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AQUIFER STORAGE AND RECOVERY ISSUES AND CONCEPTS

Aquifer Storage and Recovery Issues and Concepts

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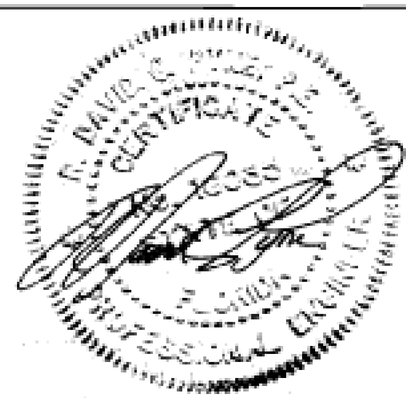

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EXECUTIVE SUMMARY

The St. Johns River Water Management District (SJRWMD) has prepared this paper to inform elected officials and other interested citizens regarding the scientific information that is available to support the decision-making process as it relates to the implementation of aquifer storage and recovery (ASR) technology. This paper has been produced as part of a current Water Resource Development Program in which multiple ASR demonstration sites throughout SJRWMD are being constructed and tested to determine the extent to which ASR can be applied to meet local or regional needs through use of alternative water supplies. The SJRWMD ASR Construction and Testing Program is a 6-year cooperative effort with an estimated expenditure of $27 million.

ASR wells have been operating in Florida since 1983. At least 65 ASR wells in 13 ASR wellfields are in operation, and more than 25 other ASR wellfields are in various stages of development. During the past several years, concerns have been expressed by several public interest groups regarding whether ASR technology has been adequately proven in Florida, in the sense of whether proposed applications for storage of drinking water, treated surface water, reclaimed water, and fresh groundwater in Florida's brackish aquifers may create unacceptable water quality and environmental problems. Concerns have focused on potential leaching of metals such as arsenic, mercury, and uranium from the limestone into the recovered water or into the surrounding aquifer; potential contamination of the aquifer with disinfection byproducts (DBPs); potential contamination with pathogenic microbiota such as bacteria, viruses, and protozoa; and mixing with surrounding brackish water so that recovery efficiency is reduced to below acceptable levels. Similarly, concerns have been expressed by the U.S. Geological Survey (USGS) related to the potential for ASR to alter native groundwater quality to the extent that it may affect the potential future use of that resource. These concerns are all relevant for ASR systems throughout the United States, and in the world. For applications in Florida, these issues can be specifically addressed by looking at data from operating ASR sites and how ASR is permitted and monitored through the regulations and policies of the Florida Department of Environmental Protection (FDEP).

Scientific literature is substantial and consistent in showing that, under hydrogeologic conditions prevalent in Florida and almost all other ASR sites nationwide, DBP constituents are reduced or eliminated rapidly through natural processes during ASR storage, if these constituents are present in the recharge water. The principal mechanism for the reduction in the DBPs is microbial degradation. Several proven approaches are currently used at various Florida water treatment plants to control or eliminate the presence of DBPs in the recharge water, if needed. As such, DBPs should not be an issue for Florida ASR sites.

Metals occur naturally at low concentrations in the limestone of the Floridan aquifer. During ASR storage, these metals may tend to dissolve out of the limestone and create elevated concentrations in the recovered water. Elevated concentrations may also occur in the ASR storage zone. Metal concentrations typically decline with time, with distance from the ASR well, and with successive operating cycles. No long-term operating ASR sites in Florida are known to have elevated concentrations of metals such as arsenic, uranium, or mercury, although metals data are sparse in most of the data sets, particularly those for the older facilities. During initial cycle testing at newly constructed ASR well sites, elevated concentrations of arsenic may occur, particularly at those sites recharging treated surface water due to the generally higher oxidation-reduction potential (Eh) of this water. This poses some concern because in January 2005, drinking water standards for arsenic decreased from 50 micrograms per liter ($\mu g/L$) to 10 $\mu g/L$, which is well within the range of concentrations observed in the recovered water during initial cycle testing at many Florida ASR sites. Typically, it is anticipated that after four to eight ASR cycles at the same storage volume, arsenic concentrations should subside to acceptable levels. This anticipated decline in arsenic is based upon testing and operational experience at 13 ASR wellfields in Florida that have been in operation for up to 21 years. In addition, several approaches discussed subsequently in this paper are available for control of such water during initial cycle testing. There have been no documented instances of water exceeding metal standards having been distributed to the public through drinking water distribution systems from Florida ASR wells.

Pathogenic microbiota are not present in recharge water to ASR wells in Florida, reflecting state and federal regulations and policies by FDEP and SJRWMD to recharge only water that meets drinking water standards for storage in our brackish aquifers. The federal regulations at 40 CFR 144.12(a) require that the injection activity not cause a violation of a primary drinking water standard or otherwise adversely affect the health of people. The state rules reflect the federal requirement. Scientific laboratory investigations and, to a lesser degree, field investigations in Florida, have shown that bacteria, viruses, and some protozoa attenuate naturally and rapidly during ASR storage and under controlled conditions approximating ASR storage. This natural attenuation serves as an additional barrier to protect groundwater quality and public health. No Florida data are currently available regarding the fate of Cryptosporidium and algal toxins during ASR storage; however, such data are available from sources outside Florida. This is not an issue for recharge water meeting drinking water standards.

Recovery efficiency is an indication of how much mixing occurs between the stored water and the native water in the aquifer system. Generally, for storage in Florida's brackish aquifers, efficiency starts out low and improves with successive operating cycles due to freshening of the storage zone around an ASR well. A majority of the ASR wells that have been operating for more than 5 years have reached acceptable and economically viable levels of recovery efficiency. The acceptable level of recovery efficiency varies among individual water users and is generally in the range of 70% to 100%, with higher levels accomplished in less brackish aquifers and lower levels in highly saline or seawater aquifers. However, among the scientific community there is considerable debate as to the definition of recovery efficiency of the aquifer formation in which the ASR well is placed. This concept is discussed in greater detail later in this paper.

BACKGROUND

ASR wells have been operating in Florida since 1983. As shown in Table 1 and on Figure 1, in 2004, approximately 65 ASR wells are currently operating in Florida at 13 sites that are fully permitted. Most of these sites are storing treated drinking water in brackish aquifers which exist under native conditions ranging from total dissolved solids (TDS) concentrations of 700 milligrams per liter (mg/L) to 6,000 mg/L. Water is typically stored during wet months when water supplies are plentiful and water demand is reduced, and is recovered during dry months to help meet peak demands. The same well is used for both storage and recovery. Water is treated prior to aquifer storage, and is usually not re-treated following recovery, other than disinfection.

Within SJRWMD, ASR wellfields have operated successfully since 1987 at two locations. In that year, the city of Cocoa ASR system at the Claude H. Dyal Water Treatment Plant began operation. That wellfield has since been expanded two times and currently has a recovery capacity of 12 million gallons per day (gpd). At Palm Bay (formerly named Port Malabar), the original ASR well has been operating successfully since 1989, helping that community to meet increasing peak demands (R. Nipper, City of Palm Bay, 2003, pers. com.).

ASR wellfields are operational at more than 72 sites in 18 states in the United States (Figure 2), and in at least seven other countries. The first ASR wellfield in the United States, at Wildwood, New Jersey, began operation in 1968 and now has four ASR wells, preventing seawater intrusion into that area's coastal aquifer and helping to meet peak season water demands. ASR has proven to be an effective means for storing large volumes of water at relatively low cost, without the need for construction of large surface reservoirs (Pyne 1995).

The success of ASR as a water management tool in Florida has led to proposals for broader applications of the technology by extending to proposed storage of treated surface water, reclaimed water, and fresh groundwater in brackish aquifers. At least 25 additional ASR sites in Florida are in various stages of planning and development. The largest ASR program in the world is planned for the Comprehensive Everglades Restoration Program, including over 330 ASR wells with a combined recovery capacity of 1.7 billion gpd. These proposals in turn have attracted the attention of public interest groups concerned that broader applications of ASR may adversely impact groundwater quality, damage our aquifers, and also damage our environment.

During the past 5 years in Florida, public attention has heightened on water quality issues associated with ASR storage, particularly relating to microbiota, DBPs, leaching of metals, organic constituents, and recovery efficiency, which is the percentage of water stored in a brackish aquifer that can be recovered. Unfortunately, lack of technical understanding has resulted in the dissemination of misinformation by the media regarding these various water quality issues, including an effort to equate ASR wells to deep injection wells used for disposal of wastewater effluent. As a result, considerable confusion has arisen regarding the effectiveness of ASR as a water management technology and whether or not ASR should be relied upon to provide sustainable, cost-effective water storage to meet projected future demands. After 20 years of mostly successful ASR operations in Florida, it still remains necessary to try to clarify some of the operational perspectives by providing scientifically based information to the decision-making water managers, elected representatives, and other interested citizens that may be faced with the development of alternative water supplies to meet future demands

This SJRWMD-sponsored paper is intended to provide information to elected officials and to other interested citizens regarding the scientific basis that is available to support the decision-making process. It has been developed as part of an ongoing ASR Construction and Testing Program that began in October 2001 to determine the extent to which ASR can be applied to meet local or regional needs through use of alternative water supplies. The goal of the SJRWMD ASR Construction and Testing Program is to examine the appropriateness of integrating ASR technology into regional water resource and water supply development projects.

The SJRWMD ASR Construction and Testing Program is designed to address the issues identified in this paper for each pilot project in a thorough and scientific manner. Therefore, the results of this program will provide information that is needed for water managers, elected officials, and other interested persons to make informed decisions regarding ASR as a water management tool. The program plan, dated April 2002, is on the SJRWMD Web site at *www.sjrwmd.com*. ASR program standard procedures and sampling protocols are periodically updated to improve scientific understanding of the technical issues discussed in this paper, and to expand the supplemental data collected to ensure that a firm basis is provided for future water management decision-making. The current geochemical testing protocol for the SJRWMD ASR Construction and Testing Program is included in the appendix.

ASR FUNDAMENTALS

Figure 3 shows a typical ASR well cross section. In Florida, water that meets drinking water standards is recharged into the aquifer during wet months (surplus available water) through the ASR well to a stored water zone and is recovered from the same ASR well when needed, such as during dry months to help meet peak demands or during emergency demands. Water is typically stored between confining layers, displacing brackish water, generally in excess of 1,000 mg/L TDS, around the ASR well.

The stored water typically extends a few hundred to 2,000 feet away from the ASR well. A buffer zone separates the stored water from the surrounding brackish water and consists of a mixture of stored water and ambient brackish water. The volume of water in the buffer zone depends upon several factors, including the natural mixing that occurs in the porous limestone of the Floridan aquifer. Observation wells are often provided at ASR sites to monitor the movement of the stored water and the buffer zone during recharge and recovery operations, and also to monitor other changes that may occur in water quality and water levels.

