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Aquifer Storage and Recovery (ASR)
A New Water Management Tool

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Introduction

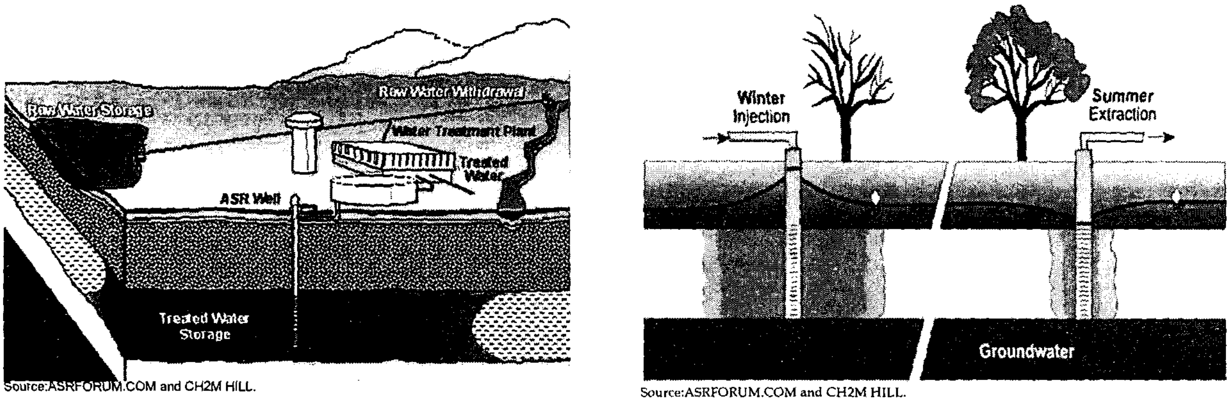
Many parts of the United States and the world are experiencing substantial population growth and drought conditions where there is insufficient water available for drinking water, agriculture, and industry. In dry areas, such as the western portion of the United States, there is a growing conflict between cities and farmers who need the water. In addition, we are seeing that many fish species such as salmon and steelhead are becoming endangered because there is an insufficient amount of high quality water remaining in the streams, particularly in the hotter summer months of the year. As a result, there are an increasing number of regulations designed to keep more water in the streams for fish, which reduces the amount of water available for drinking water supply and agriculture. In the United States and many other places in the world, it is increasingly difficult to build new dams and surface reservoirs to store water because of the environmental impacts and extreme cost of these structures. As a result, we are seeing a great deal of interest in storing water underground where it can be later withdrawn to meet peak season water demands. Underground storage of water offers many benefits over surface reservoirs including reduced environmental impacts, no evaporation losses, increased security, and lower cost.

The two most common methods for storing water underground are through surface infiltration ponds or through injection wells. Infiltration ponds are relatively low cost but require suitable land area and permeable surface characteristics. Storing water underground via injection wells allows storage of large quantities of water in deep aquifers where there is insufficient room for infiltration ponds or surface soils are not permeable. The focus of this paper is on the use of dual-purpose injection/recovery wells, or ASR wells, to store water for later use. Topics that will be covered include:

- What is ASR and How Does it Work
- Applications in the US and Internationally
- ASR Feasibility Criteria
- ASR Project Steps
- ASR Well Design Considerations
- ASR Costs
- Commonly Asked Questions

What Is ASR?

Many water supply facilities are faced with dry season demands that either approach, or exceed, dry season supplies, while wet season supplies are in excess of the wet season demands. The concept of ASR involves storing high quality water underground via wells during periods of low demand or excess supply. Water can then be recovered to meet annual peak season demands or "banked" for withdrawal at a later date (Figure 1). A primary benefit to the water utility is that this defers costly supply or treatment system expansions constructed solely to meet peak demands. ASR also provides the ability for treatment plants to supply additional water over extended peak-demand periods.



Source:ASRFORUM.COM and CH2M HILL.

