A highly conductive ASR interval (conductive fracture system or interconnected vugular system) with a transmissivity greater than 100,000 ft²/day.
- 2) A single ASR interval with transmissivity values between 20,000 and 50,000 ft²/day.
- 3) An ASR interval containing two or more permeable sections with individual transmissivity values between 20,000 and 50,000 ft²/day. Each interval should be separated from the next by a less conductive confining unit.
- 4) A single ASR interval with a transmissivity between 5,000 and 20,000 ft²/day.
- 5) An ASR interval containing two or more permeable sections with transmissivity values ranging between 5,000 and 20,000 ft²/day. Each interval should be separated from the next by a less conductive confining unit.

The goal of the well drilling and testing program will be to assemble information on the number of ASR target intervals which offer a realistic probability that ASR will be successfully applied and to develop the best information available from the perspective of wellfield design.

The aquifer testing should provide the following technical information:

- ✓ Storage interval transmissivities
- ✓ Confining unit vertical hydraulic conductivity
- ✓ Confinement Between the upper most ASR storage Interval and the water table
- ✓ Fracture pressure
- ✓ Porosity
- ✓ Regional extent of the target storage aquifers
- ✓ Salinity of aquifer water
- ✓ Pretreatment requirements for injected water

The Scope of the exploratory drilling and testing should include:

- ✓ Coring of suspected confining units and laboratory testing of their hydraulic conductivity.
- ✓ Geophysical logs including: flow velocity log, caliper log, fluid resistivity log during flowing conditions, sonic/VDL log, temperature log, natural gamma ray survey and bore hole televiewer.
- ✓ Aquifer tests (pressure drawdown and pressure buildup) designed to provide information on transmissivity, leakance, and other flow properties for each potential ASR interval encountered. This testing should be designed to evaluate lateral water movement, vertical water movement, and pressure build-up in the subsurface aquifers.
- ✓ Water quality sampling of potential injection zones.

The above information should be recorded on regional cross sections along strike and dip, isopach maps of specific permeable and confining units, a structure map based on the top of the first target ASR interval, and contour maps of aquifer transmissivity to provide an overall understanding of the subsurface environment.

Once sites for test drilling are identified, the test drilling program can be defined and bids taken for awarding of drilling and testing contracts. It's not possible at this time to accurately estimate the cost of the drilling program other than to say it will probably be about \$250,000 per site, and total several million dollars overall. The drilling program will likely take three to five years to complete. About 10 to 15 exploration/monitor wells may be needed, in addition to the pilot ASR wells.

Resolution of several other ASR issues depends on the information produced by the test drilling program. Therefore, this program should be initiated as soon as possible.

ISSUE 3

Analysis of critical pressure for rock fracturing

Description of issue

Injection of water at the scale envisioned in the Restudy will involve the simultaneous operation of a few hundred injection wells. Each injection well will require a buildup in hydraulic head sufficient to force the water into the aquifer.

In addition to the buildup in head owing to the operation of the individual injection well, additional incremental buildup in head will result from the simultaneous operation of other injection wells on each of the wells. This phenomena, known as mutual well interference will result in aquifer pressure increases significantly greater than that for the operation of a single injection well. Fluid pressures that could initiate hydraulic fracturing or propagate existing fractures in the injection/storage zone could significantly alter the containment or storage properties of the storage zone and subsequently cause upward migration of injected surface waters or other formation waters into other formations within the underground source of drinking water (USDW). For this reason, the Underground Injection Control (UIC) regulations do not allow injection pressures to exceed that which may cause hydraulic fracturing. Therefore, an analysis of the pressure values beyond which fracturing is likely to occur is required specifically by UIC Rule 62-528.415(1)(a), F.A.C.

Estimation of the critical pressure can be made using information readily available from the literature. This estimate can then be evaluated in light of the expected injection pressure buildups to determine if testing is needed to estimate the fracture pressure more precisely. If testing is deemed necessary, fracture tests can be done in connection with drilling of test holes for other needs.

Strategy

Estimate critical fracture pressure: With formulas available in the literature, estimate critical fracture pressure and compare this to likely injection pressure buildup. The estimate can be done immediately for nominal cost, but comparison with expected injection pressure buildup must await modeling analysis of the expected pressure buildup.

If the estimated critical fracture pressure is approached by the expected injection pressure buildup, then actual fracture testing is advisable to do in conjunction with the drilling of test holes. Cost of estimating the critical fracture pressure and comparing it to the expected injection - pressure buildup is nominal. Cost of actual testing to determine critical fracture pressure is about \$20,000 per target injection interval, above the well drilling costs.

ISSUE 4

Analysis of Site and Regional Changes in Head and Patterns of Flow

Description of issue

The Recommended Plan of the Central and South Florida Comprehensive Review (the Restudy) includes several large-scale ASR applications. Clusters of ASR wells are planned for the Caloosahatchee River basin, Lake Okeechobee, and several sites along the lower east coast of Florida. Although ASR is a proven technology in Florida, and across the country, the magnitude of application anticipated in the Restudy has not been attempted. Accordingly, the impacts of a regional scale ASR program need to be evaluated. The employment of many injection wells operating simultaneously in the Caloosahatchee-Okeechobee-Hillsboro basins will result in significant well interference among them owing to the highly diffusive nature of the Upper Floridan aquifer. Each operating injection well will impose an incremental head buildup on other wells in the area, such that the combined effects of all the wells operating simultaneously will result in significant regional hydraulic head changes. In addition, the displacement of the existing saline water in the Upper Floridan aquifer with the injected freshwater could result in additional regional head changes. The potential increases in hydraulic head would influence at the least the design and pump sizing of the ASR system, and perhaps the overall feasible magnitude of the ASR application. Understanding hydraulic interactions between ASR well clusters could be important to the development of operational schedules. Regional hydraulic head changes would result in changes to subsurface flow patterns throughout South Florida that could impact existing ASR, supply wells, or UIC monitoring wells in the region. The ability to predict the various head changes due to regional ASR is crucial to the ASR program.

Previous modeling of the upper Floridan aquifer conducted in connection with the Limited Aquifer Exemption applications for West Palm Beach and Miami-Dade, have demonstrated that the lack of suitable data on leakance of the ASR storage zones substantially inhibits any efforts to estimate hydraulic response of the regional system to proposed ASR operations. Until this data becomes available, modeling efforts can only bracket potential water level response of a regional system within a broad range. Accordingly field data collection is needed to gather this leakance data from several pump tests conducted on ASR wells and test wells in this aquifer.

