Frederick Bloetscher is an assistant professor at Florida Atlantic University (www.fau.edu), Boca Raton, Fla. Albert Muniz is with Hazen and Sawyer (www.hazenandsawyer.com), Boca Raton.

Is ASR a Viable Strategy for Emergency Water Supplies?

Aquifer storage and recovery has often been viewed as a panacea to solve all water supply issues. But is it? To set realistic goals, utilities must understand how the process works. **BY FREDERICK BLOETSCHER AND ALBERT MUNIZ**

AQUIFER STORAGE and recovery (ASR) systems allow utilities to store excess water during times of plenty and recover it during times of drought. The strategy benefits from an ability to store water supplies underground, which minimizes evaporation. Beneath the surface, injected freshwater displaces native water in the aquifer and creates an underground storage reservoir or bubble (Figure 1) that varies in size based on the amount of water stored.

Water systems have evaluated ASR options for more than 30 years, and the ASR concept has been used or investigated at more than 100 sites nationwide, each with the goal of storing water for later use. Most ASR programs have used similar protocols to measure effectiveness—injection of significant quantities of water followed by withdrawal of that water almost immediately until a given water quality parameter (typically chlorides) is exceeded, at which time withdrawal is discontinued. If water is available for injection, the injection cycle begins again. This protocol provides the traditional ASR graph (Figure 2).

EVALUATION CRITERIA

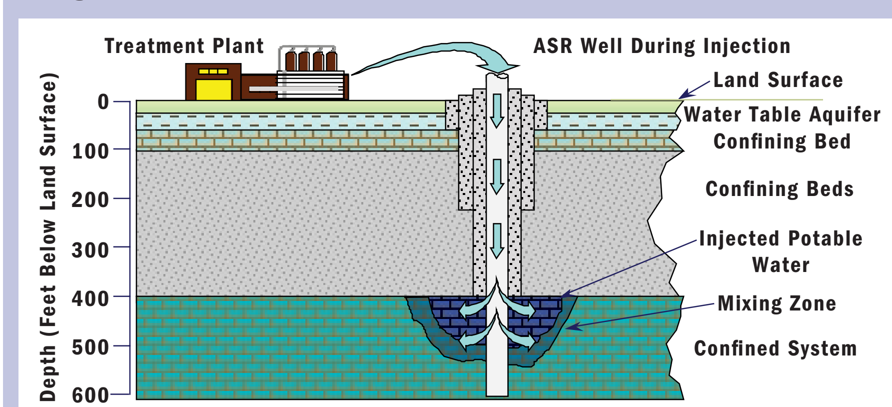
Specific issues must be evaluated when pursuing an ASR project, including

- Aquifer parameters
- Injection-zone confinement
- Bubble geometry
- Buoyancy in brackish systems
- Recovery percentage
- Water quality changes
- Cost savings and plant efficiency

Aquifer Parameters. The most important contributor to an ASR program's success is geology—you either have it or you don't. Also important are aquifer thickness, aquifer dip, and aquifer hydraulic conductivity. The theory indicates that, as aquifer thickness becomes greater, the injected water's buoyancy with respect to the native water will create the bubble faster, thereby limiting the percent of recovery. Therefore, the percent of recovery declines as aquifer thickness increases. Work in the Netherlands indicates the limit of an aquifer system's thickness is less than 50 ft, depending on the quantity injected and hydraulic conductivity. Injection horizons thicker than 100 ft make it difficult to displace the native water in a cylindrical function without injecting millions of gallons of water that aren't recoverable; the size and geometry of the transition zone simply make it so. No project has succeeded with such thick injection zones.

In theory, if all water injected into an injection horizon is removed, the bubble phenomenon will be mitigated, and the recovery system would be unencumbered

Figure 1. ASR Conceptual Diagram for Brackish Water Aquifers
Injected freshwater displaces native water in an aquifer and creates an underground storage reservoir.



A typical ASR wellhead in Destin, Fla.

PHOTOGRAPH: DESTIN WATER USERS

by differential density. However, even when thickness is limited, removing all water from a zone may not be successful.

An aquifer system's conductivity is important. This is the ability of water to move within the aquifer formation. Modeling indicates that hydraulic conductivity needs to be within a certain range to facilitate injection and recovery, and—as an aquifer system's hydraulic conductivity increases—recovery begins to decrease because of the ease with which native water returns over time, displacing the injectate and accelerating bubble formation. Transmissivity (hydraulic conductivity divided by aquifer thickness) of 50,000–200,000 gpd/ft is appropriate when significant recovery is desired.