The volume of water to be stored for recovery when needed, plus the volume of water in the buffer zone, is called the target storage volume (TSV). During the first 15 years of ASR development, the TSV was established through several test and operational cycles of recharge and recovery, during each of which a small portion of the stored water was left in the aquifer. In recent years, a different approach has proven generally successful, creating the TSV immediately after well construction and prior to cycle testing so that recovery efficiency starts out close to its ultimate value. Estimation of the TSV at this point is primarily based upon experience; however, a general range is about 50 to 300 million gallons per million gallons per day of installed recovery capacity. The lower end of the range would tend to be for sand and sandstone aquifers containing brackish water, with ASR systems designed to meet seasonal variations in demand. The higher end of the range would tend to be associated with heterogeneous limestone aquifers containing brackish water, with ASR systems designed to meet seasonal variations in supply, demand, and quality.

It is pertinent to point out that most ASR wells nationwide store drinking water in aquifers that contain fresh, not brackish, water. Some of the ASR demonstration sites within the SJRWMD area also may use fresh aquifers for seasonal water storage, even though most other ASR sites in Florida use brackish storage zones. In almost all of these freshwater applications, there may be at least one native groundwater constituent that renders the water unsuitable for drinking purposes without additional water quality treatment. Such treatment would typically remove native water quality constituents such as iron, manganese, hydrogen sulfide, color, or odor.

Experience (Stuyfzand 1998a, 2002; Toze and Hanna 2002) has shown that very close to the ASR well, typically within a radius of a few tens of feet, a treatment zone develops in which ambient microbial activity is accelerated, geochemical changes are more prevalent, and water quality changes occur (Figure 4) (Williams et al. 2002; de Ruiter and Stuyfzand 1998; Pyne 1995). Changes in water quality have generally not been problematic, so that treated drinking water quality standards that are met during recharge are also generally met during recovery. However, recent changes in water quality regulations have created compliance-related issues. All of the 13 operational, fully permitted ASR wellfields to date in Florida have had to demonstrate compliance with drinking water standards during both recharge and recovery. For virtually all of these wellfields, extensive hydraulic and water quality data sets have been generated during construction and testing. These data sets are typically included in multiple engineering reports submitted to regulatory agencies in order to support construction and operation permit applications and authorizations. However, changes in some constituent concentrations have been noted at several ASR sites, and some of these are the subject of considerable public interest and regulatory attention. Most of these water quality changes are beneficial, improving recharge water quality during storage. In particular, significant reductions in nitrogen, phosphorus, microbiota, DBPs, and other constituents have been observed during ASR storage. Where high concentrations of some water quality constituents are naturally present in the storage zone, such as iron, manganese, and hydrogen sulfide, water quality data collected during recovery of the stored water suggest that these constituents remain in the aquifer unaffected by the ASR process. Where constituent concentrations have increased in the recovered water, this effect has generally proven to be transitional, reflecting natural subsurface physical, geochemical, and microbial treatment of the recharge water around the well during early cycle testing.

REGULATORY BACKGROUND—PERMITTING

In Florida, water that is used for direct recharge of an aquifer must meet all primary drinking water standards as set forth by the U.S. Environmental Protection Agency (EPA). These standards must be met in the source water at the wellhead prior to recharge. ASR wells are considered a Class V injection well as described by EPA in their Underground Injection Control (UIC) rule. In Florida, the permitting and compliance monitoring of these types of wells have been delegated to FDEP. When such delegation of authority is given to a state, it is said that a state has "Primacy" or permitting and compliance responsibility. In the SJRWMD Construction and Testing Program, FDEP permitting will be required for the ASR well construction and cycle testing. The specific permit required is a Class V injection well permit per FDEP's "Application to construct/operate/abandon Class I, III, or V injection well systems." As part of the permitting process, major UIC considerations involve federal and state drinking water standards which must be met at the wellhead prior to injection. These considerations will also include protection of the aquifer against unintended contamination and evaluation of whether water quality of the recovered water continues to meet federal and state drinking water standards.

The following topics of discussion are intended to provide the reader with the scientific background and observations from ASR facilities regarding specific water quality permitting issues. These water quality and permit-related issues presented are some of the more pertinent concerns that are always at the forefront of questions raised by the general public.

Disinfection Byproducts

DBPs such as trihalomethanes (THMs) and haloacetic acids (HAAs), which are cancer-causing constituents at elevated concentrations, are formed when water containing natural dissolved organic carbon is chlorinated for disinfection. Other treatment processes are available to provide adequate disinfection of public drinking water supplies but which may provide better control of THM and HAA formation, such as chlorination followed by dechlorination, chlorammoniation, ozonation, and ultraviolet radiation. However, chlorination still represents a widely used disinfection treatment process in the United States. EPA has established primary drinking water standards that limit the concentrations of DBPs in public drinking water supplies in order to protect public health.

Since 1983, test and operational data from many ASR sites in Florida and elsewhere have shown relatively consistently that DBPs attenuate during ASR storage (Dillon et al., in press; Nicholson et al. 2002; Pyne et al. 1996; Pyne 1995). All or most operational ASR sites in Florida to date have obtained extensive data regarding DBP attenuation, particularly THMs, during the cycle testing programs conducted prior to receiving authorization from FDEP to direct recovered water into the distribution system. All of these data are in the public record, primarily in engineering reports (CH2M HILL 1988, 1989). Supplemental research has shown that HAAs disappear within a few days, primarily due to aerobic microbial reactions occurring underground in the ASR storage zone (Dillon et al. 2005; Pyne et al. 1996). THM concentrations are eliminated over a few weeks, primarily due to anaerobic microbial reactions that typically become established within a few days after ASR recharge. This occurs once the chlorine in the recharge water dissipates underground. Reducing conditions are re-established in the aquifer due to subsurface microbial activity, geochemical changes, and the effects of mixing and dilution in the buffer zone surrounding the ASR well. Where anaerobic conditions do not exist in the storage zone, such as may be expected in a surficial aquifer, THM reduction is minimal or absent (Fram et al. 2003). Surficial aquifers are generally unsuitable for ASR storage in Florida due to their minimal thickness, low yield, relatively high lateral flow velocities, and overlying land use. These conclusions are based upon data collected from several operating ASR sites, after adjustment for dilution and mixing effects. Adsorption to limestone has not been found to have a significant impact upon DBP reduction as compared to microbial mechanisms.

These conclusions were published in 1996 in a report prepared by the American Water Works Association Research Foundation (AWWARF) (Pyne et al. 1996). The report was vigorously peer-reviewed prior to publication. Operational ASR sites in Florida at that time included Manatee County, Peace River/Manasota Regional Water Supply Authority, the city of Cocoa, the town of Palm Bay, and the city of Boynton Beach, with a combined total of 15 ASR wells in 1995. In addition to these Florida sites, many other sites were already in operation in other states at the time this research was conducted. These operational results, which are all in the public record, are consistent in showing

DBP reduction during ASR storage in Florida ASR wells. No exceptions to these results are known to exist. The conclusions of the AWWARF research were consistent with many years of operational data from several ASR sites and were validated with field investigations under controlled conditions at five operational ASR sites. One of the five sites was at Peace River, DeSoto County, Florida, which had been in operation since 1985. Conclusions of the AWWARF report are as follows:

- Data from five sites suggest that THMs and HAAs are removed from chlorinated drinking water during aquifer storage over a period of several weeks.

- HAA removal precedes THM removal.

- The more highly brominated species tend to be eliminated earliest.

- In most cases, THM removal does not appear to occur until anoxic conditions develop, and it frequently follows the onset of denitrification. HAA removal occurs under aerobic conditions. A biological mechanism is suggested, including DBP removal under both anoxic and aerobic conditions.

- THM and HAA precursor concentrations (formation potentials) decreased at most of the sites investigated. THM precursor concentrations exhibited no clear pattern.

- The results of this study are confounded somewhat by mixing and dilution effects at some of the sites, despite attempts in the study to minimize such effects. Additional work must be conducted to establish the mechanism(s) responsible for removing DBPs and the conditions under which they occur.

- Site-specific testing of these conclusions will be required at each location in order to ensure compliance with DBP regulations.

AWWARF recently published a second report during 2005 titled "Water quality improvement during aquifer storage recovery," for which Peter Dillon, Ph.D., of the Commonwealth Science and Industry Organization, Adelaide, Australia, was the principal investigator. That project team included 41 scientists and research institutions from around the world. The final report summarizes, among other items, field investigations at eight additional ASR sites to address the fate of DBPs during ASR storage. Conclusions are consistent with those published in the 1996 AWWARF report (P. Dillon 2003, pers. com.).

A recent paper by Nicholson et al. (2002) presents some of the same data used in the AWWARF report for one of the eight sites (Bolivar, South Australia), concluding that "...the main process leading to reduced concentrations of trihalomethanes and haloacetic acids is microbial degradation, with degradation under methanogenic conditions being the most effective removal mechanism (Dillon et al. 2005)."

In May 2003, USGS published a report titled *Processes affecting the trihalomethane concentrations associated with the third injection, storage and recovery test at Lancaster, Antelope Valley, California, March 1998 through April 1999* (Fram et al. 2003). Although this report has been used to raise concerns about THMs, the conclusions contained within the report are consistent with the conclusions of the two AWWARF reports mentioned above, and include the following: "The major factor controlling the continued formation of THMs in the aquifer after injection was the concentration of residual chlorine in injected waters ... Results from these experiments showed no bacterial degradation of chloroform ($CHCl_3$) or bromoform ($CHBr_3$) under aerobic conditions, such as those in the aquifer in this study. Bacterial degradation of $CHBr_3$ under anaerobic conditions was observed. However because the Lancaster aquifer is aerobic and because $CHBr_3$ comprises only a small portion of the THMs, biodegradation is not considered an important attenuation mechanism for THMs in this aquifer."

The aquifer selected for testing at Lancaster is an aerobic, unconfined to semiconfined, siliciclastic aquifer, whereas virtually all of other ASR wells globally are sited in deep, confined, anoxic (lacking oxygen) aquifers. In announcing this USGS publication, the press release that was disseminated by USGS was misinterpreted to imply a global conclusion that THM reduction does not occur in ASR wells (USGS 2003). The press release also indicated that continued ASR operations with disinfected water would introduce large amounts of THMs into the aquifer that would not degrade. In actuality, since most ASR wells are in aquifers that are confined, deep and anoxic (similar to Florida), the data from this USGS test site would only have applicability to the few other ASR sites with similar hydrogeologic conditions. Because of the great variability of the hydrogeologic characteristics of aquifers considered for ASR, it is critical that each potential ASR program include a thorough investigation of the local aquifer and ASR's potential to impact that aquifer. Limited available data (Pyne et al. 1996) at the Peace River ASR site in Florida suggest that reducing conditions become re-established fairly rapidly during ASR storage for extended periods, even in ASR wells that have operated for many years, so that these microbial reactions appear to be sustainable. The misrepresentation of the USGS press release fostered incorrect global conclusions that are not representative of ASR applications in Florida or in many other ASR hydrogeologic settings in the world. This misinterpretation has created considerable concern from a utility planning perspective on the part of water managers and water utility directors in Florida and elsewhere, due to the confusion that it created among many individuals who will not likely read the full report.