Strategy

In order to predict the impacts of regional scale ASR, a groundwater modeling effort would be necessary. The model must cover all of south Florida and be capable of simulating variable density flows. FEMWATER, a 3-D groundwater model currently used by the Corps in South Florida, would be adequate for the regional investigation. Alternately, the model HST3D used by the USGS would also suffice. To evaluate localized

pressure changes, and solute mixing a different scale would be necessary but the same model codes could be used. The modeling simulation period could be as long as two years.

Sufficient data probably does not exist to initiate the model development; however ASR Assessment Item #2 (Characterization of regional hydrogeology of Upper Floridan aquifer) would establish data availability. Some publications have characterized the Floridan Aquifer System including a USGS publication on subsurface storage in the Floridan (Meyer, F.W., 1989, Hydrology, Ground-Water Movement, and Subsurface Storage in the Floridan Aquifer System in Southern Florida, USGS Professional Paper 1403-G). The potentiometric surface or lines of equal hydraulic head, in south Florida shows a head of about 120 feet in the area between Orlando and Tampa. The head is about 60 feet in the vicinity of the western side of Lake Okeechobee and reduces to the east, west, and south to lower levels. Flowlines generally run to the east and west of the groundwater divide (which is parallel to, and half way between, the coasts in South Florida.) Results of the regional modeling would indicate the regional changes in head and pattern of flow.

To obtain reliable leakage data, pumping tests are required on existing wells in the upper Floridan aquifer that have one or more associated observation wells nearby. Effort is needed to identify such sites and to pump these wells at high rates for durations probably in the range of several days to weeks. At some sites such data may be relatively easily obtained since the pumping facilities are in place. At other sites this will require some effort to provide the necessary equipment. Two suitable sites exist in Miami-Dade county; at least one in Broward County, and at least two in Palm Beach county. Once such data becomes available, it would be appropriate to initiate modelling efforts to estimate regional water level response to large scale ASR operations at proposed sites, and perhaps at other sites more dispersed throughout the region if local water level response is deemed too large at the initial proposed sites.

When the data required for model development are available, approximately six (6) months of effort by a senior modeler would be needed to prepare the model. After that time, modeling of various scenarios would be possible. The initial model development cost would be about \$150,000 including management costs.

A single scenario may take about two (2) weeks for evaluation. Typical scenarios would be developed to evaluate the aquifer impacts of individual clusters of ASR wells (e.g. wells around Lake Okeechobee) as well as interactions between proposed clusters (e.g. wells around Lake Okeechobee and wells in the Caloosahatchee River Basin, or among LEC clusters). The estimated cost for several scenario evaluations plus supporting graphics and documentation could be about \$150,000. Thus, the total cost of the analysis could be about \$300,000.

In the event that the available data is deemed insufficient to construct a suitable model of ground water flow in the Upper Floridan aquifer in South Florida, a superposition simulation approach could be used to evaluate likely head changes resulting from the simultaneous operation of the ASR wells. This effort would produce potential changes in head rather than actual heads and be based on assigning reasonable ranges of aquifer properties. Information from this exercise could be used to evaluate quickly the viability of

the regional ASR at the proposed scale. This analysis could be done in about six (6) months at a cost of about \$65,000, including the production of an assessment report.

ISSUE 5

Analysis of water quality changes during movement and storage in the aquifer

Description of Issue

To date, 6 ASR facilities using water treated to drinking water standards have been permitted in Florida. In addition, 7 potable water ASR facilities are undergoing operational testing and 3 are in the cycle testing stage. Attachment 1 identifies ASR facilities in Florida by their source of water and permitting status. These sites have never exceeded the maximum contaminant levels (MCL) for the Federal and state drinking water standards, or minimum criteria, nor have they posed a threat to the public health due to the geochemical interactions between storage waters and the storage zone aquifer matrices.

However, because of the nature of the injectate, the variability and complex hydrogeologic nature of the Floridan aquifer system and recent geochemical results from geochemical studies in Hillsborough and Manatee Counties, these interactions require further investigation to determine the feasibility of utilizing ASR on a regional scale as proposed in the Central and Southern Florida Project Comprehensive Review Study. Although unlikely, if geochemical analyses indicate that there may be potential concerns due to ASR interaction with the storage zone aquifers, then the ASR facilities can be designed to minimize potential problems. In addition, the stored lake water recovered from the ASR wells will be discharged back into Lake Okeechobee, which will allow for mixing and further dilution.

The effect of the aquifer matrix on surface waters stored underground and the effect on the aquifer matrix by the stored waters are matters which are worthy of investigation for the proper development and monitoring of an ASR facility.

Surface waters injected underground may have chemical and physical characteristics quite dissimilar to the native waters they displace. The rocks comprising the aquifer matrix have attained their present chemical and physical state partly as a result of interactions with the native waters. The introduction of waters with different characteristics may accelerate, inhibit or otherwise modify the previous naturally occurring rock-water interactions on a regional scale. Correspondingly, the naturally occurring rock-water interactions and geochemistry may modify the chemical constituents that are introduced through recharge and storage.

Extensive agricultural operations are common in the areas around Lake Okeechobee. In general, the typical lake water chemical parameters of concern associated with such

practices when introducing such waters into a ground water aquifer system can be broadly classified as the following:

- a. Nutrients essential for plant growth such as nitrogen (i.e., nitrite, nitrate, and ammonia) and phosphorus compounds such as total phosphorous, and orthophosphate;
- b. Organic Compounds which are defined as compounds that are comprised mainly of carbon, nitrogen, and hydrogen;
- c. Pesticides which consist of a wide range of compounds that can be generally classified by their targets such as herbicides, fungicides, or insecticides;
- d. Pathogens which are microorganisms that can cause specific human diseases include viruses, protozoa, and bacteria. Examples of these would be enteric viruses, fecal coliform bacteria, and protozoans such as *Cyrtosporidium*, and *Giardia lamblia*;
- e. Metals associated with agricultural use include lead, copper, nickel, chromium, iron, manganese, selenium, barium, and zinc. Most of these metals, however, have very low solubilities at the pH found in most natural waters, and they are readily removed by either sedimentation or sorption removal processes;
- f. Dissolved minerals and solids of primary concern are primarily salts. These salts include calcium, potassium, sodium, chloride, fluoride, bicarbonate, and sulfate;
- g. Suspended solids which are usually defined as the nonfilterable portion of a water sample after filtering through a 0.45 m m filter;
- h. Dissolved oxygen (DO) is important because ground water is typically in a depleted DO or reduced state. Increases in DO can affect the geochemical interaction between aquifer matrices and the stored waters (see discussion below) and can affect the solubility and chemical and microbiological reactions of many of the above parameters; and
- i. pH which can affect the solubility and chemical and microbiological reactions of the above parameters.

