WATER QUALITY IN AQUIFER STORAGE RECOVERY (ASR) WELLS

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EXECUTIVE SUMMARY

This position paper has been prepared to provide guidance to elected officials and to other interested citizens regarding the scientific basis that is available to support the decision-making process as it relates to the implementation of aquifer storage recovery (ASR) technology. This is intended to facilitate decisions regarding the extent to which ASR can be applied to meet local or regional needs through use of alternative water supplies.

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 two years, concerns have been expressed by several public interest groups regarding whether ASR technology has been adequately proven in Florida, and 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. These concerns have been superficially supported by two reports issued during the past year by the United States Geological Survey (USGS) regarding ASR, both of which have provided information that may not apply to ASR wells in Florida. Each of these concerns is addressed in this paper.

Scientific literature is substantial and consistent in showing that, under aquifer 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 is microbial degradation. Several proven approaches are utilized at various Florida water treatment plants to control or eliminate the presence of DBPs in the recharge water, if needed. This 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. Metal concentrations typically decline with time, with distance from the ASR well, and with successive operating cycles. No long-term operating ASR

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sites in Florida are known to have elevated concentrations of metals such as arsenic, uranium or mercury. During initial cycle testing at a new ASR well, elevated concentrations of arsenic may occur at some ASR sites, particularly at those sites recharging treated surface water due to the generally higher oxidation-reduction potential (Eh). This is of some concern since on January 1, 2005, Florida drinking water standards for arsenic will decrease from 50 micrograms per liter (µg/l) to 10 µg/l, which is within the range of concentrations observed during initial cycle testing at some Florida ASR sites. Typically, after four to eight ASR cycles at the same storage volume, arsenic concentrations should subside to acceptable levels. Several approaches 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 public drinking water distribution systems from Florida ASR wells.

Pathogenic microbiota are not present in recharge water to ASR wells in Florida, reflecting regulations and policies by Florida Department of Environmental Protection (FDEP) to recharge only water that meets drinking water standards for storage in our brackish aquifers. 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. Virtually all of the ASR wells that have been operating for more than five 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 percent, with higher levels accomplished in less brackish aquifers and lower levels in highly saline or seawater aquifers. There is considerable debate as to the definition of recovery efficiency in an ASR well, which 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, 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. 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 retreated following recovery, other than disinfection.

Within the SJRWMD, ASR wellfields have operated successfully since 1987 at two locations. During that year, the Cocoa ASR system at the Claude H. Dyal Water Treatment Plant began operation. That wellfield has since been twice expanded and currently has a recovery capacity of 12 million gallons per day (MGD). 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 (Nipper, 2003).

ASR wellfields are operational at more than 59 sites in 16 states in the United States, and in at least 7 other countries, as shown on Figure 2. The first ASR wellfield in the United States, at Wildwood, New Jersey, began operation in 1968 and now has 4 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 deep, 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 (CERP), including over 330 ASR wells with a combined recovery capacity of 1.7 billion gallons per day (gpd). These proposals in turn have attracted the attention of public interest groups concerned that broader applications of ASR may facilitate growth, adversely impact groundwater quality, damage our aquifers and also damage our environment.

During the past three years in Florida, public attention has focused 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, extensive misinformation has been disseminated through the media regarding these various water quality issues, including an effort to equate ASR wells to deep injection wells utilized for disposal of wastewater effluent. As a result, considerable confusion has arisen regarding the effectiveness of ASR as a water management technology, and whether ASR should be relied upon to provide sustainable, cost-effective water storage to meet projected future demands. After 20 years of successful ASR operations in Florida, it still remains necessary to try to correct some of the misinformation and resolve the confusion, so that informed, scientifically based decision-making by water managers, elected representatives and other interested citizens can proceed.

This paper is intended to provide guidance to elected officials and to other interested citizens regarding the scientific basis that is available to support the decision-making process.

ASR FUNDAMENTALS

Figures 3 and 4 show typical ASR well cross-sections, the first being a side view and the second being a top view, looking down on an ASR well and the surrounding stored water bubble. Treated water is recharged into the aquifer during wet months through the ASR well, 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 and displaces brackish water 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 in water quality and water levels that may occur.

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). At such time when the TSV has been achieved in an ASR well in a brackish aquifer, it is usually possible to achieve high recovery efficiency for that well. 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 (MG) per million gallons per day (MGD) 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.

Experience has shown that very close to the ASR well, typically within a radius of a few tens of feet, a treatment zone develops within which ambient microbial activity is accelerated, geochemical changes are more prevalent, and water quality changes occur, as shown on Figure 4 (de Ruiter, 1998; Pyne, 1995). Changes in water quality have generally been minor, so that treated drinking water quality standards that are met during recharge are also generally met during recovery. 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, subtle changes in some constituent concentrations have been noted at several ASR sites, and some of these are the subject of considerable public interest. Most of these subtle 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, it has been possible to leave these constituents in the aquifer and not produce them in the recovered water. 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. The principal purpose of this paper is to address public perceptions regarding ASR water quality changes that have resulted in, or may potentially result in, an increase in constituent concentrations, such as for arsenic.