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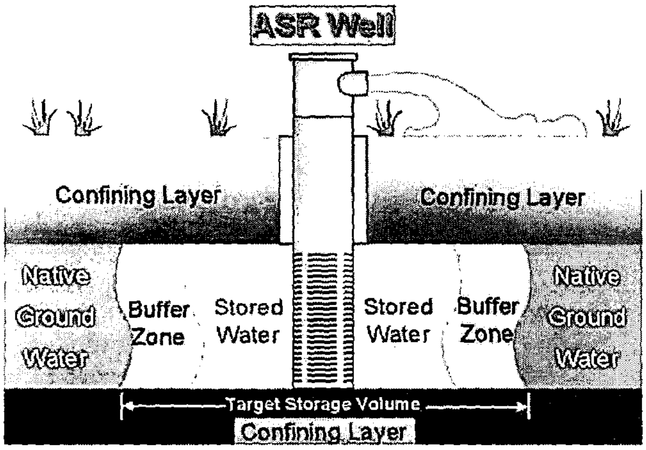
Figure 1 - Schematic of ASR injection and recovery.

ASR offers substantial benefits over traditional methods of water storage, such as surface reservoirs because there are no evaporation losses and because huge volumes of water can be stored underground without potential environmental impacts. Injection of treated surface water may also improve the quality of water produced by the well because the high quality treated water displaces the native groundwater away from the well. Over time, a storage zone is developed that consists of 100 percent treated surface water. The outer portion of the storage zone is a buffer zone that consists of a mixture of native groundwater and stored surface water. The injected water stays relatively close to the well because groundwater moves very slowly (Figure 2).



Source:ASRFORUM.COM and CH2M HILL.

Figure 2 - Generalized zones inside injection aquifer.

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How does ASR Work?

As water is injected into a well, the injected water displaces native groundwater and creates a mound or zone of increased water level around the well. Storage occurs as a result of filling previously unsaturated pore spaces in an unconfined aquifer or as a result of increasing the pressure within a confined aquifer. Most ASR systems around the world are in aquifers that are confined or semi-confined. A confined aquifer is bounded above and below by low permeability layers that limit water movement in the up or down direction. Confined aquifers are by definition under pressure whereby the water level is above the confining unit and the permeable aquifer is always fully saturated (i.e., full of water). Consequently, a well located in a confined aquifer produces water by reducing the pressure within the aquifer. Theoretically, injection of water into a confined aquifer will increase the pressure within the aquifer and cause a slight expansion of the aquifer matrix to accommodate the injected water. The pressure is highest at the injection well and gradually decreases away from the well. The water level (pressure) change caused by pumping or injection in a confined aquifer typically extends over a relatively large area (greater than 1 km). It is possible to inject water into a confined aquifer such that the pressure builds up to a level above ground surface. As long as nearby wells penetrating this aquifer are sealed and capped and there are no springs, no injected water will reach ground surface or a surface stream.

In reality, most confined aquifers are actually semi-confined because low permeability layers are rarely continuous and they are often interfingered with permeable layers or fractures throughout the aquifer. Consequently, injection causes an increase in pressure within portions of the aquifer that promotes some leakage across low permeability layers into higher permeability layers. In some cases, pore spaces in the upper portion of the aquifer that were previously unsaturated begin to fill as the water level rises during injection. The degree to which this will occur is a function of the vertical permeability of the aquifer.

Basalt and fractured rock aquifers often behave like semi-confined aquifers. Water is stored within and pumped from fracture zones or permeable interflow zones sandwiched between individual basalt flows. The interflow zones are typically rubbly, fractured, and contain sand and gravel deposits. Water is also stored within fractures, particularly near where faults have broken up the rock. Faults can sometimes act as barriers to flow and form compartments that limit the volume of water that can be stored. In these cases, the pressure in the storage zone increases faster than expected, which can cause water levels to rise above ground surface and cause surface discharge to springs.

ASR Applications

ASR is being used in a number of ways and offers many benefits over traditional water storage alternatives including:

- Seasonal, long-term, or emergency storage of water for public water supply
- Mitigation for stream flow impacts (temperature, discharge)
- Reduced environmental effects of stream flow diversions

- Improved water quality from a primary groundwater source
- Restoration of groundwater levels
- Stop land subsidence and salt water intrusion
- Defer and/or downsize expansion of water facilities at considerable cost savings
- Maintain distribution system flow/pressure

There are approximately 75 ASR projects under development in the United States and 35 in full operation. Worldwide, there are approximately 20 ASR projects that I am aware in countries including Australia, England, Canada, Kuwait, Israel, Spain and India (Figure 3).