The major constituents to be investigated should be based on the Lake Okeechobee water quality analyses that will be utilized to characterize the lake water chemistry or the final injectate chemistry if treatment is provided prior to injection. However, due to extensive agricultural practices (i.e., fertilization, irrigation, livestock and etc.) and to a lesser extent urban runoff in the area, it is probable that relatively high concentrations of many of the above chemical constituents will be observed in the lake waters and/or injectate.

The exact behavior (i.e., mobility, sorption, precipitation and microbial interaction) of these parameters once injected into a ground water aquifer system involves complex interactions which may be site specific and thus, needs to be investigated independently at each proposed ASR system. For example, the following discussion represents potential interactions of some of the above parameters in ground water systems and potential storage zone aquifer water-rock geochemistry as gleaned from the scientific literature.

Nutrients

Phosphorous in the form of soluble orthophosphate (the form of phosphorous found in most fertilizers) may be either directly precipitated or chemically adsorbed onto the aquifer matrix through reactions with iron, aluminum or calcium. The dominant precipitation reactions are pH dependent, forming mostly iron and aluminum phosphates under acidic conditions and calcium phosphates under alkaline conditions. Concentrations of nitrogen species in the form of nitrate, nitrite, ammonium and urea can be decreased through denitrification, a biological process that requires indigenous aquifer microbes, anaerobic conditions and organic carbon for food for the denitrifying bacteria which in turn produce free nitrogen gas and nitrous oxides.

Organic Compounds

Degradation of organic compounds can occur through sorption, hydrolysis, and microbial degradation. Temperature, pH, DO, and cation exchange capacity all effect microbial degradation of organic compounds. The end products of aerobic degradation include carbon dioxide, sulfate, nitrate, phosphate, and water while the end products under anaerobic conditions include carbon dioxide, nitrogen, hydrogen sulfide, and methane. For example: An industrial waste injectate containing organonitrile compounds and nitrate has been injected into the lower limestones of the Floridan aquifer system near Pensacola Florida since 1975. Chemical analyses of the water from the monitor wells and backflow from the injection well indicate that organic compounds are converted to carbon dioxide and nitrate is converted to nitrogen via indigenous anaerobic bacteria. The reactions are virtually completed within 100 meters of the injection well.

Pesticides

Adsorption and desorption control the movement of pesticides in ground water. Decomposition of pesticides can range from days to years in ground water and are dependent on many factors including pH, temperature, light, DO, compound volatility, sediment type, persistence/half-life, and microbiological activity.

Pathogens

Several factors influence the survival of enteric microorganisms in ground water. These include temperature, type of microorganism, salinity, turbidity, DO, pH, metal concentration, nutrient availability and indigenous microbial antagonism. DO and temperature are the most significant factors in the loss of enteric virus and bacteria activity. Higher concentrations of DO may cause direct oxidation of components of the virus capsid which inactivates the virus or increases the activity of the antagonistic microorganisms. At temperatures below 40C, microorganisms can survive for months or even years, whereas at higher temperatures, inactivation or dieoff occurs rapidly.

At temperatures between 22o to 28o C which are typical of Florida recharge waters and ASR storage zones, it could take as few as 1 to 3 days for 99% of the enteric bacteria to die off. Decreasing pH promotes virus adsorption and results in shorter survival times for both the enteric viruses and the antagonistic bacteria. Generally there is an inverse relationship between enteric microorganisms and salinity. Coliforms survive poorly in saline waters (at TDS concentrations of 30,000 mg/L). The development of a fresh water "bubble" in the storage zone, however, could result in a higher survival rate of enteric microorganisms.

To date the data on survival of enteric protozoa (i.e., *Cyrtosporidium*, and *Giardia lamblia*) in ground water are sparse. In waters of increasing salinities no increase in dieoff was observed between fresh waters and marine waters, unless sunlight was involved. Therefore, it is unlikely that a greater dieoff of *Cyrtosporidium* oocysts or *Giardia* cysts would be observed in a storage zone aquifer based on a salinity increase. However, other factors may influence the dieoff rate such as changes in redox conditions or compatibility with the storage zone aquifer matrix which may affect sorption or act as a filter system.

Dissolved Minerals and Solids

Major sources of dissolved solids in surface waters such as lakes are from agricultural practices and include fertilizers and pesticides. The concentrations of sodium, chloride, sulfate and other dissolved minerals vary with season and are likely related to precipitation and irrigation patterns. Addition of dissolved minerals into the aquifer system may affect the pH of the ground water resulting in high concentrations of undesirable elements, such as iron, manganese, and aluminum in acid waters, and sodium, carbonates, and bicarbonates in alkaline waters. The effects of sulfate and chloride concentrations on mercury bioaccumulation are discussed in detail in Issue 6.

Storage Zone Aquifer Water-Rock Geochemistry

A major concern for stored waters is the entrainment of various naturally occurring radioactive nuclides and trace elements such as arsenic, barium, manganese and strontium. In Florida, Eocene through Miocene carbonate rocks often have zones displaying considerable radioactivity. This is most apparent in borehole geophysical logs that reveal multiple zones of high gamma-ray activity coincident with layers rich in clay, organics, phosphate or dolomite. Members of the uranium series, which includes ²³⁸U and ²³⁴U, ²²⁶Ra, ²²²Rn, and ²¹⁰Po, are often associated with these zones. The geochemistry of each of these elements varies such that waters of a certain character could mobilize one or more of these without necessarily mobilizing all of them. If, however, the "injected" surface water being stored has the capability of actually dissolving some of the aquifer rock, all of the uranium series nuclides are mobilized and their transportability is a function of the dissolving waters.