In Florida, recharge water quality must meet all primary drinking water standards at the wellhead prior to recharge. Some other states address these issues differently. For example, Arizona requires that recharge water quality must meet all drinking water standards as measured at the edge of a "compliance zone" around the ASR well, up to 700 feet away, thereby taking full advantage of the demonstrated ability of aquifers to improve water quality due to natural treatment processes. In Arizona, ASR storage typically occurs in fresh water, unconsolidated sand aquifers that are utilized for drinking water supplies, whereas in Florida, ASR storage zones are generally brackish and are therefore unsuitable for potable water supply except following desalination treatment. In Wisconsin, compliance with water quality standards is measured either at the water treatment plant or in the distribution system during recharge. It is also measured at the ASR wellhead during recovery, in addition to compliance with state groundwater standards at a property line monitor well in the storage zone. However, an exemption for trihalomethanes (THMs) was implemented during 2001, providing a compliance zone radius of 1,200 feet. ASR wells in Wisconsin are generally in sandstone aquifers. In North Carolina, water quality compliance with drinking water standards is measured at the edge of a mixing zone in a clayey sand aquifer around the ASR well, not at the wellhead prior to recharge.

While all four regulatory programs comply with federal law (1974 Safe Drinking Water Act), the United States Environmental Protection Agency (EPA) Underground Injection Control (UIC) regulations promulgated in 1981 pursuant to this law established that primary drinking water standards should be measured at the wellhead, not in the aquifer. As such, it may be concluded that the federal law and the federal regulations are inconsistent. Arizona has followed federal law. Florida's standards are in many ways more restrictive and more costly to achieve compared to those regulatory programs that evaluate compliance at a monitor well in the aquifer.

Following are discussions summarizing the scientific basis for observations regarding specific water quality issues pertaining to ASR, from data sources that are public information.

Disinfection Byproducts

DBPs such as 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 (UV) radiation. However, chlorination still represents a widely used disinfection treatment process in the United States. The 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 and 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, in press; 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 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, City of Cocoa, Town of Palm Bay and City of Boynton Beach, with a combined total of 15 ASR wells in 1995. In addition to these Florida sites, many others 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 the Peace River, Florida, site in DeSoto County, which had been in operation since 1985. Conclusions of the AWWARF report are as follows:

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

2. HAA removal precedes THM removal.

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

4. 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.

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

6. 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.

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

AWWARF is scheduled to publish during early 2004 a second report entitled “Water Quality Improvement During Aquifer Storage Recovery,” for which Peter Dillon, Ph.D., CSIRO, Adelaide, Australia was the Principal Investigator. That project team includes 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. As indicated by Dr. Dillon, conclusions are consistent with those published in the 1996 AWAARF report (Dillon, 2003).

A recent paper by Nicholson et al (2002) presents some of the same data utilized 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, in press).”

In May 2003, the USGS published a report entitled "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 that report has been used to raise concerns about THMs, the conclusions contained within it are consistent with those of the two AWWARF reports mentioned above, and include the following conclusion: "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 aerobic, whereas virtually all other ASR sites globally are in deep, confined, anoxic (lacking oxygen) aquifers. For that USGS publication, the press release that was disseminated by the USGS was misleading in that it implied 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 which would not degrade. In actuality, since most ASR wells are in aquifers that are confined, deep and anoxic, the data from this USGS test site have very limited applicability to other ASR sites. Limited available data 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 (Pyne et al, 1996). The USGS study was conducted in an aquifer that is shallow, unconfined and aerobic. The USGS press release announced incorrect global conclusions from a site that is not representative of ASR applications in Florida or in most other locations in the world. The USGS press release has created considerable problems for 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 MG 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, limestone artesian aquifer (Tampa Formation) with a thickness of 100 feet and a background total dissolved solids (TDS) concentration of 700 milligrams per liter (mg/l), and then was 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 ft^2/day. Recharge water THMs averaged 56 µg/l while HAAs averaged 37 µg/l. Background pH in the aquifer was 7.93. No data were obtained for oxidation-reduction potential (Eh); however, dissolved oxygen was 1.3 mg/l and total chlorine was zero. Figure 5 shows the rapid 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 µg/l within three months while HAA concentrations disappeared within less than 21 days. The current THM drinking water standard is 80 µg/l and for HAA it is 60 µg/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 five 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 the SJRWMD, at Cocoa and at Palm Bay, extensive data on DBPs have been obtained, indicating that this is not a problem at either site, either in the drinking water utilized for ASR recharge or in the ASR recovered water (CH2M HILL, 1988 and 1989).

It is anticipated that ASR demonstration projects to be implemented within the SJRWMD will be generally in deep, 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 in ASR wells at such times, and blending it with water from primary water sources, can ensure compliance with drinking water standards at minimal cost while also achieving the other peak-shaving benefits of ASR. Recovered water from ASR wells will probably have little or no DBPs and also will have probably 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.

Regardless of all research conducted to date, in Florida and elsewhere, as well as in all field data showing consistent removal of DBPs during ASR storage in Florida, the projects to be undertaken as part of the current ASR Demonstration Program by the SJRWMD will not recharge water into ASR wells that exceeds the allowable concentrations in drinking water. Data will be collected during each of the ASR demonstration projects to verify that DBPs attenuate 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 others 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 problem requiring further careful investigation.

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. In the past three years, samples obtained from water recovered from several new ASR wells in Florida 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 µg/l. At one representative site, the initial arsenic concentration at the beginning of recovery on the first cycle was about 88 µg/l. In subsequent cycles, arsenic concentrations declined, reaching maximum levels of 58 and 34 µg/l in Cycles 2 and 3, respectively. At another site, the peak arsenic concentration during the first recovery cycle was 39 µg/l, while during the second recovery cycle it was 7 µg/l. During January 2005, the Florida drinking water standard for arsenic is expected to drop to 10 µg/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 present at unacceptably high concentrations, water recovered would require treatment and also disposal of the residuals from the treatment process, thereby increasing 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 µg/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 utilized 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 since 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 follow.

"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 et al, 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, 1998[b]). "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, 1998[c] and 2002; Stuyfzand et al, 2002).