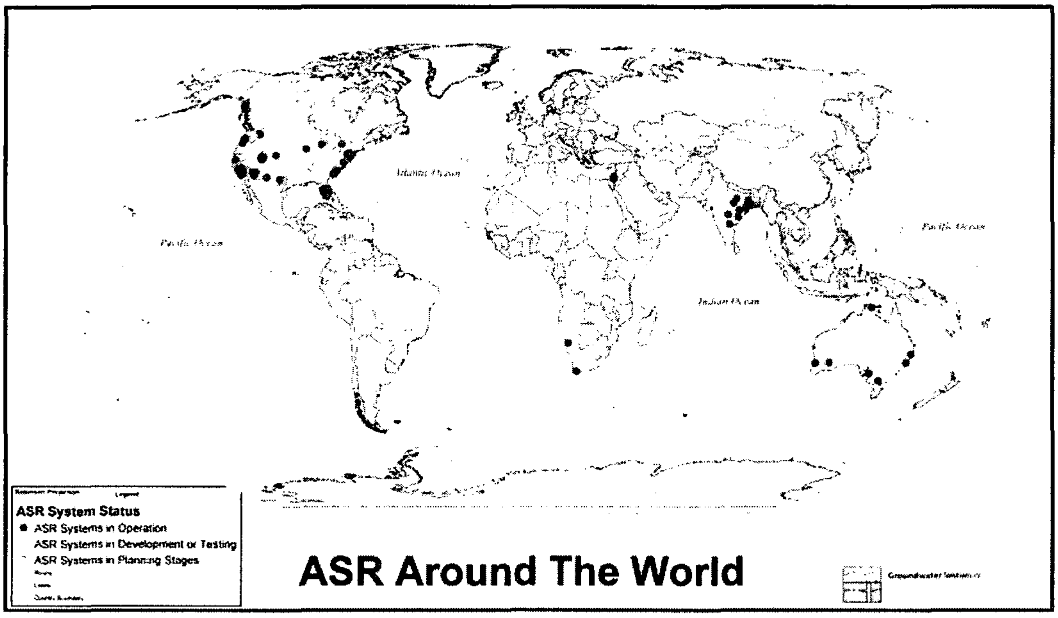


Figure 3 - Location of ASR systems around the world.

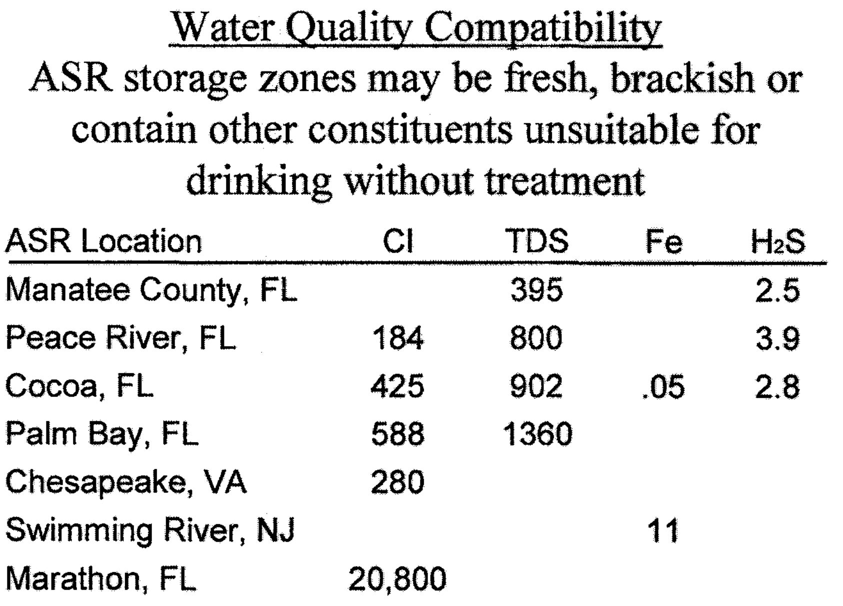
Typical characteristics of the ASR projects include the following:

- 60% use surface water; 40% use groundwater supplied by wells in other aquifers or different locations in the same aquifer.
- Typical ASR well depths are 30 to 300 m.
- Individual well yields are 2 to 20 Ml/d
- Storage zone radius is typically under 300 m, although pressure effects extend further from the well

ASR has been applied in a number of geologic environments including:

- Confined and unconfined aquifers
- Sand, gravel and alluvial deposits
- Clayey-sand
- Limestone and dolomite
- Sandstone
- Basalt, Granite and Metamorphic Rocks

Water has been stored in potable drinking water aquifers, poor quality aquifers affected by high levels of H_2S, iron, and manganese, and brackish aquifers containing high total dissolved solids (Figure 4).