Uranium is quite mobile when in contact with oxic waters whereas it is essentially immobile when exposed to waters of a reducing nature. Under reducing conditions uranium near the surface of a grain or crystal becomes somewhat depleted in the isotope ^{234}U because of recoil effects associated with the radioactive decay of its parent ^{238}U . The surrounding reduced water would be the recipient of some of the recoiled nucleus (effectively, ^{234}U). Thus the "native" water would tend to have a low uranium concentration coupled with an excess of ^{234}U relative to ^{238}U . Aggressive oxic waters, which then come in contact with the aquifer matrix, would tend to mobilize all of the uranium near the grain surfaces, partially by dissolution of the grain itself. The result would be a water having a relatively high concentration of uranium which is relatively deficient in ^{234}U compared with the ^{238}U .

Also of interest is the well documented observation that the ratio of two isotopes (^{87}Sr and ^{86}Sr) of strontium, an element always incorporated in marine limestones as well as in other rock types, is found to vary essentially monotonically in rocks of Eocene age to the present. In other words, the isotopic ratio of strontium in marine carbonate rocks is unique to the time at which the rocks were deposited. Thus, if surface waters (having a particular strontium isotope ratio) are aggressive and dissolve some aquifer rock when injected, the resultant strontium ratio in the waters will be some mixture of the two strontium sources. Under favorable circumstances it is possible that a reasonable estimate of the amount of rock dissolution could be calculated. Moreover, ground water flow paths can be traced using $^{87}\text{Sr}/^{86}\text{Sr}$ ratios based on mixing models between older and younger (or deeper and shallower) waters.

A recent Florida Geological Survey study (Open File Report 61) in Hillsborough County demonstrates that up to 32 percent of the uranium in Floridan aquifer system rocks can be leached when exposed to oxidizing conditions in the laboratory. This further underscores the need to investigate the effects of pumping oxygen-rich surface waters into the aquifer. Analysis of both rock and water samples is necessary to track the source and mobility of uranium.

Water quality analyses for trace elements from the City of Tampa, Rome Avenue potable water ASR system on the Cycle 2 recovered waters were recently conducted by the Florida Geological Survey (FGS). The uranium concentrations increased from ~ 0.5 to 7 m g/L (which equates to approximately 3 pCi/L of gross alpha). Arsenic concentrations increased from <2 to 35 m g/L. The Federal primary drinking water standard maximum contaminant level (MCL) for gross alpha is 15 pCi/L and for arsenic is 50 m g/L.

The potential for high concentrations of arsenic in the recovered waters should be a concern at the Okeechobee ASR sites. At this time, the source of arsenic is not known (i.e., anthropogenic or naturally occurring). Arsenic occurs naturally in carbonate sediments at approximately 1 part per million (Drever, J., 1988, *The Geochemistry of Natural Waters*, Table 15-1) and can occur in higher concentrations in organic or phosphate bearing sediments. As stated above, waters in aquifer systems may exist in equilibrium with the aquifer rock matrix. The introduction of oxygen rich surface waters may modify the previously geochemically stable water-rock conditions.

Like uranium, arsenic can be leached from the sediment when the ambient redox potential changes from reducing to oxidizing conditions or when dissolution of the aquifer matrix occurs as a result of introducing aggressive oxygen-rich injection waters.

Water-rock geochemical processes occur during the ASR cycling process that affect water chemistry and quality. These processes can affect the minerals comprising the aquifer system matrix and characteristics of native and recharge waters. Current research at the Florida Geological Survey demonstrates that the nature and magnitude of geochemical processes related to ASR are site specific. Subtle changes in the composition of the aquifer system matrix may affect water chemistry to levels that approach a human health concern. Site specific research is needed to characterize these geochemical processes to better understand their effects and facilitate science-based recommendations regarding site design and monitoring programs.

Radium, which is a decay product of uranium, has not been investigated in the ASR setting. Uranium concentrations measured at other ASR facilities in Florida have approached 14 pCi/L. The Florida Department of Health and Rule 62-550.519(c), F.A.C., requires that radium be analyzed when reported gross alpha values exceed 5 pCi/L. It would be pertinent to include radium as a measured parameter within this investigation to clarify its role in the ASR geochemical process.

Strategy

In order to observe changes in the storage zone aquifer chemistry during recharge, storage and recovery, it is recommended that each proposed ASR storage zones be monitored by an on-site monitor well. The storage zone monitor well should be located near enough to the ASR production well to intercept the storage bubble during periods of recharge yet far enough to monitor the affect of returning ambient waters to this zone during periods of recovery.

It is proposed that a study of an ASR project be carried out, measuring the native waters, the waters being injected, the stored waters and waters withdrawn after storage, and appropriate rock samples (cores and cuttings) of the aquifer matrix. The major parameters of concern should be based on the Lake Okeechobee water quality analyses utilized to characterize the lake water chemistry and/or the injectate water quality analyses if the lake waters undergo treatment prior to injection. Samples should be collected from both the production well and storage zone monitor well during all phases of ASR.

Water quality data, at a minimum, should include conductivity, temperature, pH, DO, iron, phosphorus, nitrate, nitrite, ammonia, total kjeldahl nitrogen (TKN), biological oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), pathogens such as total and fecal coliform and protozoans (i.e. *Cryptosporidium* sp. and *Giardia lamblia*), sulfate, chloride, fluoride, bicarbonate, and pesticides, metals and organic

compounds that are specific to the injectate, and all other parameters of concern as determined by the lake and injectate water quality analyses.

Other analyses to be carried out that are directly related to the storage zone aquifer water-rock geochemical interactions will be uranium concentration and the radioactivity ratio of ^{234}U to ^{238}U , strontium concentration, $^{87}\text{Sr}/^{86}\text{Sr}$, radium, and trace metals analyses (including, but not limited to As, Ba, and Mn). Major ion analyses (such as Na, Mg, Ca, Cl, SO_4 , and HCO_3) should be evaluated in the context of water-rock chemical interaction.

ISSUE 6

Aquifer Storage and Recovery Potential Effects on Mercury Bioaccumulation for South Florida Ecosystem Restoration Projects

Description of the Issue

There is presently no information about whether ASR will make the South Florida mercury problem worse. Its potential to do so requires investigation. Even if ASR proves to have the potential to exacerbate the South Florida mercury problem, which would not necessarily rule it out as a method for storing water. Its effects may be negligible or it may be possible to limit them to an acceptable level through operational controls. Methylmercury is a highly toxic derivative of inorganic mercury, which is synthesized by sulfate reducing bacteria under anaerobic conditions from inorganic mercury and a reduced carbon source.