Figure 5 shows a data set from one of the two original ASR wells at the Peace River ASR wellfield in Desoto County, Florida, as presented in the 1996 AWWARF report. After 7 years of continuous ASR operations at this well, 9 million gallons of drinking water was recharged and stored for 89 days between the end of recharge and the beginning of recovery. The water was stored in a confined, artesian limestone aquifer (Tampa Formation) with a thickness of 100 feet and a background TDS concentration of 700 mg/L, and was then recovered. Using a natural tracer, no significant mixing or dilution was evident in samples pumped from the center of the stored water bubble after 1, 21, 43, 64, 91, 99, and 107 days. The theoretical radius of the stored water bubble was 157 feet, while lateral movement of the bubble during the storage period was estimated at 7 feet, based on an aquifer transmissivity of 4,900 square feet per day. Recharge water THMs averaged 56 $\mu g/L$, while HAAs averaged 37 $\mu g/L$. Background pH in the aquifer was 7.93. No data were obtained for Eh; however, dissolved oxygen was 1.3 mg/L and total chlorine was zero. Figure 5 shows the attenuation of HAAs and THMs during ASR storage, from an ASR well that had already been in operation for 7 years. THM concentrations attenuated to background levels below 10 $\mu g/L$ within 3 months, while HAA concentrations disappeared within less than 21 days. The current THM drinking water standard is 80 $\mu g/L$, and for HAA, it is 60 $\mu g/L$. From this long-term experience, it is evident that the microbial and other processes contributing to DBP attenuation are sustainable. For Peace River, typical storage times are seasonal; however, long-term storage has already been utilized to help meet water demands during two sequential recent years of extreme drought, recovering water stored at least 5 years previously.

ASR storage times are typically several months, between the mid-point of recharge to the mid-point of recovery. At some sites, particularly in southwestern states, ASR storage is primarily designed for several years, between wet years and dry years. At other sites, storage occurs between early years after a water treatment plant expansion to later years when limited opportunities for storage are available. At a few sites, such as at Myrtle Beach, South Carolina, some ASR storage is diurnal, storing water at night for recovery during the day. At no additional capital cost, most sites store water to meet multiple objectives, such as diurnal, seasonal, long-term, and emergency storage. Consequently, for most ASR sites, adequate opportunity for DBP attenuation will be available, particularly if DBP attenuation is defined as a prime objective of storage as opposed to an incidental secondary benefit.

For the two ASR sites within SJRWMD, at Cocoa and Palm Bay, extensive data on DBPs have been obtained, indicating that DBPs are not a problem at either site, either in the drinking water used for ASR recharge or in the ASR recovered water (CH2M HILL 1988, 1989).

It is anticipated that ASR demonstration projects to be implemented within SJRWMD will generally be in confined, anoxic aquifers in which DBP elimination would be expected to occur during storage periods of several weeks to months. In any event, under current Florida regulations, the recharged water will meet applicable DBP water quality standards, and all other applicable standards.

ASR provides a potential significant cost-saving opportunity to those water utilities that are faced with the need for supplemental expensive treatment processes to reduce DBPs to below drinking water standards, when such need occurs for only a few days or weeks per year. Recovering water stored from ASR wells at such times, and blending it with treated water from primary water supply sources that exhibit elevated DBP levels, can help achieve compliance with drinking water standards at minimal cost while achieving the other water demand benefits. Recovered water from ASR wells will probably have little or no DBPs and will also probably have experienced a reduction in the DBP formation potential during ASR storage. When this water is chlorinated following recovery, DBP concentrations will likely increase, but to lower concentrations than levels, which occurred in the recharge water.

The projects to be undertaken as part of the SJRWMD ASR Construction and Testing Program will not utilize recharge water that contains DBPs exceeding the allowable concentrations in drinking water. Data will be collected during each of the ASR demonstration projects to verify concentrations of DBPs at these sites during ASR storage. Data will also be collected regarding DBP decomposition products such as dichloromethane, chloromethane, and dibromomethane to ascertain their concentrations relative to drinking water standards.

Arsenic

Minerals such as pyrite and iron oxides are present in Florida limestone aquifers. When these minerals are exposed to oxygen, such as during well construction or ASR cycle testing operations, geochemical and microbial changes occur in the subsurface that leach trace metals out of the minerals and into solution. Trace metals that have been noted or that have otherwise been a subject for concern at various ASR and well recharge and surface recharge sites have included arsenic, uranium, mercury, nickel, chromium, cobalt, and zinc. EPA primary drinking water standards have been established for arsenic, mercury, nickel, and chromium, and other trace metals have secondary drinking water standards. Based upon consideration of trace metal concentrations in ASR recovered waters in Florida from early stages of cycle testing, and drinking water standards, it appears that arsenic is the only trace metal that may be considered a potential problem requiring further careful investigation. The current EPA standard for arsenic in drinking water is 50 μg/L. The national standard for arsenic will reduce to 10 μg/L effective January 2006. However, a recent change of regulations in Florida reduces this standard to 10 μg/L effective January 2005, a year earlier than the change in the national standard.

Arsenic is a relatively common element in nature. Trace concentrations of arsenic occur naturally in Florida groundwaters, but typically at levels of under 3 μg/L, well below current or projected drinking water standards. Concentrations of total and dissolved arsenic from Upper Floridan aquifer wells sampled in east-central Florida as part of the FDEP Ambient Ground Water Quality Monitoring Network (1987–94) averaged 1.54 μg/L. In the past 3 years, samples obtained from water recovered from several new ASR wells outside of SJRWMD have shown arsenic concentrations exceeding background levels. During early ASR cycles, concentrations in the recovered water have sometimes exceeded current drinking water standards of 50 $\mu g/L$. At one representative site outside SJRWMD, the initial arsenic concentration at the beginning of recovery on the first cycle was about 88 $\mu g/L$. In subsequent cycles, arsenic concentrations declined, reaching maximum levels of 58 and 34 $\mu g/L$, respectively, in cycles 2 and 3. At another site outside SJRWMD, the peak arsenic concentration during the first recovery cycle was 39 $\mu g/L$, while during the second recovery cycle it was 7 $\mu g/L$.

As a result of this Florida experience, concern exists that ASR operations in the Floridan aquifer may release arsenic into recovered water and also into the subsurface environment, thereby potentially contaminating drinking water supplies and also potentially contaminating adjacent wells. If arsenic is at unacceptably high concentrations in the water recovered, additional water quality treatment and disposal of the residuals from the treatment process would be required. These additional treatment and disposal processes would have an impact on the overall ASR operating costs. Research regarding treatment technologies for arsenic removal from contaminated water is under way at the University of South Florida. It is important to point out that there is no documented instance of ASR recovered water with elevated arsenic levels exceeding drinking water standards being distributed to the public. All samples indicating high arsenic levels were collected during initial cycle testing of the wells, during which time recovered water is routinely discharged to waste or recycled back to the water treatment plant for further treatment. At one ASR system, re-treatment of the water through the water treatment plant has been shown to effectively remove arsenic to less than 1 $\mu g/L$. No additional cost has been realized in the sludge disposal for this facility.

Extensive research on this issue has been conducted in the Netherlands showing arsenic attenuation during recharge of oxic water into anoxic, typically sand, aquifers. Field experiments in the Netherlands typically utilize "dual infiltration wells," which have been utilized for decades and are pairs of wells, approximately 300 feet apart: one for recharge and the other for recovery. These pairs of wells are used for water treatment, not for storage, which is in ironic contrast to current practice in the United States, which relies upon ASR wells for storage but does not facilitate reliance upon such wells for treatment. The treatment provided by dual-infiltration wells is primarily disinfection, since the use of chlorine is banned in the Netherlands for public water supplies. The dual-infiltration wells in the Netherlands are not ASR wells because water is recharged into one well and recovered from another well; however, the findings are applicable to assist in better understanding such issues in Florida. Some typical findings from the Netherlands research are as follows:

"During aquifer passage, the amounts of the trace elements arsenic and nickel temporarily increased at the two locations [Langerak and Nieuwegein]. Both elements arise from oxidizing pyrite, but are subsequently re-adsorbed by the aquifer matrix" (Timmer and Stuyfzand 1998). "Pyrite oxidation leads to mobilization of As, Co, Ni and

Zn, of which only As may reach the recovery well ... These metals probably coprecipitate with or strongly adsorb to the neoformed $Fe(OH)_3$" (Stuyfzand 1998b). "Also Arsenic as AsO_4^{3-} is adsorbed by these oxides, but 10% (as H_3AsO_3) escapes adsorption thanks to its lack of charge (de Ruiter et al. 1998)." Two models have been developed and calibrated, INFOMI and EASY-LEACHER, based upon the extensive research work that has been conducted in the Netherlands regarding arsenic transport and other issues (Stuyfzand 1998c, 2002; Stuyfzand et al. 2002).

Further investigations have been conducted by the Florida Geological Survey (FGS) and others to gain improved understanding of the geochemical mechanisms involved (Williams et al. 2002). Additional scientific investigations are under way, and others are planned by SJRWMD as a part of the current ASR Construction and Testing Program. The appendix to this paper presents a geochemistry sampling protocol that has been developed to support the SJRWMD ASR Construction and Testing Program. This protocol will be applied at each of the ASR demonstration sites, thereby improving our understanding regarding this issue. However, tentative findings to date, based upon data collected from operating ASR sites and others in various stages of cycle testing, are discussed in the text that follows.

The occurrence of arsenic in the recovered water from ASR wells in Florida, at concentrations higher than in the recharge water, appears to be a transitional phenomenon but is recently of greater concern with the new arsenic standard. It has been more prevalent in new wells during initial cycle testing, which typically continued for about 12 to 18 months and included about four to eight cycles. During this period, recovered water was discharged to waste or re-circulated to the water treatment plant for treatment. Typical cumulative volumes stored and recovered during this testing period were in a range of 100 to 300 million gallons.

Based on analysis of information from 13 Floridan aquifer ASR sites, arsenic has not been detected at elevated concentrations in ASR wells that have been operating for several years and that have developed a buffer zone around each well. It appears that, through natural attenuation processes occurring in the aquifer during ASR operations, arsenic concentrations generally diminish with distance from the ASR well, and also with repeated operating cycles at the same storage volume. It is estimated, based upon results from cycle testing conducted for at least the first 10 operating ASR wellfields in Florida (Table 1), that potable drinking water concentrations are achieved after an estimated three to six operational cycles at about the same storage and recovery volume, in wells that have initially elevated concentrations of arsenic and that have developed a buffer zone around the well. Where no buffer zone is formed, arsenic attenuation proceeds at a slower rate.