Water Quality Compatibility

ASR storage zones may be fresh, brackish or contain other constituents unsuitable for drinking without treatment

ASR Location	Cl	TDS	Fe	H_2S
Manatee County, FL		395		2.5
Peace River, FL	184	800		3.9
Cocoa, FL	425	902	.05	2.8
Palm Bay, FL	588	1360		
Chesapeake, VA	280			
Swimming River, NJ			11	
Marathon, FL	20,800			

Concentration units = mg/L

Figure 4 - ASR water quality compatibility

ASR projects utilizing highly treated wastewater are being developed in portions of the United States as a barrier to salt water intrusion and in aquifers that have naturally poor quality where there is a need for a non-potable water source (e.g., wetlands restoration, irrigation).

ASR Feasibility Criteria

General criteria for determining the feasibility of ASR include the following:

- There must be a suitable target aquifer for storing the water.
  - Confined or semi-confined aquifer with transmissivity > 125 m^2/day (10,000 gpd/ft); this will enable production rates of at least 1,900 l/m (2.7 Ml/day or 500 gpm)
  - Available drawup for injection so that the injection head in the ASR well does not exceed ground surface (unless the well head is designed for this)
  - Aquifer hydraulics are favorable - boundaries (e.g., faults) do not compartmentalize the aquifer and limit the size of the storage zone
- There is an adequate and reliable source of high quality water available for recharge in the winter.
- The source (injection) water does not contain turbidity exceeding 1 NTU.
- The native groundwater and source water quality is compatible.

- Well clogging potential is minimized and can be managed.
- Loss of stored water via other wells, springs, or streams, is minimal.
- There is a place to discharge large volumes of turbid water (water containing sediment) without impacting streams or residences.

ASR Project Steps

ASR projects are typically developed in three phases. Phase 1 is a feasibility study to determine if there are any fatal flaws, estimate the amount of water that can be stored and recovered, and estimate project costs. This is typically a paper study using available information. Phase 2 is a pilot project where either an existing well is retrofitted or a new well is drilled and tested. This phase is designed to verify the results from Phase 1 under a field application, assess well performance and aquifer response, and identify full scale operational features such as target injection and recovery rates and back flushing frequency (more on this later). Phase 3 is an expansion phase where new sites are identified and developed.

The Phase 1 feasibility study typically consists of the following elements:

- Identify a suitable aquifer and target storage zone utilizing published reports and well logs. Construct geologic cross sections to understand the hydrogeology.
- Conduct aquifer tests at an existing well to measure aquifer transmissivity and storage coefficient.
- Assess the availability of the source water and its quality.
- Estimate how much water can be stored and rates of injection and recovery.
- Evaluate potential for loss of stored water to other wells, springs, or streams.
- Assess availability of suitable infrastructure to convey the water to and from the ASR site.
- Evaluate water quality compatibility between the native groundwater and recharge source water to determine if there will likely be precipitation reactions that could clog the well or dissolution reactions that could affect taste or potability.
- Evaluate potential environmental impacts.
- Estimate project costs relative to other alternatives.

The Phase 2 pilot project typically consists of the following elements:

- Obtain permits from the appropriate regulatory agencies to withdraw the source water and to inject water.
- Construct an ASR well or retrofit an existing well. Consider installing observation wells if no existing wells are available.
- Obtain water level and water quality samples from the aquifer prior to testing.
- Conduct testing of the ASR well. A typical testing program consist of the following:
    - Step rate pumping test of the well to establish pre-ASR well efficiency.
    - One-day shakedown test consisting of one hour of injection and pumping to make sure the valves and piping work properly.
    - Injection cycle lasting one week to three months.
    - Storage period lasting from one week to two months.
    - Recovery/pumping cycle lasting long enough to recover all of the stored water.