Methylmercury is readily concentrated at the base of the food web and biomagnified at each trophic level. Water quality modulates the potential for these conversion and accumulation processes to occur; a number of studies elsewhere have found that correlates of methylmercury bioaccumulation, under certain circumstances, are pH, chloride and sulfate. Bioaccumulation of mercury in South Florida fish has necessitated consumption warnings from the Florida Department of Health. The Florida Department of Environmental Protection has determined that these health warnings impair the beneficial use of recreation for which these waters are to be protected. Everglades' populations of top predators feeding in the aquatic food web also may be at risk. Because there is already a mercury problem in South Florida, it is necessary to determine if ASR is likely to exacerbate that problem and, if it does, to determine if the result can be made to meet Florida water quality standards.

Inorganic mercury is deposited on South Florida from the atmosphere from sources that are both natural and anthropogenic, and both local and global. Although much research is in progress under the South Florida Mercury Science Program¹, there are no immediate prospects for control of sources of inorganic mercury or its conversion to methylmercury. For the near future, only local sources of atmospheric mercury are subject to potential

control. Because such controls may have little effect on mercury methylation and bioaccumulation rates, they cannot be imposed until they have been shown to be effective.

In certain circumstances, the rate of bioaccumulation of methylmercury may depend upon the concentrations of sulfate and chloride, which are constituents of salt water that may be added to recovered water by the ASR process. This is the principal reason for believing that ASR has the potential to affect mercury bioaccumulation. It is important to understand that we do not know that adding chloride or sulfate to South Florida waters will actually exacerbate the mercury problem; we only know that these ions have the potential to do so. In ASR, the ability to recover usable water depends in part upon the salinity of the receiving aquifer. Where the density of the receiving water is considerably greater than that of the stored water, buoyancy may result in mixing. In this situation, there will be some degree of mixing of the original fresh water with the brackish water of the storage matrix.

Where the density difference is large, the recovered water will have additional salts compared to injected water. The resulting increase in salts in the recovered water is difficult to eliminate entirely and may limit the percent of injected fresh water that can be recovered. Where the density difference is less, the buffer zone may be increased to reduce mixing and the increase of salts in recovered water to a low level.

Water recovered from ASR wells using Lake Okeechobee as a source will be discharged back into Lake Okeechobee and there afforded some opportunity for mixing. Lake Okeechobee contains sulfate and chloride. In some scenarios, Lake Okeechobee water will be transported via canals in the Everglades Agricultural Area (EAA) to Stormwater Treatment Areas (STAs, which are man-made marshes) and, thence, to the natural Everglades. Along this route, the Lake water will mix with EAA drainage which contains sulfate from oxidation of sulfur used as a soil amendment as well as sulfate and chloride from entrained, connate sea water. Chloride would be expected to pass through the STAs. At times, STAs may remove a portion of the sulfate.

Based on current data and understanding, ASR enhancement of mercury methylation or bioaccumulation is not expected in Lake Okeechobee, the EAA canals or the STAs. If there is an effect, it is likely to be in the Everglades. Water discharged from the STAs into the natural areas, will contain sulfate and chloride from ASR, Lake Okeechobee, and the EAA. The relative contribution of ASR is not known, but its range can probably be estimated from available data. If the relative contribution of ASR to sulfate and chloride in the STA discharges is negligible, ASR is unlikely to affect the bioaccumulation of mercury in Everglades biota.

If the relative contribution of ASR to sulfate and chloride in STA discharges is not negligible, additional investigation is required to determine if potential mercury effects require further consideration before ASR implementation. Work is in progress to determine how changes in chloride or sulfate concentrations will affect the rates of methylation of mercury and its bioaccumulation. This work is independent of the Restudy and will proceed at a pace limited by its funding.

The South Florida Mercury Science Program has developed much useful information about the transformations of mercury in the Everglades marsh, but the state of knowledge of biogeochemical mechanisms for the production and destruction of methylmercury is still incomplete and mostly qualitative. There is an added complexity in that trophic state affects both the biogeochemistry and the food web relations that help determine bioaccumulation of methylmercury in top predators. Many of the primary variables have been defined, but for the most part, we are not able to predict the direction of change of methylmercury bioaccumulation that would result from altering one or more of these variables.

Research investigating the effects of chloride and sulfate from ASR may be completed before the time necessary to make decisions about using ASR. If research shows that ASR effects on mercury bioaccumulation impair enjoyment of the beneficial uses of the Everglades, this would not necessarily rule out the use of ASR. It may be possible to limit contributions of chloride and sulfate through operational controls. It may be possible to offset the contributions of ASR through controls on other activities. It is also possible that a relative ecological impact study would show that the net effect of ASR is beneficial.

Strategy

If the changes caused by ASR in chloride and sulfate concentrations have a negligible effect on the rate of bioaccumulation of methylmercury, there is no cause for concern. This situation may arise if ASR increases chloride and sulfate concentrations, but those increases have no effect on bioaccumulation rate. To determine if this will happen requires basic biogeochemical studies and modeling to simulate the effects of chloride and sulfate concentrations on methylmercury production and its bioaccumulation. It also requires knowledge of the changes in marsh chloride and sulfate to be brought about by ASR. A negligible effect on the rate of bioaccumulation of methylmercury may also arise if there is a negligible change in the concentrations of chloride and sulfate in the marsh due to ASR. This may be the result of operational controls or as the result of mixing with surface waters prior to discharge into natural areas.

Consideration of all of these situations requires the ability to simulate, from the routing and dilution, the effects of ASR on chloride and sulfate concentrations at the point of discharge from the STA into the Everglades². This is a fairly straightforward process that can probably be done with existing data and needs to be done. A request for proposal is required to estimate the cost and time required.

Work is in progress to create a mathematical model that will simulate mercury transformations in the Everglades. However, much detailed information about aquatic cycling processes and their rates is needed before this model can be applied with confidence. Such a model is essential to predicting effects on mercury cycling induced by water quality changes and for determining if control of mercury bioaccumulation is feasible.

The time required to make this model useful for various purposes depends mostly upon funding. Both the USGS and USEPA have made major contributions to this work but their continued commitment to either biogeochemical process studies or model development are most uncertain.