Further investigations have been conducted by the Florida Geological Survey (FGS) and others to confirm the initial results and to gain improved understanding of the geochemical mechanisms involved (Williams, 2002). Additional scientific investigations are under way, and others are planned by the SJRWMD as a part of the current ASR Demonstration Program. A geochemistry sampling protocol has been developed to support the SJRWMD ASR Demonstration Program. This comprehensive 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 appears to be a transitional phenomenon, and has only been seen 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 MG.

Arsenic has not been detected at elevated concentrations in ASR wells that have been operating for several years. It appears that, through natural attenuation processes occurring in the aquifer during ASR operations, arsenic concentrations generally diminish with time, with distance from the ASR well, and also with repeated operating cycles at the same storage volume. It is estimated that potable drinking water concentrations are achieved after an estimated four to eight operational cycles at about the same storage and recovery volume, in wells that have initially elevated concentrations of arsenic.

During cycle testing at the two ASR wellfields located within the SJRWMD, 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, samples were collected during March 1987 at 19 percent and 90 percent of recovery during Cycle 4M, both of which indicated less than 5 µg/l 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.

It is not known whether arsenic was previously present at higher initial concentrations at the Cocoa and Palm Bay sites; however, it was present at very low concentrations at this point in the cycle testing programs (CH2M HILL, 1988 and 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, with arsenic attenuation to acceptable levels usually after four to eight test cycles. It is possible that background arsenic concentrations in the upper Floridan aquifer are lower in east-central

Florida as compared to west-central Florida, where arsenic issues have arisen in some new ASR wells during initial cycle testing.

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 since water quality monitoring was focused initially on other constituents in the recovered water. No problem was ever detected at any of the ASR sites. 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 that may be present than waters with high levels of Eh. As described above, such reactions at operational ASR sites have proved to be transitional.

ASR wellfields utilizing groundwater sources have been typically less likely to have a problem with arsenic in the recovered water during cycle testing and initial operations. ASR systems utilizing surface water sources 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.

Most of the concern to date in Florida has centered on the occurrence of arsenic in recovered water from ASR wells. Concern has also been expressed regarding 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 completed, 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. 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 after February 1, 2006, 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 has 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 since 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 contain arsenic at different Florida ASR locations. 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.

If arsenic concentrations are above acceptable levels, several ways may be appropriate to mitigate the problem:

- Conducting initial cycle testing with discharge of water to waste, retreatment or blending with water from other sources until initially high arsenic concentrations subside to below drinking water standards.
- Adjustment of pH of recharge water to reduce the potential for arsenic solution.
- Chemical feed to induce rapid re-precipitation of arsenic in the aquifer.
- Treatment of the recharge water to reduce or remove oxygen, such as by bank filtration or addition of chemicals.
- Treatment of the recovered water.
- Overpumping the well during initial recovery cycles to purge arsenic from the aquifer around the well.
- Creation of a buffer zone around the well to leach arsenic out of this portion of the storage zone.

- Improved 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.
- Location of a storage zone monitor well at a greater radius from the ASR well than the buffer zone surrounding the ASR well.

Overpumping the well during initial recovery cycles is considered to be less likely 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 been recently applied successfully at an ASR site in Green Bay, Wisconsin. The particular way to address each situation will vary, depending on the extent of the problem (i.e., the treatment processes available). One approach that is deemed worthy of further consideration for Florida is bank filtration of surface water prior to ASR recharge, to reduce or eliminate pathogenic microbiota, to provide natural filtration, and also to reduce the Eh of the recharge water so that it is less likely to dissolve metals from the limestone during ASR storage.

Uranium

In addition to arsenic, the 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 Florida standard is 30 µg/l for uranium in public drinking water supplies, effective December 8, 2003. 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 µg/l. Background concentrations are approximately 1 µg/l, and concentrations in the recovered water appeared to decrease with time (Williams et al, 2002).

The mechanisms for release of uranium from the limestone appear 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 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 (SFWMD) as part of the CERP, including 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.

Microbiota

Public concerns have been expressed regarding the potential for microbiota in the ASR recharge water that might contaminate the aquifer and endanger groundwater supplies. As a result, under current Florida policy, ASR wells will only recharge treated drinking water. By definition, such water is free of pathogenic bacteria, viruses and protozoa, since the water will have undergone treatment at a central water treatment plant that is subject to stringent water quality monitoring requirements.

While recharged treated drinking water is free of pathogenic microbiota, public misconception about ASR and microbiota contamination remains. For this reason, it is important to point out that extensive scientific investigations and field data collection programs indicate that pathogenic microbiota concentrations attenuate rapidly during ASR storage. Such a reduction in any pathogenic microbiota concentrations would provide an additional barrier to protect groundwater quality, while also considering that natural groundwater quality at most of the ASR sites within the District will be brackish, unfit for human consumption. Such water may be rendered suitable for consumption following desalination treatment, which would remove any pathogenic microbial constituents present in the recharge water. It is pertinent that many of the potential ASR applications under consideration by water users include proposed seasonal storage of treated surface water, reclaimed water and fresh groundwater. These other applications would be for storage of very high quality water that may possibly contain disinfection byproducts or microbiota.

During the past few years, extensive microbial research has been conducted by CSIRO in Adelaide, Australia, in brackish, limestone, confined aquifers that are very similar to those in Florida (Medema et al, 2002; Gordon et al, 2002; Toze et al, 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, salinity, and probably other mechanisms.