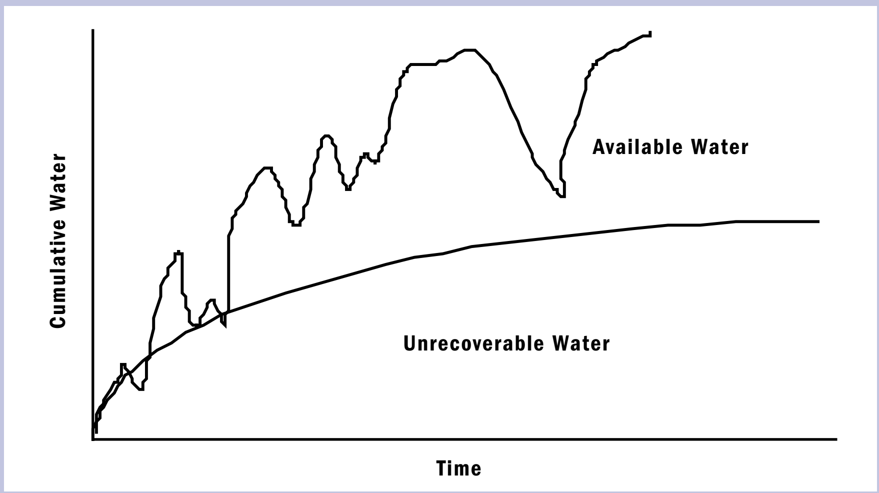
Higher conductivity may mean flow paths that will not create a cylindrical bubble. Low-conductivity aquifers will not accept water easily, leading to a pressure buildup in the system. As a result, pressure increases as the injected volume increases. In a hydraulically conductive aquifer system, the pressure rise may be minimal; but in a tighter formation, the pressure increase may be significant and could grow exponentially. The problem is what happens to the formation when pressure increases as the volume of water is increased and then is suddenly withdrawn. Highly favorable injection formations may suffer significant hydraulic fracturing and could lead to long-term collapse. It's helpful to develop curves that indicate the quantity of water to be injected in a given well at a given conductivity value.

Hydraulic conductivity is at play during injection and recovery cycles. Personnel at Grand Strand Water and Sewer Authority, Myrtle Beach, S.C., pump in 1 mgd per well and withdraw 2 mgd in a denuded, freshwater aquifer. However, in Fort Lauderdale, Fla., pumping 1 mgd in and withdrawing 0.5 mgd provided useful yields when higher pumping didn't because the higher withdrawals tended to pull in more saltwater from the bottom part of the well.

An aquifer system's incline must be considered, especially if the system's conductivity is high or thickness is great. Either of these circumstances will accelerate bubble movement along the top of the formation out of the range of the ASR well, thereby quickly reducing recovery from the same well. The only time when the angle dip/slope/incline is significantly beneficial is when a second, downstream

Figure 2. Comparison of Available Water and Injected Water

When source water is available, it's injected into the aquifer. The water retrieved is the same water that was injected; there's no evaporation.



well is used for recovery. Then, one must develop the appropriate model and calibration to measure the amount of time between injection and recovery.

Other factors affecting water recovery include the quantity of injection fluid, secondary porosity (connection between pores), the aquifer formation's diffusive characteristics, and native water density. In looking at large injection projects, it's difficult to describe the effects of the quantity of injected water compared with the amount of recovery, given differences in aquifer formations.