During cycle testing at the two ASR wellfields located within SJRWMD (the cities of Cocoa and Palm Bay), samples were collected for analysis for primary and secondary drinking water standards, to demonstrate compliance prior to receiving authorization from FDEP to recover water to the distribution system. This has been standard practice at most, if not all, existing Florida ASR wellfield sites since 1983. For Palm Bay, two samples were collected during cycle 3 recovery, dated August 9 and August 11, 1988. Arsenic concentrations were 4 and 8 μg/L, respectively, well below the 50 μg/L standard (CH2M HILL 1989). For the city of Cocoa, water quality samples were collected for arsenic analysis during March 1987 at 19% and 90% of recovery during cycle 4M; both indicated less than 5 μg/L of arsenic concentration (CH2M HILL 1988). Mercury, which has a primary drinking water standard of 2 μg/L, was measured at less than 0.5 μg/L and at less than 0.2 μg/L at Cocoa and Palm Bay, respectively. No analyses were obtained for uranium.

Whether arsenic was previously present at higher initial concentrations at the Cocoa and Palm Bay sites is not known; however, it was present at very low concentrations at this point in the cycle testing programs (CH2M HILL 1988, 1989). The data from the Cocoa and Palm Bay ASR sites are consistent with extensive data sets from many other ASR operating wellfields in Florida that were placed into operation between 1983 and about 2000 (Table 1) with arsenic attenuation to acceptable levels usually after three to six test cycles.

During 2004, samples were collected at each of the Cocoa ASR wells during a recovery period that extended over about 6 weeks. Samples were collected at the beginning, middle, and end of the recovery period. For five wells which had been in operation since prior to 1991, all but one of the arsenic samples were below 10 μg/L, and the single elevated sample was 12 μg/L at the end of recovery. For the three wells which had been operational only 2 years, arsenic concentrations ranged from 3.8 to 14 μg/L.

For the first 18 years of ASR operations in Florida, authorization to recover water to the distribution system was issued by FDEP only after demonstration that recovered water meets all drinking water standards, including arsenic. Consequently, no water with elevated concentrations of arsenic was pumped into a water distribution system. It is possible that during early test cycles at some or all of these sites, elevated concentrations of arsenic occurred and were not noticed because water quality monitoring was focused initially on other constituents in the recovered water. No problem was ever detected at any of these ASR sites in Florida. In retrospect, each of these sites had been subject to at least three ASR test cycles prior to obtaining samples for analysis for arsenic and other metals. It is apparent that leaching of arsenic from minerals in the formation around each ASR well was essentially complete by the time that the samples were collected, or alternatively that the arsenic was not present initially at significant concentrations. Ambient groundwater pH values at the Cocoa and Palm Bay ASR sites, which are representative of other ASR sites in Florida's limestone aquifers, ranged from 7.4 to 7.8.

Elevated initial arsenic concentrations are believed to be caused by leaching or by dissolution from the arsenic naturally present in the limestone of the Upper Floridan aquifer. Arsenic is often associated with the presence of pyrite and phosphorite minerals, or organic matter, and is adsorbed to oxides of iron and manganese in natural groundwaters. The mobilization of arsenic appears to be linked to an oxidation-reduction reaction, possibly reinforced by natural bacterial activity within the aquifer. Some of the water quality parameters that influence the rate of leaching appear to be Eh, pH, and possibly organic carbon concentrations. Water sources with low Eh and near neutral pH values are less likely to dissolve arsenic from aquifer minerals than waters with high levels of Eh. As described above, such reactions at operational ASR sites have proved to be transitional.

ASR wellfields using treated groundwater as a source have been typically less likely to have a problem with arsenic in the recovered water during cycle testing and initial operations. ASR systems using treated surface water as a source appear to be more likely to experience arsenic in the recovered water during cycle testing and initial operations. Surface waters tend to have higher dissolved oxygen concentrations and also higher concentrations of natural organics that can increase bacterial reactions underground, potentially altering pH and mobilizing arsenic that may be present in the rock. Again, this is the result of limited testing and should not be assumed to be true in all cases. The possibility also exists that ASR storage zones that do not have iron present in the native groundwater may be less likely to attenuate arsenic dissolved from the limestone during recharge. Most wells, including ASR wells, have at least low concentrations of iron, in Florida and elsewhere.

To date, in Florida, most of the concern has centered on the occurrence of arsenic in recovered water from ASR wells as well as potential lateral movement of dissolved arsenic in the aquifer. There are two components of such movement. First, water will move away from the well during ASR recharge operations and will move back toward the well during recovery operations. At such time as the TSV has been developed, approximately equal volumes will move seasonally each year. Any dissolved arsenic present in this water will tend to be slowly purged from the aquifer during normal ASR operations at approximately equal recharge and recovery volumes each year. Second, any water that is stored and not recovered will tend to move away from the well at a rate determined from the regional hydraulic gradient, the transmissivity and porosity of the storage zone. Typical lateral flow rates in Florida ASR wells are less than about 100 feet per year. Research in the Netherlands has shown that almost all of the dissolved arsenic re-precipitates in the aquifer under changing Eh conditions, primarily due to adsorption onto ferric hydroxide precipitates. This finding is consistent with limited Florida experience, showing much lower arsenic concentrations at monitor wells, even as close as about 170 feet from an ASR well. This will need to be evaluated at SJRWMD ASR demonstration sites; however, it suggests that arsenic present naturally in the limestone at an ASR well site will be dissolved upon contact with oxygen, whether during drilling and well development operations or during initial ASR testing operations. Some of the dissolved arsenic will be recovered during pump testing and cycle testing while the remainder will stay underground and will be re-precipitated within the buffer zone surrounding the ASR well.

Disposal of arsenic-contaminated water may be a challenge for some of the newer Florida ASR sites effective January 1, 2005, when the arsenic standard for drinking water is scheduled to be lowered from 50 to 10 μg/L. Where water with arsenic levels between 10 μg/L and 50 μg/L could previously be recycled to a water treatment plant, alternatives will need to be considered to reduce concentrations to acceptable levels through process control and blending until the aquifer is sufficiently conditioned around an ASR well so that recycling the water is no longer necessary. Alternatively, the focus may be on ways to leave the arsenic in the aquifer, such as through accelerated oxidation of the arsenic-bearing minerals around the ASR well. It may also be desirable to implement wellhead treatment of the recovered water to remove arsenic, although this does not account for water left in the aquifer, which may have elevated arsenic levels in close proximity to the ASR well. The latter approach will also entail consideration of the long-term stability of residuals disposed from the wellhead treatment process.

For the first 17 years of ASR operations in Florida, arsenic was not known to be a problem. However, until recently, arsenic had not been studied intensively during initial cycle testing programs. Typically, these programs have demonstrated that natural groundwater, recharge water, and recovered water at the end of the cycle testing programs have complied with drinking water standards. Great effort has not been invested in continuous wireline coring and geochemical analyses in Florida limestone ASR systems because there appeared to be no need. In other states with finer-grained aquifer systems, such coring and geochemical analyses are routine elements of ASR programs. As a result, little information exists on differences in, for example, the amount of pyrite or other arsenic-bearing minerals that may be contained within the limestone. In the absence of such information, we can only assume that the potential for mobilization of arsenic from the aquifer is roughly the same throughout central and south Florida, which is generally where ASR systems are located and planned.

SJRWMD is taking a proactive, rather than a reactive, approach to arsenic and to other geochemical issues of potential concern. The ASR demonstration projects being implemented by SJRWMD will reach a level of scientific research that has not been typically conducted during the approximately 20 ASR development programs that have been completed by Florida water utilities since 1978, and many others that are under way.

If arsenic concentrations are above acceptable levels, several ways may be appropriate to mitigate the problem in the aquifer or with the recovered water:

Conduct initial cycle testing with discharge of water to waste or re-treatment, or blending with water from other sources until initially high arsenic concentrations subside to below drinking water standards.
Adjust the pH of recharge water to reduce the potential for arsenic solution.
Treat the recharge water to reduce or remove oxygen, for example, by bank filtration or addition of chemicals.
Treat the recovered water.
Over-pump the well during initial recovery cycles to purge arsenic from the aquifer around the well.
Create a buffer zone around the well to leach arsenic out of this portion of the storage zone.
Improve well design, such as with appropriate casing setting depths, installation of liners, or partial plugging of the bottom of a well to close off intervals with known high concentrations of arsenic-bearing minerals.
Locate a storage zone monitor well at a greater radius from the ASR well than the buffer zone surrounding the ASR well.

Over-pumping the well during initial recovery cycles is considered less likely to be effective at purging arsenic from an aquifer around an ASR well since arsenic-bearing minerals are considered least soluble in formation water and most soluble in recharge water. The following cycle of recharge would be expected to again leach arsenic. The opposite approach of rapidly oxidizing an aquifer to create ferric hydroxide precipitates and thereby trap dissolved arsenic is considered a more promising approach. This approach has recently been applied successfully at an ASR site in Green Bay, Wisconsin. The particular way to handle each situation will vary, depending on the extent of the problem (i.e., the treatment processes available). One approach for further consideration in Florida is bank filtration of surface water prior to ASR recharge. Further investigation is needed to access the effectiveness of this approach in reducing or eliminating pathogenic microbiota, providing natural filtration, and also reducing the Eh of the recharge water so that it is less likely to dissolve metals from the limestone during ASR storage. Recovered water from this type of bank-filtration ASR system, however, cannot be directly used for drinking water supply purposes and must comply with EPA surface water treatment regulations before being distributed for drinking water purposes.

Uranium

In addition to arsenic, FGS has also focused on leaching or dissolution of uranium into solution during ASR operations in Florida. There is no current federal primary drinking water standard for this element; however, the proposed EPA standard is 20 $\mu g/L$ for uranium in public drinking water supplies. FDEP has adopted a drinking water standard for uranium, effective December 8, 2003, of 30 $\mu g/L$. During testing at two Florida ASR sites, Tampa and Punta Gorda, uranium concentrations in the recovered water increased to above background levels. The highest concentrations recorded during recovery were 6.44 $\mu g/L$. Background concentrations are approximately 1 $\mu g/L$, and concentrations in the recovered water appear to decrease with time (Williams et al. 2002).

One of the more plausible mechanisms for release of uranium from the limestone appears to be primarily related to Eh and to pH of the recharge water. There is also the possibility that uranium is distributed non-uniformly from the top to the bottom of the ASR storage zone, and that the measured concentrations represent an average of flows from different depths. Treated surface water containing oxygen and carbon requires some time during ASR storage to reach equilibrium underground. Until that chemical equilibrium is reached, leaching of metals such as uranium occurs. However, the uranium generally re-precipitates in the aquifer. Although of some geochemical interest, this does not appear to be a significant water quality issue for Florida ASR wells based upon the data from Tampa and Punta Gorda. Baseline native water quality definition at Cocoa and Palm Bay included metals scans; however, these did not include analyses for uranium concentrations.