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 possible 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 since 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 Florida policy-makers to recharging only treated drinking water is quite conservative, protecting existing brackish groundwater quality from potential contamination by microbial constituents in fresh recharge water. As a point of reference, in Australia, ASR is utilized for storage of treated fresh surface water and reclaimed water in brackish aquifers, at more than seven operational sites and at others in development. The perspective in Australia is that it is more useful to turn a brackish aquifer into a fresh water resource, utilizing 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. Such a high level of pretreatment in Florida would greatly increase the cost to taxpayers for capital investment in treatment facilities required to achieve these policy objectives. By comparison, taxpayers in Arizona, North Carolina, the Netherlands and Australia rely upon natural processes in the aquifer surrounding an ASR well to achieve these objectives at no additional cost.

Figures 6 and 7, prepared by Joan Rose, Ph.D. and David John at the University of South Florida, show attenuation rates for conservative bacterial and viral indicators under temperature and salinity conditions approximating those that would be expected during ASR storage in central Florida. A reasonable approximation is that 90 percent reduction in microbial concentrations will occur about every five days under the temperature and salinity conditions prevalent in Florida. For a reasonably good quality surface water source, 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 (SWFWMD) and SFWMD. Results are posted on a website, www.asrforum.com, as shown on Figure 8. The website 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 percent 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 website mentioned above.

Further research is needed regarding pathogenic microbiota attenuation during ASR storage. Such research is under way in connection with the CERP, and also it is being addressed by the SJRWMD as part of another field investigation on water quality issues associated with drainage wells in central Florida. 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 have 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, 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 surface reservoir storage, any recovery efficiency in Florida greater than about 40 percent is a net gain to the regional water supply due to high evaporation, transpiration, seepage and conveyance losses. Recovery efficiency can therefore be less than 100 percent 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 generally has 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 percent. However, with successive cycles to purge brackish water from around the ASR well, recovery efficiency has climbed progressively, typically reaching about 100 percent after a few cycles. In other words, once a buffer zone is formed around an ASR well in a brackish aquifer, subsequently stored water usually can be fully recovered so long as the volume recovered is reasonably consistent from one cycle to the next. The buffer zone volume therefore partly depends 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, quickly achieving high recovery efficiency 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 be quickly 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 the 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 percent 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 different 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 target storage volume 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 has not been a major issue at Florida ASR sites until 2002, when the USGS issued a report entitled “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 percent. Only one of the sites, Boynton Beach, had been in operation for several years. The reported final recovery efficiency for that site was 98.6 percent. 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 that has recently been disseminated regarding ASR technology and experience in Florida. As a result, many water managers, regulatory agency staff and elected officials in Florida have recently gained the impression that ASR recovery efficiency is unacceptably low, when in fact it is usually quite high. Such a misperception is already manifesting in discussions and decisions by water managers regarding the likely future role of ASR in Florida water management, and the additional testing and monitoring facilities and programs that are being required for new Florida ASR sites.

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, including the USGS, since 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 percent, and more often closer to 50 percent, 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.

For water managers and elected decision-makers, recovery efficiencies much different than about 100 percent, 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, utilized since 1983 and as proposed at the beginning of this section. 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. 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, he/she usually views this as 100 percent recovery efficiency. With this definition, recovery efficiencies at established Florida ASR sites have generally achieved 100 percent levels within a few years, as shown in Table 2.

The difference between the two definitions of recovery efficiency is far more than semantic since major water management decision-making likely will be based upon perceptions regarding recovery efficiency without really gaining a full understanding of the science behind the perceptions. If water management options such as ASR are not perceived as achieving full recovery efficiency, they will 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.

It is likely that scientists and water managers will 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 percent recovery efficiency is desirable, and often achievable, less than 100 percent recovery efficiency still may 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 the 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 percent 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 percent recovery efficiency while one well has always had poor performance due to high turbidity in the recovered water. This is a well construction problem, not an indication of mixing with 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 with ambient brackish groundwater.

The first ASR well at Palm Bay went on line in 1989 with 90 MG stored. However, the well was then idle for five years when a major industrial wholesale customer implemented a self-supplied water system, reducing the water demand at Palm Bay by 40 percent. When the stored water was finally recovered, recovery efficiency was reduced to about 66 percent 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 the ASR well as originally designed, storing and recovering water on a seasonal schedule.

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TABLE 1
Aquifer Storage Recovery Wells in Florida that are Operating and Fully Permitted
September 2003

	Location	Since	Number of Wells
1	Manatee County WTP and Reservoir Site	1983	8
2	Peace River/Manasota Regional WSA WTP and Reservoir Site	1985	22
3	City of Cocoa Water Treatment Plant	1987	10
4	Palm Bay	1989	1
5	Boynton Beach East WTP	1993	1
6	Miami-Dade Water and Sewer Department West Wellfield	1999	3
7	Florida Water Services Marco Lakes	2001	3
8	Collier County Manatee Road		1
9	Lee County Regional WSA Corkscrew WTP	2001	5
10	City of Tampa Rome Avenue Park	2001	8
11	City of Punta Gorda Shell Creek WTP	2002	1
12	City of Delray Beach N. Storage Reservoir	2002	1
13	West Palm Beach Water Treatment Plant	2003	1
	TOTAL ASR Wells		**65**

Note: 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 ASR Wellfields in Operation for More than Five 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