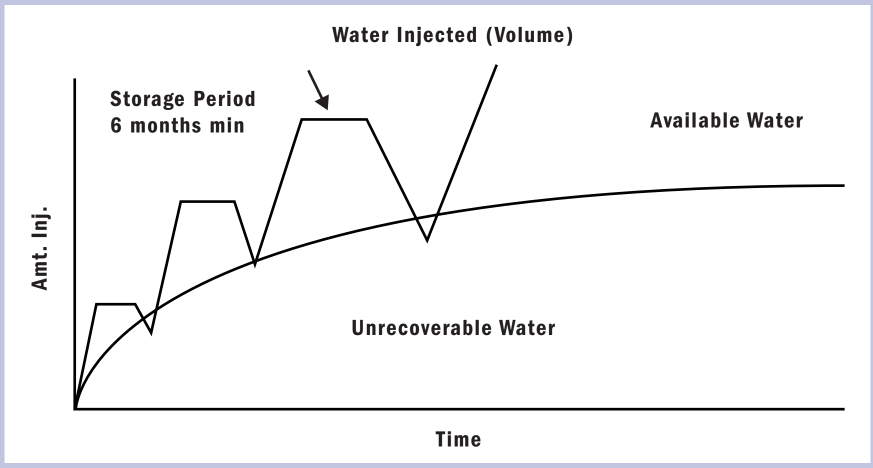
Injection-Zone Confinement. Buoyant water may rise in the formation. Significant confinement will keep water in the injection zone by preventing vertical migration. Wells in Collier County, Fla., and Boynton Beach, Fla., have clay above them. Wells in Broward County, Fla., and Fort Lauderdale, Fla., appear to be cased below the formation that Boynton Beach used, so water may be migrating upward and away from the injection zone in both cases. So even wells close together may have significantly different recovery percentages. The Boynton Beach well is deemed successful, but the others aren't.

Bubble Geometry. The ideal geometry of a freshwater bubble is a cylinder or half sphere inside a larger cylinder or half sphere. The concept is that the bubble will move consistently through the aquifer; reality is somewhat different. Isotrophic aquifers that lend themselves to consistent movement are rare. Aquifers that contain fissures or cracks through which water moves are more common. The result is that water moves more quickly through cracks, and the bubble is more splintered.

There's also a tendency for aquifers to be more transmissive at the top of the formation than at the bottom, so that water may move into the top of the formation instead of throughout the injection zone. Partially penetrating wells and mixing or movement in the formation may complicate the situation further. As a result, the ideal geometry is the least common.

Figure 3. Amount of Water Injected and Withdrawn Over Time

The amount of water being stored over time increases.



Buoyancy in Brackish Systems. When the difference in water quality of the native and injected water is significant, buoyancy forces will cause the bubble to rise toward the top of the formation. The higher the salinity, the faster the vertical migration will occur. Likewise, if hydraulic conductivity is high, migration worsens.

Accordingly, at some point withdrawals may contain high quantities of native water. Therefore, withdrawals may occur less than 50 percent of injection under ideal conditions. During initial development, a transition zone from injected to native water must be created. This water can't be recovered. In addition, demand may not dictate recovery at will.

Recovery Percentage. Figure 3 compares the amount of water injected and withdrawn over time and shows a general increase in the amount of water being stored. This leads to recovery, perhaps the most difficult term to define in the use of an ASR system. Recovery is the amount of water that can be gained from an ASR well without contravening water quality limitations. In ASR projects where freshwater is being injected to a fresh aquifer, the buoyancy doesn't occur and the chemistry differences dominate. Recovery can exceed 100 percent.

Figure 3 represents a brackish water system. The curved line represents the volume of water that isn't recoverable without exceeding the chloride parameter. This figure demonstrates that 100 percent recovery of the injected stored water at any point in time isn't possible because, as the freshwater bubble expands, the transition zone volume expands. What's not readily discernible with this type of graphical information is the actual quantity of water in storage available for withdrawal compared with the quantity of stored water that isn't recoverable without exceeding water quality parameter guidelines. Therefore, the graph should be revised to indicate the increasing trend of storage, as well as an increasing trend of nonrecoverable water, because recoverable stored water is only a fraction of the total water stored.

Unfortunately, the literature typically shows the amount of water injected into an ASR system, but the representation doesn't correctly depict the factual situation for brackish systems. This creates the impression of there being more water to withdraw in an ASR system than is truly available. This depiction is one of the problems in assessing ASR systems perceived to be successful. The line between recoverable and