Mercury

Concern has been expressed that ASR operations in the Upper Floridan aquifer may facilitate formation of methylmercury and its release to the environment in the recovered water. This concern has been expressed primarily in connection with the Comprehensive Everglades Restoration Program (CERP), specifically that methylmercury would accumulate in the food chain as a result of stored water recovered from ASR wells and released to the aquatic environment.

Investigations of this potential problem are being conducted by the South Florida Water Management District as part of the CERP and include several ASR demonstration projects that are under way. The only known data regarding this issue are from operating ASR wells, some of which have been storing treated surface water in the Upper Floridan aquifer for over 20 years. None of these wells have experienced elevated mercury levels in the recovered water. Recent investigations of the potential sources for relatively high mercury levels found in the Everglades and also in fish from some other areas of Florida point to atmospheric precipitation, not to the occurrence of mercury in the limestone of the Floridan aquifer.

The SJRWMD ASR Construction and Testing projects will address the occurrence of mercury and other trace metals in the water recovered from ASR wells, and also the water sampled in adjacent monitor wells in the storage zone. Geochemical modeling will first be conducted to evaluate the probability that leaching of metals may occur and to provide a reasonable basis for implementation of mitigating measures. This will be supplemented during well construction and testing with field sampling. Metals will be analyzed in samples collected at various times during recovery to characterize the variation of concentrations with both time and distance, and with recovery volume percentage. If metals are identified at elevated concentrations exceeding existing or new drinking water standards, mitigating measures will be evaluated. As discussed above, it is anticipated that any leaching of metals will be a transitional phenomenon during the startup of ASR facilities.

Microbiota

Public concerns have been expressed regarding the potential contamination of native potable groundwater resources by the introduction of microbiota in the ASR recharge water. Pertinent to that concern, many of the potential ASR applications under consideration by water users within SJRWMD include proposed seasonal storage of treated surface water, reclaimed water, and fresh groundwater. However, none of these applications of ASR are proposed for testing as part of the SJRWMD ASR Construction and Testing Program. The SJRWMD Governing Board has established a policy that ASR demonstration projects funded by SJRWMD will only recharge treated drinking water during the construction and testing phase of the FDEP UIC permitting process. By definition, such water is free of pathogenic bacteria, viruses, and protozoa because the water will have undergone treatment at a central water treatment plant that is subject to stringent water quality monitoring requirements.

When treated drinking water is used as a recharge source, it is free of pathogenic microbiota. Yet the public misconception about ASR and microbiota contamination remains. Extensive scientific investigations and field data collection programs where other than treated sources are used indicate that pathogenic microbiota concentrations reduced rapidly during ASR storage. Such a reduction in any pathogenic microbiota concentrations provides a preliminary level of treatment of water that may be used as an alternative source. Considering the ambient groundwater quality at most of the ASR sites within SJRWMD will be brackish, such water may be rendered suitable for consumption following desalination treatment, which would remove any pathogenic microbial constituents present in the recharge water.

Extensive microbial research has been conducted by CSIRO in Adelaide, Australia, during the past few years, in brackish limestone confined aquifers that are very similar to those in Florida (Medema and Stuyfzand 2002; Gordon et al. 2002; Toze and Hanna 2002; Banning et al. 2002). This research has shown that native microbiota that are naturally present in the aquifer are effective in attenuating pathogenic microbiota that are introduced with the recharge water. Other factors that attenuate microbiota concentrations include temperature and salinity and probably other mechanisms as well.

The research in Australia has been conducted using diffusion chambers, which enable very high concentrations of pathogens to be contained within a small chamber wrapped in a membrane and lowered through a well into an ASR storage zone. The diffusion chamber is designed to allow for water movement into and out of the chamber, with the microbes being too large to escape the membrane. Until very recently, such research was not believed to be permissible in Florida. However, FDEP has recently indicated a willingness to allow such research to occur for the CERP. This diffusion chamber research is the only way to obtain Florida-specific scientific data under relatively controlled field conditions because ambient concentrations of pathogens in the environment are invariably too low to support conclusive field investigations of pathogen attenuation rates during ASR storage.

It is pertinent to recognize that the commitment by the SJRWMD Governing Board for its ASR Construction and Testing Program to recharge only treated drinking water is conservative in order to protect existing brackish groundwater quality from potential contamination by microbial constituents that may occur in sources of untreated freshwater used in the ASR recharge process. In order to assure such microbial constituents are not introduced into the subsurface, the state of Florida requires a high level of water quality pretreatment to drinking water standards. Such a high level of treatment increases the cost of capital investment in treatment facilities required to comply with these regulations. As a point of reference, in Australia, ASR is used for storage of partially treated fresh surface water and reclaimed water in brackish aquifers at more than seven operational sites with others in developmental stages. The Australian perspective is that it is more useful to turn a brackish aquifer into a potential freshwater resource, using ASR technology, than to protect the brackish aquifer against potential contamination by pathogenic microbiota that are known to attenuate rapidly in the subsurface due to natural biological, geochemical, and physical processes. ASR projects in Arizona, North Carolina, the Netherlands, and Australia rely upon natural processes in the aquifer surrounding an ASR well to achieve these treatment objectives at no additional cost.

In related work in Florida, Joan Rose, Ph.D., and David John, Ph.D., at the University of South Florida, showed attenuation rates for conservative bacterial and viral indicators under temperature and salinity conditions (Figures 6 and 7) approximating those that would be expected during ASR storage in central Florida. A reasonable approximation is that 90% reduction in microbial concentrations will occur about every 5 days under the temperature and salinity conditions prevalent in Florida. For a reasonably good quality surface water source (such as Clear Lake in West Palm Beach and Ward Lake in Bradenton), such pathogens might require less than a month of ASR storage for complete inactivation, compared to months of storage time typically provided in the aquifer during ASR storage.

An extensive literature search regarding the fate of microbiota during ASR storage has recently been completed, jointly funded by the Southwest Florida Water Management District and the South Florida Water Management District. Results are posted on a Web site, www.asrforum.com (Figure 8). The Web site presents the results of laboratory scientific investigations and also the results of field investigations, mostly in Florida, to corroborate the laboratory studies. Based on the findings, the natural attenuation of pathogenic microbiota during ASR storage is clearly evident. Pathogen attenuation appears to be partially due to native microbiota in the storage zone, which are acclimated to the subsurface environment and derive energy from carbon in the aquifer and also in the recharge water, and are effective in reducing pathogenic microbiota in the recharge water. Furthermore, pathogen attenuation is also believed to be attributable to temperature changes, with higher temperatures tending to accelerate attenuation rates, particularly for viruses. Salinity is another factor affecting attenuation rates, but perhaps to a lesser extent than temperature or native microbiota. Time periods for pathogen attenuation are on the order of a few days for each log cycle, or 90% reduction in concentration. Laboratory results are corroborated by field data from Florida sinkholes, drainage wells, monitor wells for deep injection well systems, ASR wells, and bank filtration systems, which are reasonably consistent in showing that pathogens introduced into the aquifer attenuate to acceptable levels within about a month or less at concentrations typically found in Florida surface waters. Examples are listed in the Web site mentioned above.

Further research is needed regarding pathogenic microbiota attenuation during ASR storage. Such research is being conducted by the South Florida Water Management District in connection with the CERP, and also by SJRWMD as part of another field investigation on water quality issues associated with drainage wells in central Florida, known as Phase I of the Central Florida Aquifer Recharge Enhancement project. Of particular interest will be the fate of protozoa and toxins from blue-green algae that are usually present in surface waters that may be stored in ASR wells or may otherwise enter limestone aquifers, such as through sinkholes and drainage wells. Early indications for *Giardia* suggest that attenuation rates are similar to those for bacteria. No published information is known to be available on the fate of Cryptosporidium during ASR storage. Baseline testing of surface water sources under consideration for ASR programs in Florida has generally shown the absence of these protozoa in the source water. The only known information regarding the fate of cyanotoxins during subsurface storage and movement is from Germany (Grutzmacher et al. 2002). Field observations indicate almost complete removal of microcystin concentrations as a result of bank filtration under anaerobic conditions, due to filtration, degradation and adsorption.

RECOVERY EFFICIENCY

Recovery efficiency is an important water quality and operational criterion for successful ASR programs in Florida. It is defined as the volume of water that can be recovered that meets established water quality criteria during an individual ASR cycle, as a percentage of the volume stored in that cycle. Recovery efficiency is an important operational criterion since the recharge water to an ASR well typically has considerable economic value, having been treated to meet water quality standards. It is important to water utilities to recover all or most of the stored water. Similarly, it is important to achieve high recovery efficiency as early as possible so that the capital investment in

ASR facilities can be put to beneficial use, instead of spending months or years in a succession of test cycles to slowly achieve recovery efficiency goals. From a regional water management viewpoint, it is important to achieve high recovery efficiency to avoid wasting water, although when compared to the high evaporation, transpiration, seepage, and conveyance losses of surface reservoir storage, any recovery efficiency in Florida greater than about 40% is a net gain to the regional water supply. Recovery efficiency can therefore be less than 100% and still be a net benefit to overall water management. It is not a waste if water can be captured during the wet season before it is lost to tide and then stored for recovery during the dry season or emergencies, with some of the water remaining underground.

Experience with ASR storage in brackish aquifers since 1983 has generally shown an improvement in recovery efficiency with successive ASR operating cycles at approximately the same volume stored and recovered in each cycle. In early ASR cycles, recovery efficiency has often been low, sometimes below about 25%. However, with successive cycles to purge brackish water from around the ASR well, recovery efficiency has climbed progressively, typically achieving high percentages after a few cycles. In other words, once a buffer zone is formed around an ASR well in a brackish aquifer, subsequently stored water can usually be fully recovered so long as the volume recovered is reasonably consistent from one cycle to the next. The buffer zone volume therefore depends in part upon the volume to be recovered. From this experience, a new approach to ASR well development in brackish aquifers has been implemented in recent years, storing water to create the buffer zone around the well before beginning cycle testing. This new approach is more rapid and cost-effective, achieving high recovery efficiency quickly rather than over a period of many cycles, and sometimes many years.

A significant issue facing Florida water managers is the tradeoff between the need to form a buffer zone so that full recovery efficiency can quickly be achieved in Florida ASR wells, and the possibly opposing need to control the potential migration of arsenic dissolved from the limestone during initial ASR operations, such as due to Eh conditions discussed previously, and movement of this arsenic into surrounding areas of the aquifer at the edge of the buffer zone. Research in the Netherlands, discussed previously, suggests that almost all of the dissolved arsenic will re-precipitate in the aquifer at the edge of the buffer zone. However, such research has not yet been conducted in Florida. Testing will be required to gather such data, and such testing will be a key part of the ASR demonstration projects being implemented by SJRWMD. If such testing is implemented through a series of small operating cycles at equal volumes of water stored and recovered, it will take a long time to achieve ultimate recovery efficiency at each site, possibly several years. If testing is implemented through initial formation of the TSV, this process can be accelerated.