The preceding discussion has been concerned with the indirect effects of ASR derived chloride and sulfate on mercury bioaccumulation in the Everglades marsh. There is a slight possibility that inorganic mercury present in the injected water or in the aquifer matrix may become methylated by sulfate reducing bacteria during storage and become a constituent of recovered water. Sulfate reducing bacteria are known to be active in some underground waters. Depending upon the resulting methylmercury concentration in the recovered water and its ability to pass through any treatment process, underground methylation of mercury could have an effect on biological systems receiving the waters or on the health of consumers of this recovered water. While the concentrations of methylmercury in recovered water, if any, are likely to be too low for significance to human health, the possibility of mercury health effects on consumers of ASR recovered water should be examined. This concern can be addressed readily and at minimal cost by analysis of representative samples of injected and recovered water.

1. 1 The South Florida Mercury Science Program (SFMSPP) is a consortium of the Department of Environmental Protection, the South Florida Water Management District, the U.S. Environmental Protection Agency and the U.S. Geological Survey, the Florida Game and Freshwater Fish Commission, the U.S. Fish and Wildlife Service, the U.S. Park Service, the U.S. Army Corps of Engineers, the University of Florida, Florida State University, Florida International University, University of Miami, University of Michigan, University of Wisconsin, Texas A & M University, Oak Ridge National Laboratory, Academy of Natural Sciences of Philadelphia, Florida Power and Light, Florida Electric Power Coordinating Group, and the Electric Power Research Institute.
2. 2 Note that the relative contribution must be estimated as a function of time and antecedent conditions and not as a time average. This information is also required to ensure that ASR will not result in unacceptable changes in ionic strength (conductivity), which may have ecological effects independent of mercury.

ISSUE 7

Relationship between ASR storage zone properties, recovery rates and recharge volume

Description of issue

For large scale regional ASR storage, uncertainty exists regarding the storage interval(s) to be selected within the upper Floridan aquifer, the hydraulic properties of potential storage intervals, potential recharge and recovery rates, and associated volumes that may be recharged, stored and recovered. In particular, concern has been expressed that the proposed scale of ASR operations (1.7 BGD) is so much larger than any current ASR operations in this aquifer, that considerable demonstration testing will be required to verify whether this aquifer can efficiently store the required volume of water, without unacceptable levels of adverse effect, and yield an acceptable percentage of that water during recovery.

Until recently, very little significant testing or wellfield operations had been conducted in this aquifer. During the past five years, initial data has become available to guide planning of ASR operations in the upper Floridan aquifer, however further field investigations, modeling and operating experience are required to address these important questions. ASR demonstration projects are currently planned at the north end of Lake Okeechobee and on the Hillsboro Canal. These sites were selected to test the applicability of ASR in two functions:

1. Water level control in Lake Okeechobee, and
2. Reductions in the discharge of surface water to tide through the major canals.

More test ASR projects will have to be constructed in other locations before it can be determined if the technology can serve all of the purposes to which it is applied in the Restudy. The recharge volume, recovery volume and recovery rates required in the applications of ASR are dictated by the site selection and recharge water source. It will be the challenge of the ASR system designers to identify a storage zone that can perform to meet these requirements. In this section, we would like to propose that the storage zones be tested in a thorough way that will enable the designer to select the zone that meets the needs.

Strategy

Demonstration testing of ASR wells and well clusters at several sites is needed to address these uncertainties. Several factors need to be considered in the design, location and implementation of the demonstration tests. These include site selection, scale of testing, storage interval selected, recovery yield, recharge and recovery volume, and recovery efficiency. These factors are discussed below in greater detail, followed by recommended actions to achieve the level of confidence that is desired.

Site Selection and Scale of Testing:

Sites should be selected for demonstration tests that represent not only the geographic range of regional scale ASR opportunities, but also the range of potential applications to meet urban, agricultural and ecosystem needs. Two sites are currently planned for demonstration testing by the SFWMD, one at the north end of Lake Okeechobee and one on the Hillsboro Canal. These two sites address ecosystem, urban and agricultural water storage needs. In addition, several other ASR demonstration test sites are either already underway or about to begin in Dade, Broward and Palm Beach counties, addressing primarily urban and ecosystem water storage needs. As the data from these tests becomes available, it will be possible to improve understanding of this aquifer system and its response to proposed ASR operations.

Future ASR demonstration sites should be located where large seasonal volumes of water with acceptable quality are available for storage, and where recovered water would provide regional benefits.

Such future sites might include Buffer Preserve Areas and other locations along major canals where they exit the Water Conservation Areas; along the Caloosahatchee River, and probably other locations.

A key initial element of site selection is the need for identification of potential regional ASR sites; analysis of existing water quality data at these sites, determination of additional data needs; collection and analysis of supplemental water quality data; and prioritization of potential sites according to technical criteria such as available recharge flows and associated recharge water quality. Early completion of this task can guide future ASR demonstration site selection.

The number of ASR demonstration test sites required to address the key areas of uncertainty is probably in a range of five to ten, depending primarily upon the scale of testing at each site, and the extent to which it is representative of the range of hydrogeologic conditions and proposed ASR applications. Each site should include several full size ASR wells, each equipped to recharge and recover water at rates as high as can reasonably be sustained during seasonal operations, probably in a range of 5 to 10 MGD. Almost all ASR wells constructed to date in S. Florida have been equipped for testing or operation at rates substantially below well capability. It is particularly important that large

diameter (ie: 24", 30" and possibly larger) ASR wells should be constructed and tested, since experience has shown that ASR testing on small diameter wells in this productive aquifer will not provide representative results and cannot be relied upon to provide firm conclusions regarding the identified areas of ASR uncertainty.

As the number of ASR wells and well clusters increases, and years of operating experience are gained with these systems, the level of uncertainty will decline. At the same time, these wells will be contributing toward meeting regional water storage needs, providing immediate and tangible benefits. For example, if it is assumed that 10 ASR demonstration projects are constructed and placed into operation, with an assumed total of 50 ASR wells, regional recharge capacity will be in an expected range of 0.25 to 0.50 billion gallons per day (BGD), which may be compared to planned total capacity of 1.7 BGD.