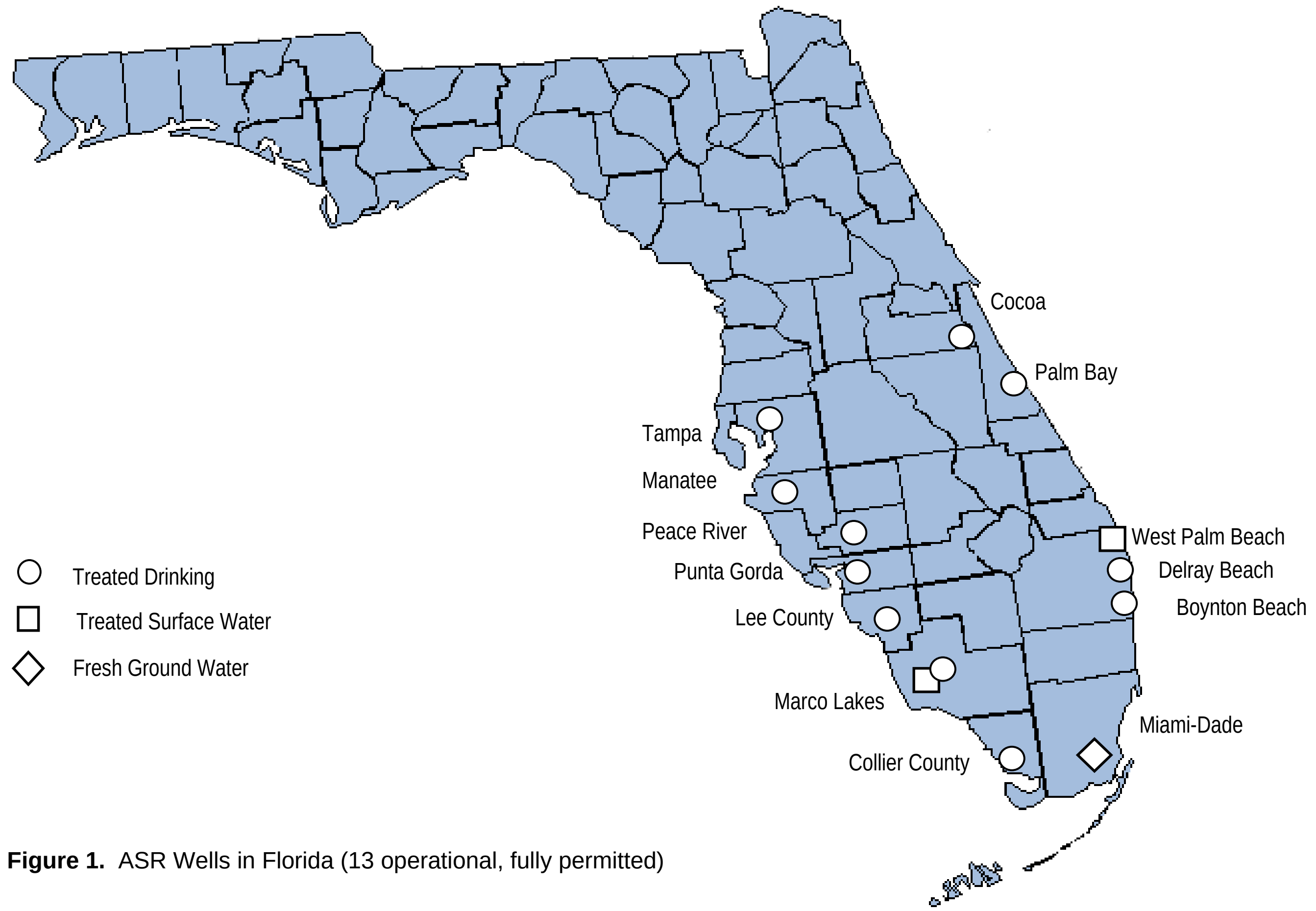


Figure 1. ASR Wells in Florida (13 operational, fully permitted)