Table 2 shows recovery efficiency at several Florida operating ASR sites that have been in operation for many years. Most of these are at about 100% recovery efficiency, meaning that in each new cycle, they can recover the same volume that they recharge during that cycle, while still meeting drinking water standards in the product water going to the distribution system. Each site has slightly different constraints and opportunities. Although some require that recovered water meet drinking water standards at the wellhead during recovery, most blend the ASR recovered water with water from other sources, meeting drinking water standards with the blended water going to the distribution system. The difference between the two approaches is unlikely to affect ultimate recovery efficiency; however, it would affect the associated TSV at each site.

At two Florida sites, Bonita Springs and Northwest Hillsborough County, ASR recovery efficiency has proven to be unacceptably poor in spite of efforts to build a TSV or to freshen the storage zone through repetitive, large-volume test cycles. It appears that the principal problem at these two sites has been the upwelling of highly brackish groundwater from beneath the storage zone during recovery, reflecting inadequate confinement beneath the storage zone. Fortunately, this situation is not common, yet it underscores the need for initial testing to properly characterize a proposed storage zone, particularly including the hydraulic properties of underlying aquifers and confining layers.

Recovery efficiency had not been a major issue at Florida ASR sites until 2002, when USGS issued a report titled "Inventory and Review of Aquifer Storage and Recovery in Southern Florida" (Reese 2002). In that report, 27 ASR sites in various stages of development in South Florida were inventoried and data from 16 of those sites were evaluated to determine recovery efficiency. All but one of the considered sites were in early stages of cycle testing and storage zone development, for which recovery efficiency is often low. Reported recovery efficiencies for 14 of the 16 sites were in a range of 6% to 76%. Only one of the sites, Boynton Beach, had been in operation for several years. The reported final recovery efficiency for that site was 84%, assuming that recovery had been terminated at a chloride concentration of 250 mg/L. However, operations at Boynton Beach typically continue until chloride concentration reaches 350 mg/L since the recovered water is blended with a much greater volume of fresher water from another source. Consequently, a recovery efficiency of 98.6% at the end of the cycle is also reported. The Miami-Dade West Wellfield achieved full recovery efficiency within three cycles; however, that was achieved after initial formation of the TSV. None of the other long-term operating ASR sites in South Florida were evaluated in this project. Consequently, the conclusions are biased on the low side, thereby inadvertently adding to the confusion regarding ASR technology and experience in Florida. As a result, many interest groups in Florida may have the impression that ASR recovery efficiency is unacceptably low, when in fact it is usually quite high. Such misperception must be clarified and resolved to facilitate sound decision-making by water managers regarding the likely future role of ASR in Florida water management. Additional testing and monitoring facilities and programs that are being required for new Florida ASR sites need to clarify these issues along with an economic and resources-benefits analysis of the initial "investment" needed to establish TSV. Typically the cost of TSV formation is very small since it occurs during times of the year when water supply is plentiful and water demands are below peak levels.

Recovery efficiency has been defined by some in Florida as the percentage of the same water molecules stored that are recovered, either cumulatively or in an individual cycle, at a standard recovered water quality cutoff criterion such as the drinking water standard for chloride, 250 mg/L. This "counting the molecules" approach is often favored by scientists because it facilitates comparison of recovery efficiency between various ASR sites. Unfortunately, this approach in Florida's karst aquifers rarely will lead to recovery efficiency estimates much greater than about 70%, and more often closer to 50%, due to mixing underground between stored water and ambient groundwater, or more likely between stored water in the current ASR cycle and residual water remaining underground from previous ASR cycles.

With the traditional approach, recovery efficiency is defined as the volume of water recovered in a particular cycle that meets site-specific criteria for acceptable recovered water quality, divided by the volume of water recharged during that cycle, that is, "cycle recovery efficiency." This approach facilitates evaluation of the relative performance between ASR wells and wellfields based upon their overall usefulness to meet water utility and water management needs. If a water manager recharges a billion gallons and is able to recover a billion gallons and use it fully for its intended purpose, the manager usually views this as 100% recovery efficiency. With this definition, recovery efficiencies at established Florida ASR sites have generally achieved 100% levels within a few years (see Table 2). For water managers and elected decision makers, recovery efficiencies much different than about 100%, whether higher or lower, are difficult to justify and to support, regardless of the technical and economic merits. This reflects the intense focus in Florida on water conservation and the overriding need to avoid wasting water, or the perception of wasting water. As such, it may be prudent to consider the traditional, more practical approach to evaluating recovery efficiency, used since 1983 and as proposed at the beginning of this section. In some cases, however, it is recognized that repeated "investment" of water is needed to continue to maintain desired ASR performance.

The difference between the two definitions of recovery efficiency is far more than semantic because water management decision-making will likely be based upon more than just semantics alone. If water management options such as ASR are not perceived as achieving full recovery efficiency, they may tend to be at a distinct disadvantage compared to other water management options that may cost many times as much, but are perceived, correctly or incorrectly, to not waste water. For this reason, the definition of recovery efficiency that has been followed in Florida since 1983 by water utilities and water managers appears to be more appropriate as a yardstick for evaluating ASR performance.

Scientists and water managers will likely continue the debate over ASR recovery efficiency. Many scientists will argue a need to define a single criterion that enables direct comparison between all ASR sites, regardless of site-specific constraints and opportunities, after each site has achieved its TSV. Water managers will likely continue to view ASR success, or its failure, depending upon whether they can recover essentially the same volume that they recharge in each operating cycle while meeting drinking water standards going to their consumers or other end users. An important message is that both perspectives are correct, and that while 100% recovery efficiency is desirable, and often achievable, less than 100% recovery efficiency may still be beneficial and cost-effective. Presenting this message in a way that does not appear as a justification for "wasting water" will likely be a challenge.

For the two long-term operating ASR sites within SJRWMD, Cocoa and Palm Bay, ASR operations have continued since 1987 and 1989, respectively. Cocoa has 10 ASR wells, constructed in three phases. The first well, placed on-line in 1987, has been operating at 100% recovery efficiency for at least 10 years. The next construction phase added five more wells, which went on-line in 1992. Four of these wells are operating at 100% recovery efficiency, while one well has always had poor performance due to high turbidity in the recovered water. The poor performance of this well is a construction problem and is not an indication of the mixing between the recharge water and the ambient brackish water in the aquifer. The third expansion phase added four more wells that went on-line in 2002, all of which are still in development. However, three of these wells are operating normally, while one is highly productive but shows signs of relatively greater mixing of the recharge water with ambient brackish groundwater.

The first ASR well at Palm Bay went on-line in 1989, with 90 million gallons stored. However, the well was then idle for 5 years when a major industrial wholesale customer implemented a self-supplied water system, reducing the water demand at Palm Bay by 40%. When the stored water was finally recovered, recovery efficiency was reduced to about 66% when the recovered water became too salty for drinking. It then became apparent that the industrial self-supply was from two new reverse osmosis supply wells in the same ASR storage zone, less than a mile from the ASR site. The industrial brackish water supply well operations had pulled some of the stored water away from the ASR well. That ASR system continues in successful operation, but uses their ASR well as originally designed, storing and recovering water on a seasonal schedule.

CONCLUDING STATEMENT

The use of ASR as a water management tool, in conformance with state and federal regulations, has proven to be both scientifically sound and environmentally responsible. Emerging policies of FDEP continue to steer the development and implementation of ASR. ASR is a site-specific technology that is still evolving, and there is much to learn regarding its application in the different geological settings of Florida. SJRWMD has identified the potential impacts of proposed water use through year 2020 on the water resources in SJRWMD (Vergara 1998) and is performing the same evaluation through year 2025 as part of developing the District Water Supply Plan. Areas have been identified in which water resource problems have become critical or are projected to become critical by at least 2020. These areas, referred to as priority water resource caution areas (PWRCAs), include all or portions of Orange, Osceola, Seminole, Volusia, Lake, St. Johns, Flagler, and Brevard counties and may extend to new areas as the water supply planning process continues. The SJRWMD ASR Construction and Testing Program involves eight cooperators within PWRCAs in the east-central Florida area where ASR, if found to be feasible, will help to address these problems by playing a positive role in utility infrastructure planning and the development of sources of alternative water supplies.

This SJRWMD-sponsored paper is intended to provide an overview of ASR issues and the current availability of scientific information to support the ASR implementation decision-making process. It has been developed as part of SJRWMD's ongoing ASR Construction and Testing Program that began in October 2001 to determine the extent to which ASR can be applied to meet local or regional needs through use of alternative water supplies. The goal of the SJRWMD ASR Construction and Testing Program is to examine the appropriateness of integrating ASR technology into regional water resource and water supply development at specific pilot project sites. It is designed to address many of the issues presented in this paper in a thorough and scientific manner, so that water managers, regulators, elected officials, and other interested persons can observe the results and make informed decisions regarding ASR as a water management tool.

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APPENDIX

AQUIFER STORAGE RECOVERY CONSTRUCTION AND TESTING PROGRAM

GEOCHEMICAL SAMPLING PROTOCOL

(This document was prepared for the St Johns River Water Management District by a team of consultants selected by the District to implement an ASR Construction and Testing Program at multiple sites. Consultants included ASR Systems; CH2M HILL; Barnes, Ferland & Associates; CDM; and Water Resources Solutions. The work was completed during December 2002.)

This scope of work is designed to be a cost effective strategy to obtain basic geo-chemical data to evaluate the potential for adverse fluid-rock interactions during ASR system operation. Sample collection would not require additional work beyond that which would be proposed to evaluate storage zone hydraulics.

Sampling

1. Cores (5 or 10 ft) shall be taken of proposed storage zone interval and potential overlying and underlying confining strata. At least 2 cores shall be taken of the storage zone. Core samples shall be analyzed for hydraulic parameters (at a minimum porosity, grain size distribution (sands), specific gravity, vertical and horizontal hydraulic conductivity, and colored pictures of the cores).

2. The remaining (not cored parts) of the storage zone shall be drilled using the reverse-air method. Cuttings from the likely storage zone shall be collected at 5 ft intervals. Care shall be taken to ensure accurate determination of sample depth, such as recording travel time and periodically circulating borehole to clear out cuttings.

3. Reverse-air water quality samples shall be collected at 20 ft intervals (every rod change) and a full suite of geophysical logs run at the end of drilling.

4. Packer tests shall be performed on the potential storage zone to obtain both hydraulic and water quality data. Alternatively, specific capacity pumping tests shall be run on the open borehole at different depths during construction to confirm flow characteristics.

<u>Rock Sample Analyses</u>

1. Cuttings shall be examined for composition and texture using a stereomicroscope. Particular attention shall be paid to the presence of any potential reactive minerals (e.g., sulfides) and organic matter.