During wet years, these wells would have the capability to store between 0.3 and 0.6 million acre feet per year (MAF). This storage volume is a significant portion of total planned storage requirements contemplated in the Restudy (2 MAF). This stepwise approach to ASR development will provide the opportunity to "learn as we go," making adjustments to system design and operation as new experience is gained, and integrating results into adjustment of the overall Restudy plan and its implementation, as appropriate.

Storage Interval:

Two storage intervals are of significance for proposed regional scale ASR operations in south Florida, both within the upper Floridan aquifer (UFA) at depths ranging between 800 and 1700 ft. These are referred to as the upper and lower intervals.

The upper interval, between depths of 800 and 1350 feet, is recommended to meet regional water storage needs with ASR wells. This interval has high yield for individual wells, and storage capacity far exceeding requirements for regional storage suggested in the Restudy Plan. Water quality is within a range for which successful Florida ASR experience has already been demonstrated within the LEC. The upper interval is reasonably well documented and is typically comprised of one or two production zones, starting in the first competent limestone beneath the base of the Hawthorn formation at depths of 800 to 900 feet and extending to a depth of around 1350 feet. Water quality in the upper interval ranges in TDS concentration between 3000 and 4000 mg/L within the LEC. The greatest uncertainty about the upper interval is its leakage, or hydraulic connection with underlying zones with more brackish water quality. Early indications are

that the degree of separation is adequate for proposed ASR seasonal operations, however operational testing is required to confirm this. Such testing has been initiated and data should start to become available within the next year. Proposed ASR demonstration testing will further define early leakage estimates, providing a firm basis for subsequent hydrogeologic modeling to predict regional water level response to ASR operations.

The lower interval, at depths extending below 1,300 feet, also offers potential for regional ASR purposes, however this represents a higher level of risk due to lack of adequate data to support current planning. Future ASR demonstration test programs should focus initially on the upper interval, but also where possible incorporate data collection in the lower aquifer to evaluate whether its use for storage could substantially reduce program costs by allowing more concentrated storage at fewer, more desirable sites, and thereby reducing infrastructure requirements. The lower interval is less well documented due to the very small number of adequately-sized test holes extending to this depth, and may not be present at some sites.

It has been identified at the Miami-Dade and also at the Lake Okeechobee ASR wells. Where found, it is very productive and occurs just above the base of the upper Floridan aquifer at depths of around 1600 to 1700 feet. Water quality appears to be more brackish, with TDS concentrations ranging from 4000 to 7000 mg/l.

At each demonstration test site, initial test hole construction should be implemented to gather data on local geology, production intervals and water quality. Data from this small diameter test hole would then be utilized to provide a basis for design of the subsequent large diameter ASR wells. These wells should be constructed and tested before pump selection is completed, so that recharge and recovery rates are matched to well and aquifer hydraulic characteristics.

Separating the upper and lower production zones are limestone formations of relatively low yield and probably low vertical permeability, although some minor production occurs within this interval in wells penetrating the full thickness of the upper Floridan aquifer.

The lower interval offers the opportunity for achieving regional storage objectives at lower cost than with use of the upper interval, since ASR wells could be constructed within both intervals, or possibly could be open to the full thickness of the UFA.

However, the level of uncertainty is much higher at this time in the lower interval, primarily due to the absence of data on the occurrence and storage properties of this interval. Since it is probable that all ASR objectives can be achieved cost-effectively in the upper interval, there is little incentive at this time to base planning on use of the lower interval or the full aquifer thickness. At such time as regional ASR demonstration testing is initiated within the LEC, consideration should be given to designing well construction and testing programs to gather data on both the upper and lower intervals, and their interaction. However, for current purposes it is sufficient to base planning upon use of the upper interval alone.

Recovery Yield:

Based upon test data from the Miami-Dade, Broward, West Palm Beach and Lake Okeechobee ASR wells, the recovery yield of individual ASR wells penetrating the upper interval is probably in the range of 5 to 10 MGD. Existing ASR wells have been equipped

for production at rates ranging from 2.5 to 5 MGD, since wellhead designs had to be finalized before these wells could be constructed and tested. However properly sized and equipped wells penetrating the upper interval should be able to recover at substantially higher rates.

In the lower interval, higher production rates are probably achievable, perhaps in the range of 10 to 15 MGD based upon limited available data. This high capacity production zone may not be present at all sites, however.

Of equal importance to regional scale ASR operations is the combined recovery rate attainable from a series of ASR well clusters distributed throughout the LEC. Interference between wells and well clusters may create substantial hydraulic response in the upper aquifer, with increasing wellhead pressures during seasonal recharge and substantial drawdowns during seasonal recovery. Net effect upon average water levels would be neutral if recharge and recovery volumes are equal. More likely is that recharge volume will exceed recovery volume on a long-term sustained basis, causing some increase in average water levels in the upper interval. Part of this increase would be due to freshening of the interval with marginally lower density water, but most of the increase would be due to a regional mounding of the potentiometric surface due to net recharge.

For a regional scale ASR system with a planned recovery capacity of 1700 MGD, perhaps distributed among about ten ASR clusters totaling 170 to 340 wells, water level effects would be substantial but short term. Experience to date suggests the possibility that water level effects may be more substantial in southern portions of the LEC than in more northerly portions. Modeling efforts to date have highlighted the critical need for ASR demonstration testing to confirm representative leakance values for the upper interval. Once leakance values have been determined for existing ASR sites that are beginning testing (Miami-Dade, Broward, West Palm Beach, Delray Beach), refinement of existing models would permit improved assessment of well and wellfield interference effects during ASR operations. Until such data becomes available, further modeling can do little more than bracket a very wide range of possible water level response.

ASR demonstration test programs will provide a steadily increasing basis of operating experience to guide subsequent planning with regard to recharge and recovery rates from individual ASR wells in selected storage zones, and the combined rates attainable with multiple wells and well clusters distributed throughout the region.

Recharge and Recovery Volume:

Recharge volume required to meet Restudy objectives is dependent primarily upon the recovery volume that is desired at each site, and the recovery efficiency characteristics at that site.

The upper interval is roughly equivalent in storage properties to a surface reservoir overlying the storage bubble around each well or well cluster, with a depth of over 100

feet. Storage of one million acre feet per year of water that would otherwise have flowed to tide, would require lateral displacement of brackish water in the upper interval beneath an area of less than 10,000 acres, distributed among all operating ASR wells in this interval. Clearly the volume available for storage far exceeds the volume contemplated for storage to meet south Florida ecosystem, urban and agricultural needs.