Ideally, the Phase 2 testing should be done at approximately the same scale and duration as what is planned for full-scale operation. The turbidity of the source water should be less than 1 NTU in order to avoid clogging the well. Because most water supplies used for ASR source water contain some amount of sediment, it is important that the injection rate be 50 to 75 percent of the pumping rate so that pumping can introduce enough velocity to dislodge and remove the sediment from the well bore and aquifer. In addition to minimizing introduction of sediment in the recharge water, air should not be allowed to enter the well; otherwise, the air may become lodged within the aquifer pore spaces and reduce the aquifer permeability.

Data collection during the testing includes measurement of water levels in the injection well and observation wells, flow rate (injection and recovery), and water quality for the source water and native groundwater prior to injection, and recovered water quality at roughly 25%, 50%, 75%, 100%, and 125% of the stored water volume. The water quality data is collected to determine if there are chemical reactions occurring that would either clog the well (e.g., precipitation of calcite or iron hydroxides) or affect the taste and potability of the water. In some areas, water quality data are used to estimate how much of the injected water was actually recovered.

During the injection phase, the groundwater level and specific capacity of injection (injection rate divided by the drawup) should be monitored in the injection well to assess the rate of clogging (indicated by an increase in slope) and to determine when injection should be temporarily stopped so that the well can be pumped to remove the injected sediment.

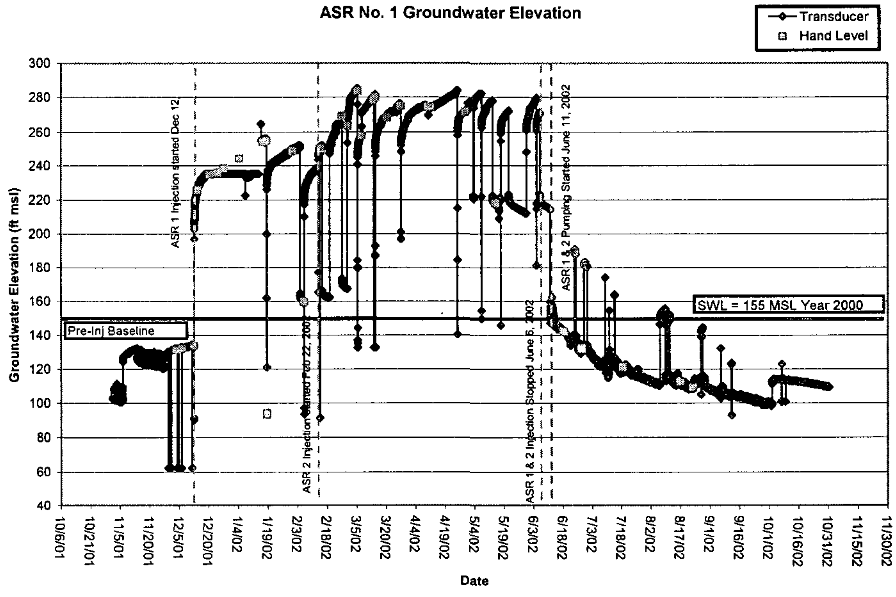


Figure 5 - Groundwater elevation at a typical ASR site during injection and recovery. Sharp drops in water elevation are back flushing events to increase well efficiency.

This is referred to as back flushing (Figure 5). Back flushing may be required once every one to four weeks. The duration of the back flushing is anywhere from 15 minutes to 1 hour, depending upon how much sediment is being removed from the well.

ASR Well Design Considerations

ASR wells are similar in design to standard municipal production wells with some important differences (Figure 6):

- Larger diameter than typical wells (>40-cm)
- Casing often stainless or epoxy lined, particularly within the wet/dry zone where corrosion is greatest.
- Well screens are stainless steel- double strength
- Larger filter pack size and slot openings to promote more efficiency during injection
- Liners often used in rock holes to protect pumps
- Substantial grout seal so that injection pressures do not cause short circuiting