2. Thin sections shall be prepared of core and cutting samples and petrographically analyzed (10 samples minimum). Selected samples shall include representatives of the various rock types present. If possible, some thin sections should be prepared of core plugs or core

plug trims so that rock composition and textures can be related directly to petro-physical properties.

3. Whole rock analyses shall be performed on several core or cutting samples for trace elements that would be diagnostic of carbonate mineral reactions or fluid-rock interactions of concern (Mn, Mg, Sr, As, Fe, Gross alpha, isotopic uranium). A radionuclide analysis sample shall be taken from the part of the storage zone with the highest gamma ray log activity. Samples of any materials that might have high arsenic or radionuclide concentrations, such as lignites should also be tested.

4. As leaching of arsenic and radionuclides is a concern in ASR systems, simple bench-top batch experiments shall be performed. Leaching can be simulated by placing samples of cuttings in containers filled with distilled/deionized water, actual samples of the recharge water, and/or mildly acidic solutions. Analysis of the water after a month or so, will provide a reasonable simulation of fluid-rock interaction in the ASR system. A standard EPA method may be utilized, such as the Synthetic Precipitation Leaching Procedure (SPLP) test, in which rock samples and treated surface water are mixed in a bottle and rolled for a specified time period such as 24 hours, following which water samples are removed for analysis.

Water Chemistry Analyses

Samples of the storage zone water and likely recharge water shall be analyzed for field parameters (pH, temperature, DO, Eh, specific conductance) and all major cations and anions, and other elements of concern (at a minimum Na, Ca, Mn, Fe, Mg, Sr, K, Al, Si, Cu, Zn, Cd, Se, Cl, F, HCO_3, SO_4, TDS, As, total and non-carbonate hardness, calcium hardness, nitrate, phosphate, ammonia, hydrogen sulfide, total organic carbon, total coliforms, trihalomethane species, gross alpha and uranium).

Geo-chemical Model

The saturation state of the native and recharge water with respect to sedimentary minerals shall be calculated using a low-temperature geochemistry speciation and saturation program, such as PHREEQC or GEOCHEMIST WORKBENCH. Simulations shall also be performed of the mixing of various percentages of native and recharge waters.

Additional Scope Of Work (Not included except under separate authorization)

The following additional scope of work will be considered for authorization at one to three sites where treated surface water is available to conduct full scale testing at an ASR well to be constructed as part of this construction and testing program. A more comprehensive geo-chemical characterization of a potential ASR site could be performed by expanding upon the above tasks. Additional work would include:

1. Continuous wireline coring of the entire storage zone and parts of the overlying and underlying confining strata.

2. More comprehensive petrologically and geochemical analysis of core samples and cuttings, which could include such techniques as scanning electron microscopy, x-ray diffractometry, cation and base exchange capacity, and possible electron microprobe analyses of suspected arsenic-rich phases.

3. More rigorous bench-top leaching experiments.

4. Analysis of available recharge and recovered water quality data from existing Florida sites storing treated surface water in ASR wells, to ascertain the nature and significance of any apparent geochemical reactions affecting recovered water quality. These would include Manatee County (since 1983); Peace River (since 1985); Tampa (since 1999); and Marco Lakes (since 2000).

5. Design and implement a cycle testing plan for a full-scale ASR well at the same site to confirm geochemical response to ASR operations over a period of several cycles of similar small volume but varying storage periods. Geochemical response is expected to be at a maximum during the initial cycle, decreasing in subsequent cycles.

End of sampling protocol.

Table 1. Aquifer storage and recovery wells in Florida operating and fully permitted as of September 2003

	Location	Year Began Operations	Number of Wells
	Manatee County Water treatment plant and reservoir site	1983	8
2	Peace River/Manasota Regional WSA Water treatment plant and reservoir site	1985	22
3	City of Cocoa Water treatment plant	1987	8
4	Palm Bay	1989	1
5	Boynton Beach East water treatment plant	1993	[illegible]
6	Miami-Dade Water and Sewer Department West wellfield	1999	3
7	Florida Water Services Marco Lakes	2001	3
8	Collier County Manatee Road	2002	
9	Lee County Regional WSA Corkscrew water treatment plant	2001	5
10	City of Tampa Rome Avenue Park	2001	8
11	City of Punta Gorda Shell Creek water treatment plant	2002	3
12	City of Delray Beach North storage reservoir	2002	1
13	West Palm Beach Water treatment plant	2003	1
	Total		**65**

Note: WSA = Water Supply Authority

All wells are storing treated drinking water except
No. 6—storing fresh groundwater
No. 7—storing partially treated surface water
No. 13—storing partially treated surface water

Table 2. Recovery efficiency at Florida aquifer storage and recovery wellfields in operation for more than 5 years

Site	Year Began Operations	Recovery Efficiency
Manatee	1983	100
Peace River	1985	100
Cocoa	1987	100
Palm Bay	1989	100
Boynton Beach	1993	98.6
Miami-Dade	1999	100

Note: Recovery efficiency as shown does not account for establishment of target storage volume or changes in water quality in the recovered water.

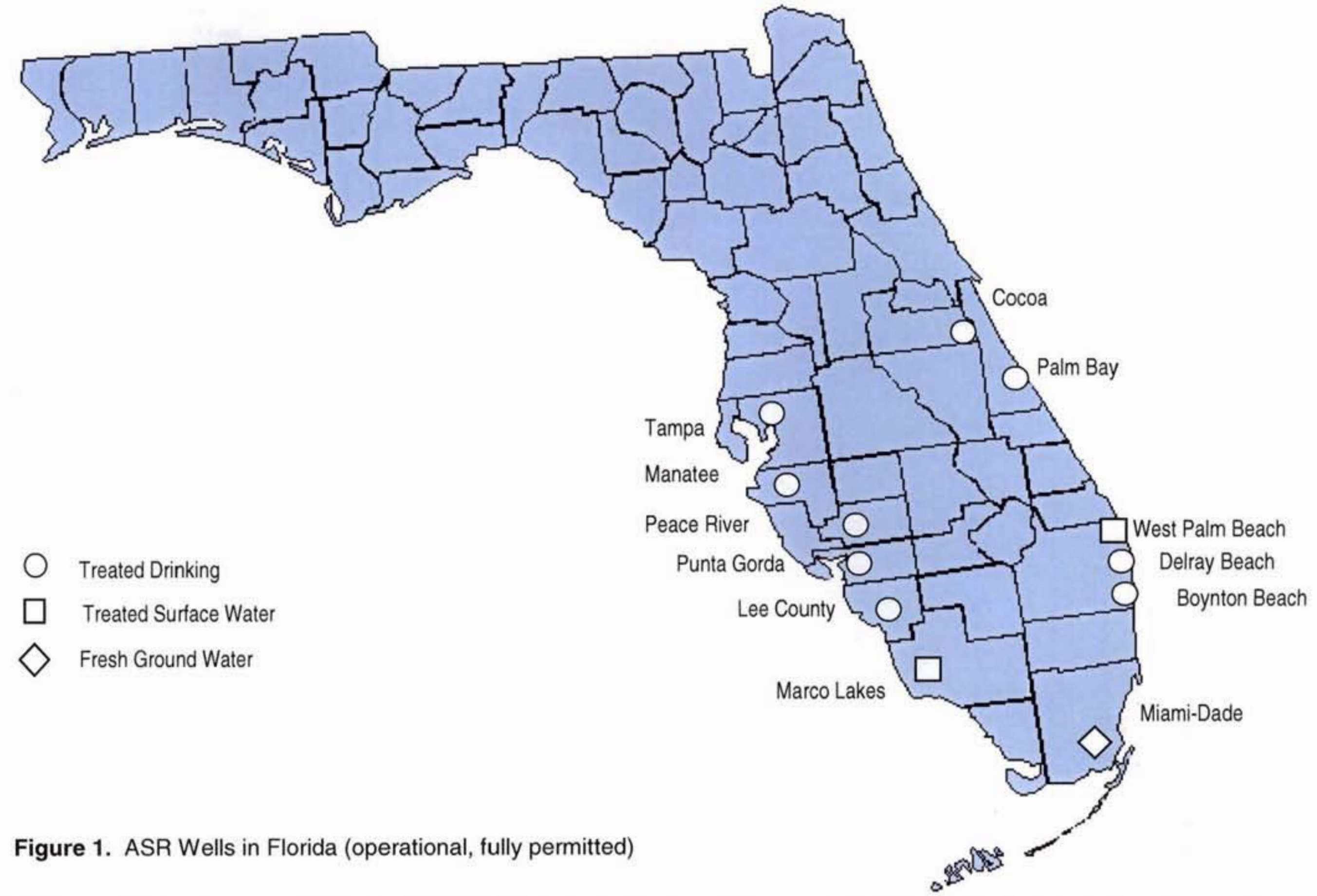


Figure 1. ASR Wells in Florida (operational, fully permitted)