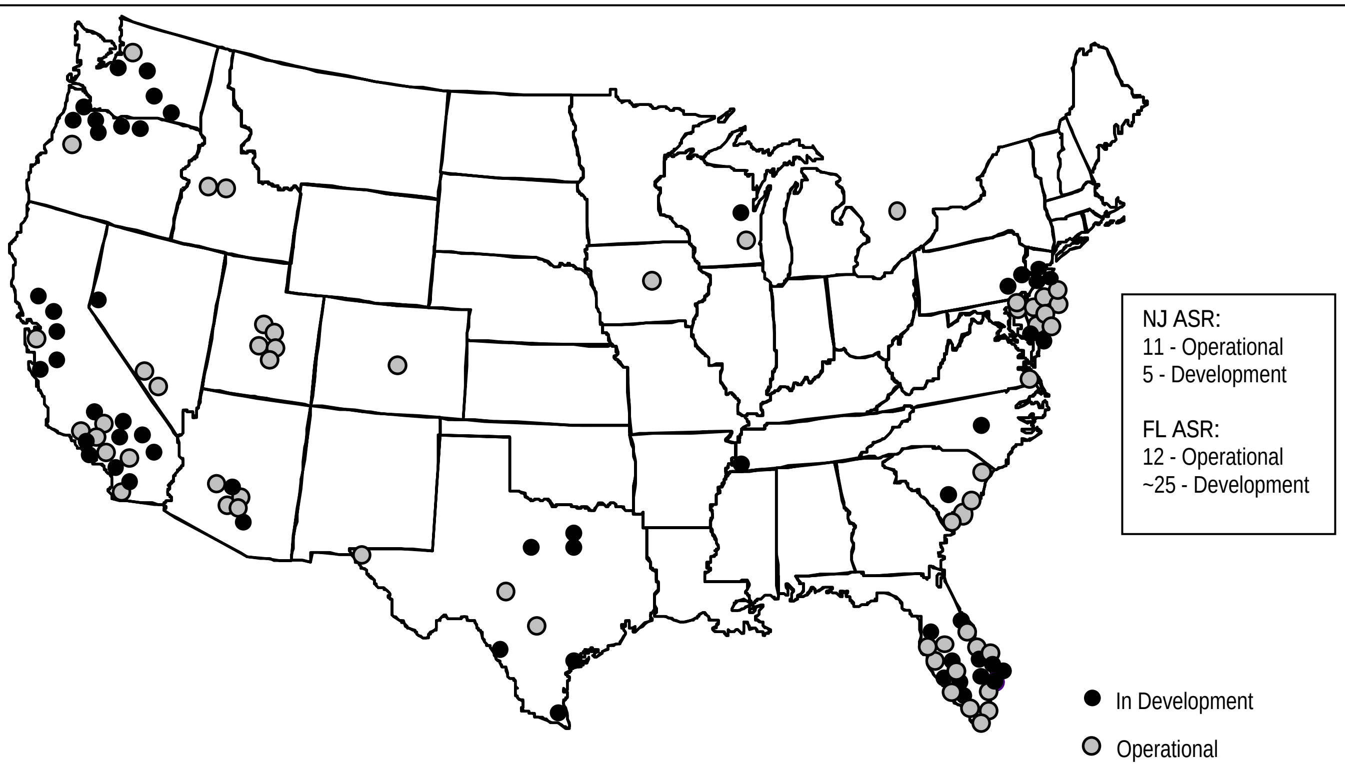


Figure 2. ASR Wellfields in the United States, July 2003

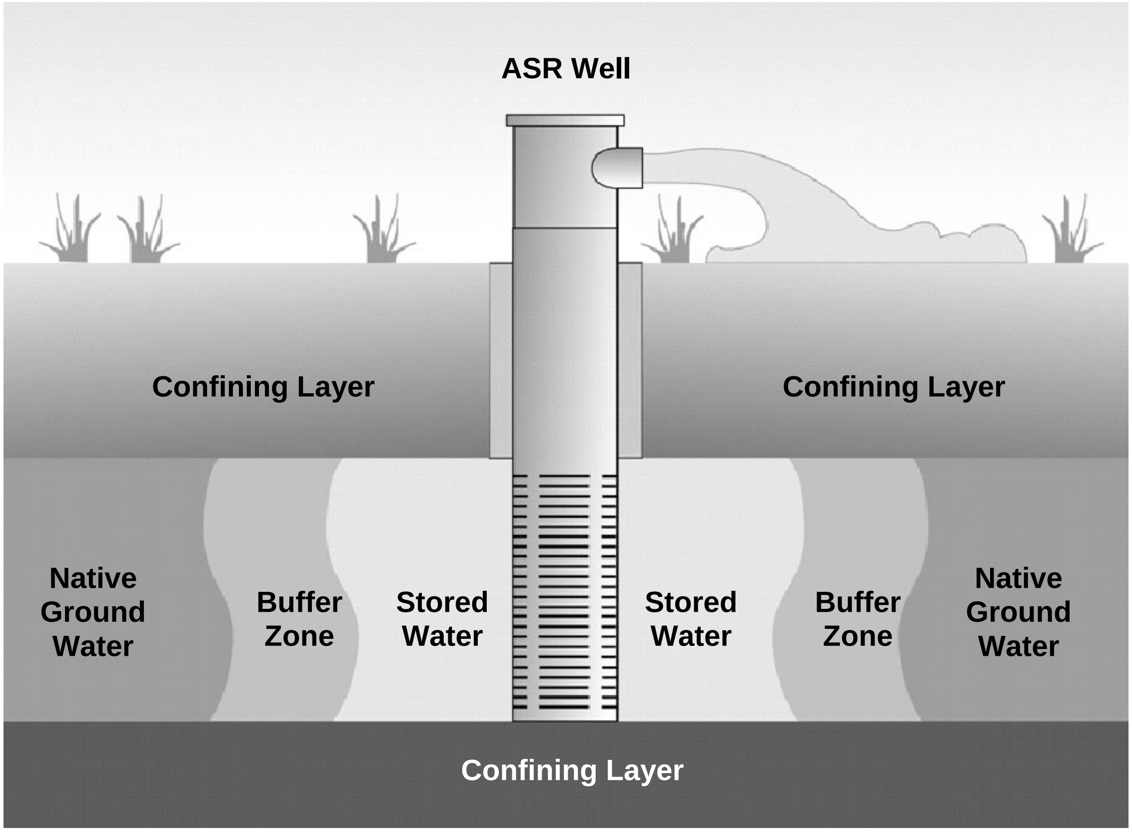