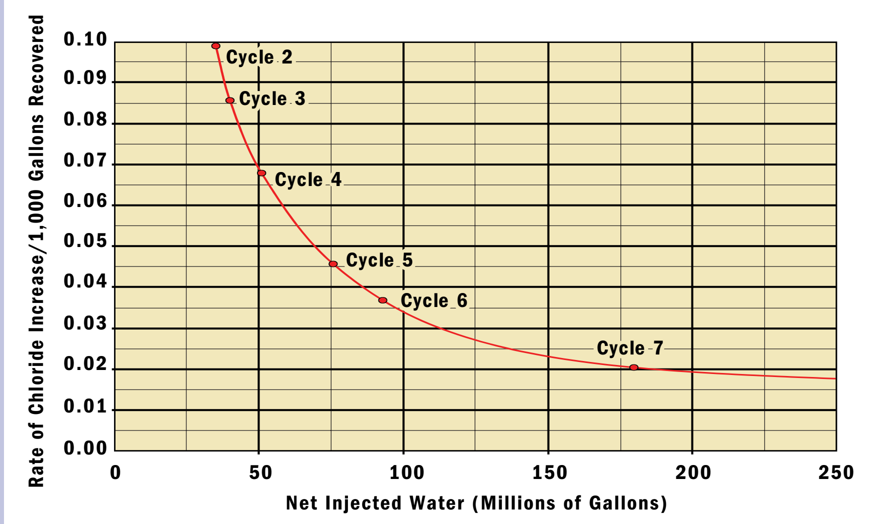
ASR is beneficial for long- and short-term storage, for later recovery and use where conditions permit, and for improving water treatment plant efficiency.

unrecoverable water hasn't been defined, and any modeling performed using the traditional groundwater modeling efforts may not correctly depict the dynamics of injection into native waters. Consequently, the only available information is the quantity and quality of water injected and/or withdrawn over a specified duration. Also, to further confuse the issue, there may be a point in ASR systems that have received substantial amounts of injected water where the quantity of water currently being injected is fully recoverable. In this scenario the transition zone between the native and injected water would stabilize (the asymptopic line in Figure 3).

Given a series of seven injection cycles, in varying amounts and holding them in the ground for up to a year, Figure 4 was developed for the Collier County ASR well. The figure indicates that 300–500 mil gal would be contained in the mixing zone volume of water within the 1-mgd Collier County well. This was in an injection horizon where the transmissivity was 50,000 gpd/ft and the thickness of the zone was about 40 ft. Therefore, the appropriate literature recommendations for ASR optimization were pursued. After various cycles, it was determined that the bubble effect began to occur in one to three months, and the water began to migrate along the top of the formation, being replaced on the bottom of the formation with native water. Recovery then decreased as a function of time. It was proposed that an in-line valve be placed within the borehole of the formation to prevent withdrawal of native water from the bottom of the injection formation, thereby increasing recovery at the top.

Figure 4. Collier County ASR Project

Recovery efficiency improves for each succeeding cycle.



Water Quality Changes. Among the more important issues currently being evaluated are changes in water quality. The Willows Water District ASR pilot in Colorado evaluated the fate of disinfection by-products over time. The finding was that most of these compounds disappeared in 90 days, which is helpful to the water system.

Less helpful are oxidation–reduction (redox) reactions, which potentially cause leaching of metals from the formation. The Lake Okeechobee pilot project was drilled into the Floridan aquifer and uses surface water for injectate. However, the pH and saturation of the surface water are different from the native water's. Of importance is that the formation also includes pyrite crystals, a potential indicator of arsenic. In actuality, the recovered water does leach significant amounts of arsenic from the formation. The leaching may be a temporary situation but adds another dimension to evaluating and testing the ASR system.

Cost Savings and Plant Efficiency. Water treatment plants will often evaluate cost as a part of an ASR option. Plants that are underutilized for major parts of the year, such as in resort or coastal communities, may benefit from improved use throughout the year. Stored water may delay the need to expand plants. The cost of an ASR is less than $1/mgd and operations costs less than $1/1,000 gal. A comparison of these costs with treatment plant expansion costs clearly demonstrates that ASR is beneficial for long- and short-term storage, for later recovery and use where conditions permit, and for improving water treatment plant efficiency.

ASR GOALS

The first issue is to understand a utility's goals for storing water. Is ASR to be used for emergencies, short-term storage, or seasonal use? Future ASR projects should focus on understanding the geology and associated aquifer parameters. Careful attention must be paid to hydraulic conductivity, dispersion, dispersive effects of water flow, absorption and desorption, and change in density of water stored or injected after the bubble has been formed. Understanding the geology and extensive data collection will permit the utility to verify theoretical expectations with groundwater models or provide sufficient data to modify them. A revised testing protocol should be used in future projects to evaluate these factors. A utility should understand that determining whether an ASR project is successful may take 3–5 years of field testing, given the need for storage periods to measure what the bubble does over time. Trying to expedite the process decreases the potential for data gathering and sets unreal expectations.