Recovery volume will need to be determined based upon consideration of the rate and duration of water needs by all users. Ecosystem needs are more likely to require recovery durations of several months, and associated large storage volumes.

Urban needs are likely to be relatively small since consideration of the time distribution of urban water needs within the LEC suggests that peak demands occur at high rates, but for periods of only a few days each event, and may occur almost any time during the year. Similarly, agricultural water needs occur during dry months and may not represent significant volumes compared to those available with ASR storage.

With south Florida's characteristic variability in rainfall, not only seasonally but also from wet years to drought years, the opportunity exists to utilize storage available within the upper interval to establish a large subsurface reservoir of fresh water to meet both seasonal and long-term water storage needs. Facilities sizing and construction requirements are more likely to be determined by available recharge rates than recovery rates, so the only additional significant expense to build long-term storage would be the cost of pumping more water down the same number of wells.

Recovery volume will also be affected by the proximity of ASR wells to the point of intended use for the recovered water. Substantial evapotranspiration and conveyance (seepage) losses occur within the District's surface water management system. Location of ASR wells at or close to the point of intended use can dramatically reduce the required storage and recovery volumes, and associated costs. Location of ASR wells at locations far removed from the point of intended use will correspondingly dramatically increase the volumes that need to be stored and recovered to meet intended uses, and thereby increase associated costs. Recovery volume, combined with recovery efficiency, will determine the volume required for recharge in order to meet system objectives.

It is anticipated that recharge rates will approximate recovery rates in individual wells. Interference effects within well clusters, and between well clusters, may tend to inhibit recharge rates during extended wet periods however they should not represent a significant constraint during typical recharge operations that would tend to be more intermittent. To the extent that interference effects may prove significant, it will become more desirable and cost-effective to distribute ASR storage sites over a wider area.

Recovery Efficiency:

Until such time as better data becomes available from testing and operations at LEC ASR sites within the next few years, a recommended assumed recovery efficiency is 70%. This

is believed to be a conservative estimate that is below all of the long-term recovery efficiencies attained at five operating ASR sites in Florida during operations ranging in duration from four to 13 years. Each of these sites evaluates recovery efficiency relative to drinking water standards, usually for chloride or TDS although many other constituents are also monitored to ensure compliance. For the Restudy Plan, a primary user of the recovered water may ultimately be the south Florida ecosystems, which may eventually use the water for hydroperiod maintenance if suitable recovered water quality is clearly demonstrated. It is possible that criteria other than drinking water standards may be more appropriate, such as phosphorus. Further investigations are needed to evaluate the recovered water quality needs of the ecosystems, allowing some small vegetated buffer zone around each wellhead so that compliance can be measured at the edge of the buffer zone before the recovered water is discharged into the adjacent wetlands.

It is normal for some mixing to be allowable underground between the native groundwater and the stored freshwater, however the amount of allowable mixing determines the size of the buffer zone required underground in order to achieve ultimate recovery efficiency.

Assuming that recovery efficiency is 70% for regional ASR systems, recharge volumes would need to be at least 40% higher than expected recovery volumes. The concept of a Target Storage Volume (TSV) is appropriate for LEC planning purposes. The TSV is the volume required in storage at any ASR site in order to sustain expected recovery demands for urban, agricultural and ecosystem needs while also meeting recovery water quality criteria. It may be characterized as including the volume that needs to be recovered, plus an additional volume that represents a buffer zone separating the fresh stored water from the brackish native groundwater. It is not yet possible to exactly calculate TSV numbers for proposed ASR sites within the LEC, however experience elsewhere in Florida suggests that TSV estimates are probably in the range of 100 MG to 300 MG per MGD of recovery capacity.

For a 10 MGD ASR well, this would equate to storage of one to three billion gallons. There is no shortage of water in south Florida to achieve this TSV within a reasonable period of time.

Once this TSV is attained, typically during a period of a few years of initial operations, full recovery efficiency should be achieved for all water subsequently stored. Until such time as the TSV is attained, recovery efficiency will tend to be less than 100 percent.

As an example, ASR operations at the Boynton Beach site have shown steadily improving recovery efficiency during the past five years, over 13 cycles of operation, each at a volume of about 40 to 60 MG. Recovery efficiency has climbed from 28-percent initially to 95-percent early in 1998, and should reach 100 percent in the near future. The volume of water stored, but not recovered from this well represents the buffer zone, and has a cumulative volume of about 200 MG, while well design yield is around 2.5 MGD. This well is open to the interval 800 to 900 feet and therefore penetrates only the top portion of the upper interval. It is probable that a greater TSV would be required if the well fully

penetrated the upper interval at this site, however such a well would probably have a much higher yield.

ASR demonstration testing should be conducted in such a way as to show, as rapidly as possible, the recovery efficiency that can be achieved at several sites and the Target Storage Volumes required in order to achieve such levels of recovery efficiency. This will require early development and maintenance of a buffer zone around each well. It will also require care in the spacing of ASR wells at each site, to achieve a reasonable balance between recovery efficiency and well hydraulic interference. More closely-spaced wells achieve the ultimate level of recovery efficiency sooner, at the expense of greater changes in recharge and recovery water levels due to well interference.

Further Investigations Needed:

1. Conduct full-scale demonstration testing of several large diameter ASR wells constructed in the upper interval at 5 to 10 sites selected based upon their proximity to the location where the water is most needed for recovery, their proximity to a suitable source of water for recharge, and their representation of the range of S. Florida hydrogeologic characteristics and ASR applications. This test program will require several years to implement, however the associated ASR facilities should provide immediate water storage benefits to the region.
2. Characterize recovery water quality requirements at the edge of a small buffer zone around each ASR wellhead, for discharge into adjacent aquatic ecosystems.
3. Characterize the typical time variability of recovery water demands for urban, agricultural and ecosystem needs.
4. Evaluate available data sources and conduct additional field investigations to document the reduction in nitrogen and phosphorus that has been observed at some ASR storage facilities. If demonstrated in the LEC, this could offer a major beneficial application of ASR.
5. Develop storage zone testing protocol.
6. Identify individual storage zone producing features
7. Model behavior of the fluid in the aquifer.
8. Estimate pre-injection rates of recharge and recovery and TSV.
9. Develop a cycle testing protocol.
10. Develop techniques to address operational problems.

**See Attachments