Figure 3. ASR Typical Cross-Section

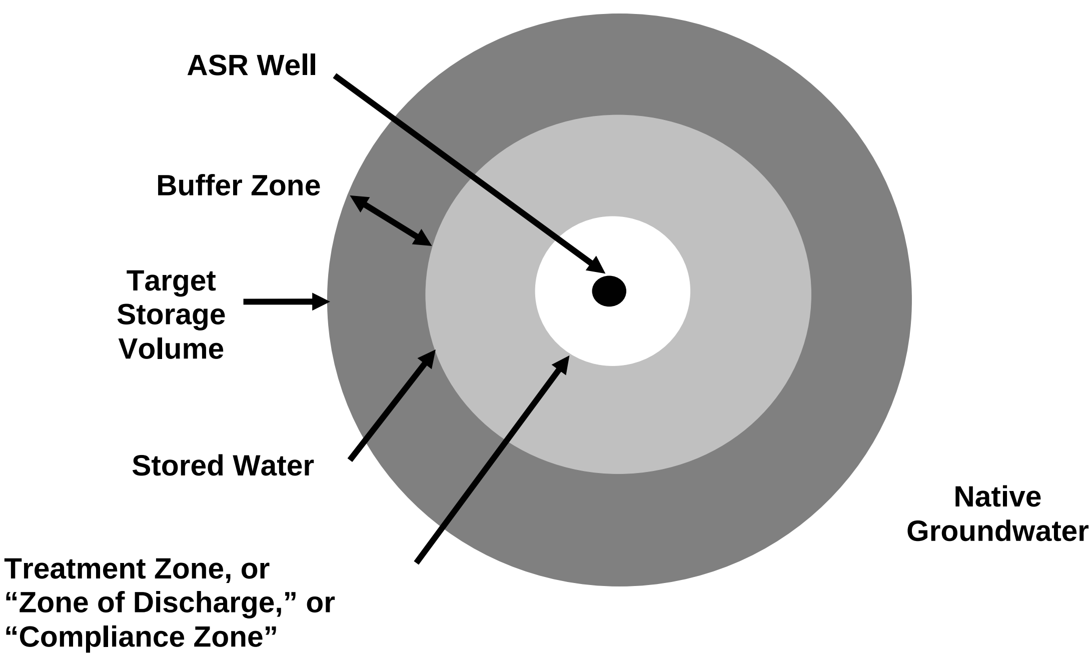
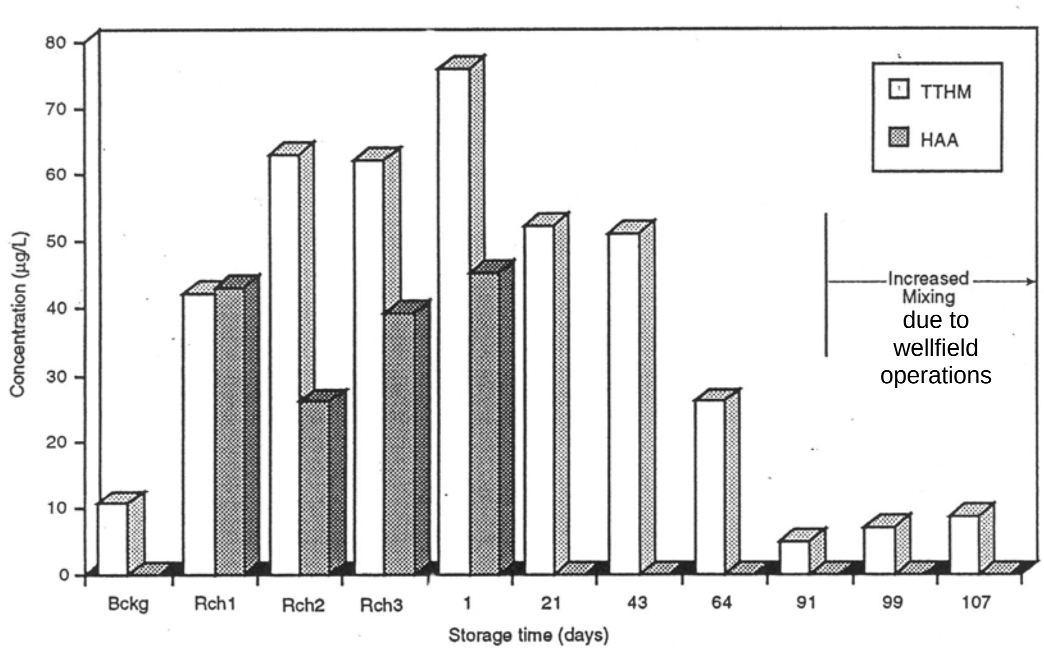