Figure 2. ASR Wellfields in the United States, July 2003

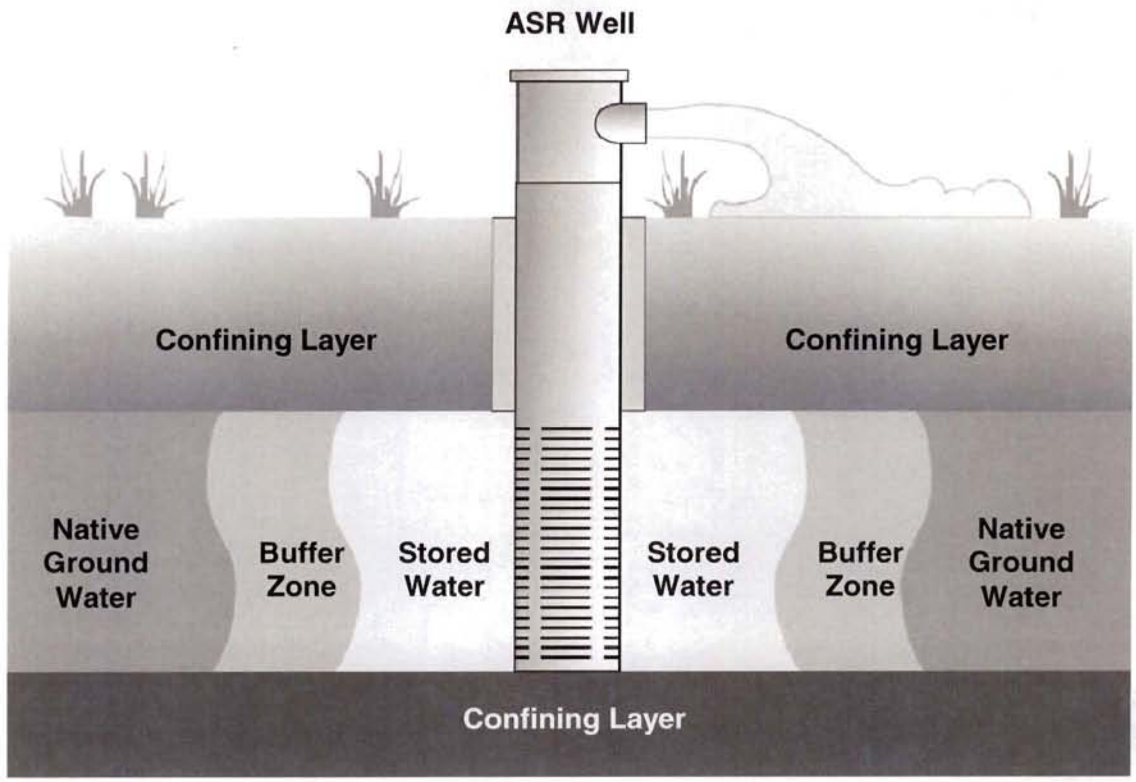


Figure 3. ASR Typical Cross-Section

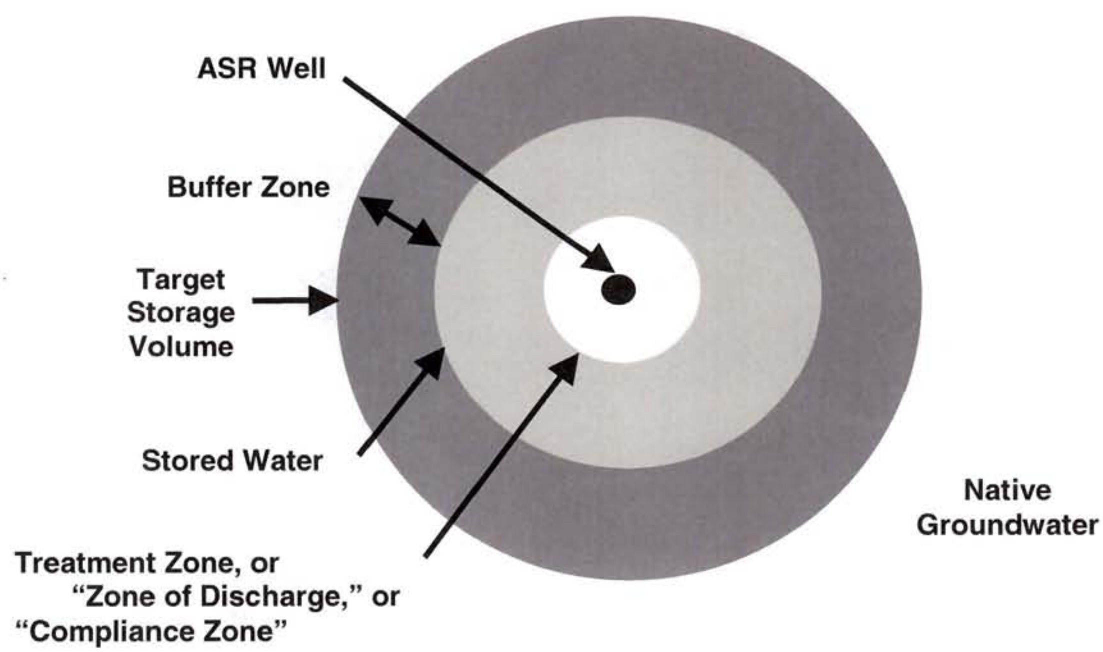


Figure 4. ASR Bubble —Top View

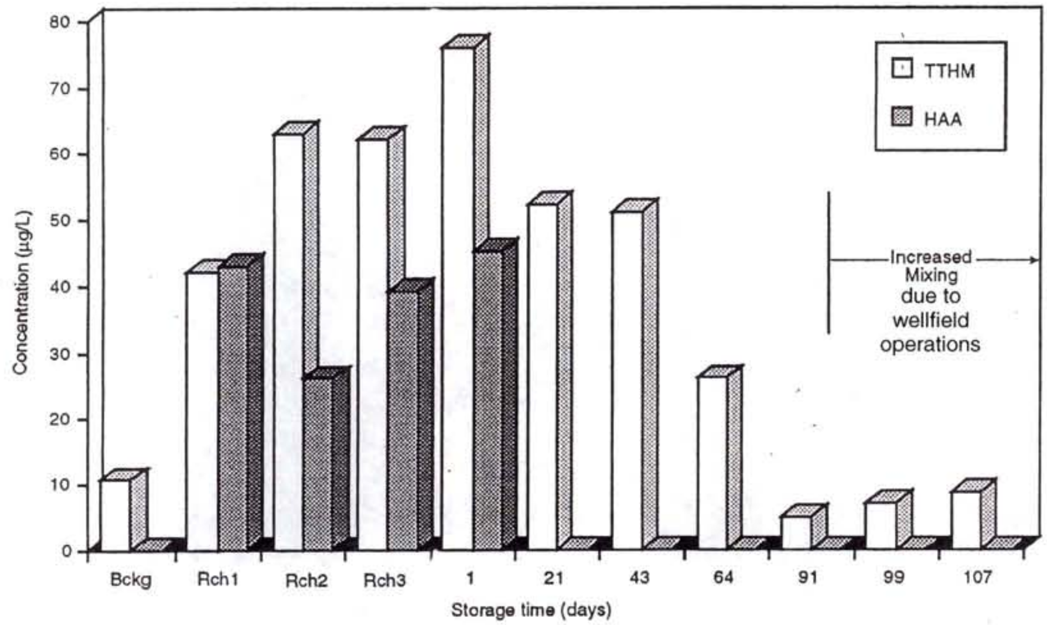
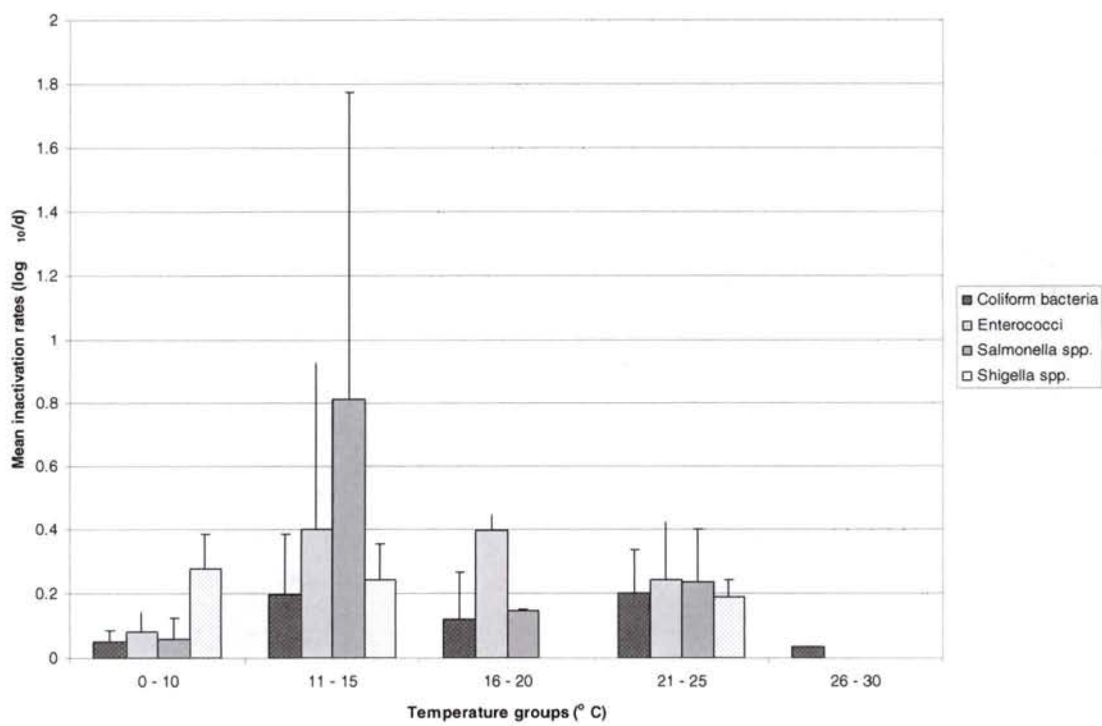


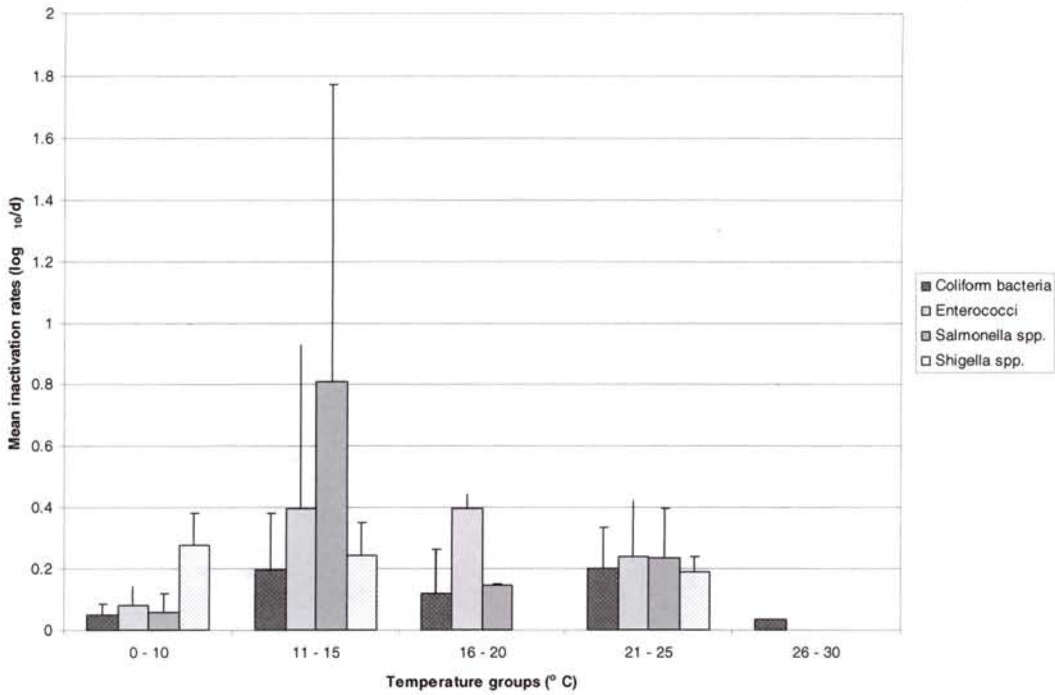
Figure 5. Disinfection By-products – Peace River

Error bars reflect standard deviation of rate values observed in each temperature group.



Credit: Joan B. Rose, PhD and David E. John, University of South Florida, 2002.

Figure 6. Bacteria Mean Inactivation Rates in Temperature Groups



Credit: Joan B. Rose, PhD and David E. John, University of South Florida, 2002.

Figure 7. Virus Mean Inactivation Rates in Temperature Groups

Figure 8. ASR Forum “Splash” Page