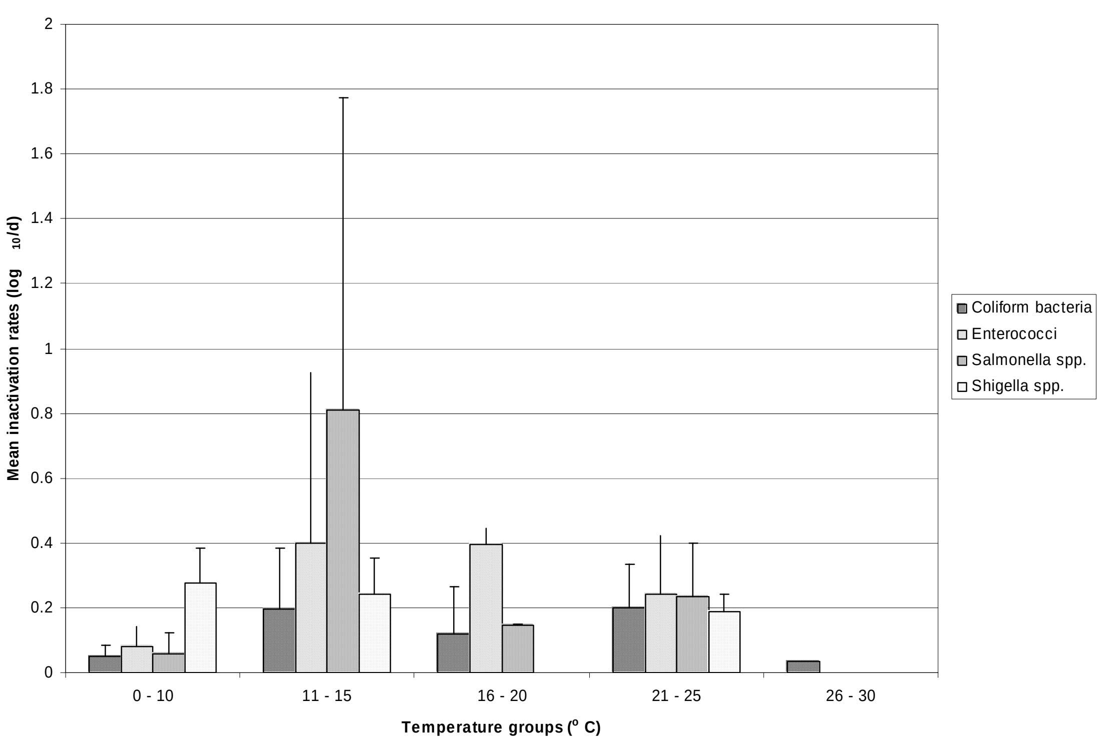
Figure 4. ASR Bubble – Top View



Bckg	background
Rch	recharge

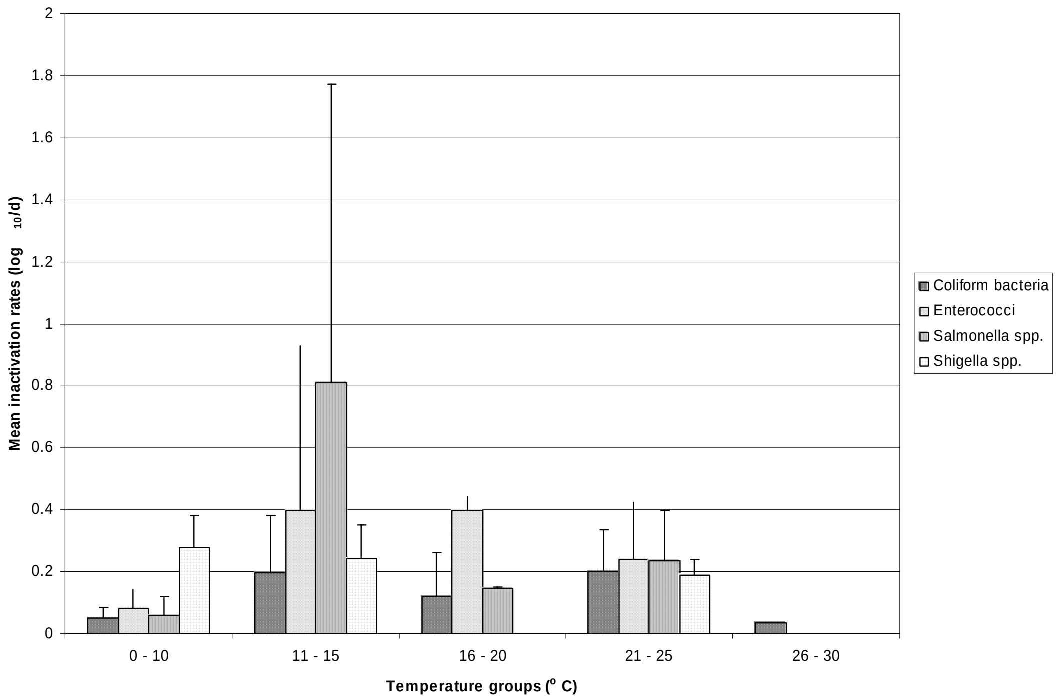
Figure 5. Disinfection By-products – Peace River

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

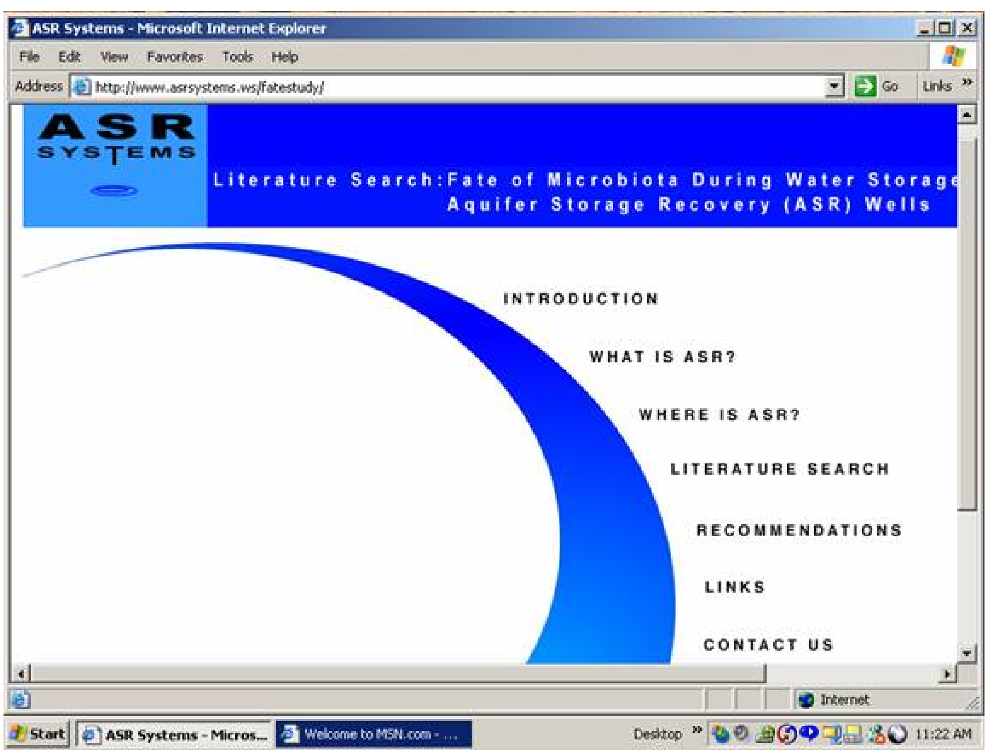


Figure 8. ASR Forum "Splash" Page