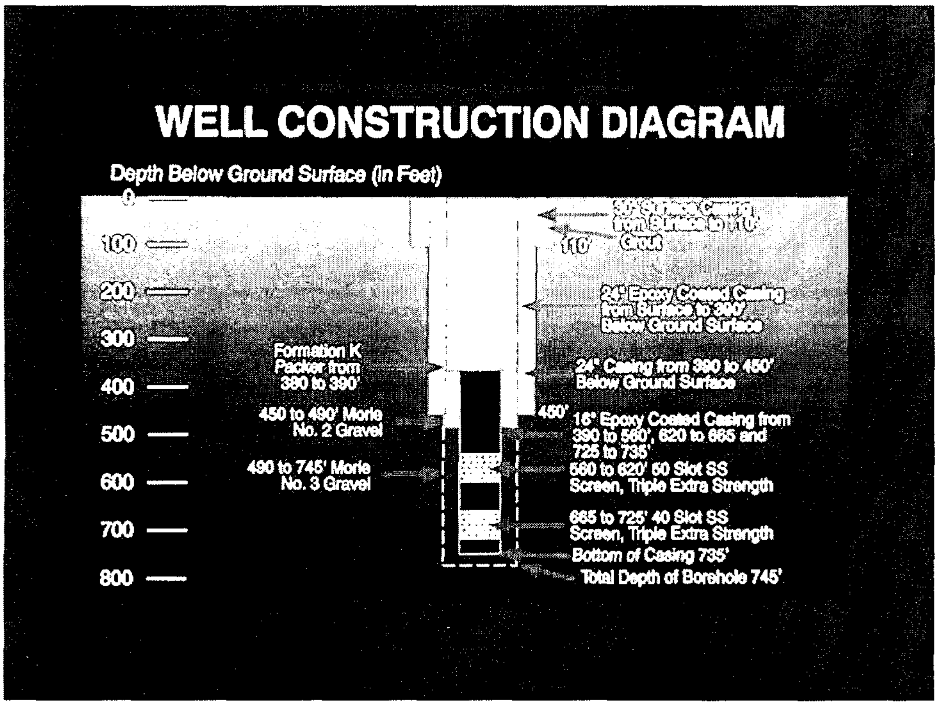


Figure 6 - ASR well construction diagram.

ASR Costs

ASR typically meets peak demands at less than half the cost of other water supply alternatives and a fraction of the cost of surface reservoirs. It is common for a single ASR well to store more than 380 Ml (100 million gallons) of water during a single injection season, which far exceeds the volume that can be stored by a water storage tank. A field of ASR wells can easily store billions of liters of high quality water. ASR capital costs range from US$250K to US$500K to provide 3.8 Ml/day (1 million gallons per day) of peaking or emergency capacity. ASR operating costs average about US$15K per year per 3.8 Ml/day recovery capacity, within a typical range of +/- US$10K.

Commonly Asked Questions

Commonly asked questions about ASR include the following:

1) *Will the stored water flow away so that it cannot be recovered?*

In general, groundwater moves very slowly - on the order of ten to 100 feet per year, depending on the permeability of the aquifer and the natural gradient (slope of the water table). In most cases, nearly 100 percent of the water that is stored in a given year is recoverable. Large pumping wells located near an ASR well can promote faster migration. Should this occur, less of the stored water and more native groundwater will be recovered. If the native groundwater quality is relatively poor, water quality benefits from ASR will be diminished. It is important to identify the location of larger production wells early in the project. In addition, the natural gradient and aquifer permeability can be measured so that a rate of stored water movement can be calculated.

2) *What aquifers are most suitable for ASR?*

ASR has been done successfully in a wide range of aquifers including basalt, sand and gravel, limestone, and glacial till. Aquifers most suitable for ASR are: 1) confined or semi-confined, 2) have limited interconnection with surface streams, 3) have high transmissivity (readily transmit water to wells), and 4) have enough available drawup to accommodate a rise in water level without loss of water to other aquifers, the ground surface, or surface streams. A hydrogeologic characterization study is often done to determine if these characteristics are present.

3) *Will the quality of water produced meet drinking water standards be aesthetically acceptable, and will the water require re-treatment?*

After several cycles of recharge and recovery, the target storage zone becomes developed so that the recovered water is very similar in quality to the treated surface water used for recharge. Some chemical reactions will occur between the injected water, native groundwater, and aquifer matrix. These reactions can be predicted using geochemical models. No re-treatment has been necessary other than re-disinfection. Thus far, disinfection byproducts or formation potential have not been problems.

4) *Will ASR cause my well to clog and reduce capacity?*

Some well clogging should be expected even when using very high quality recharge water. Small quantities of sediment from the distribution system accumulate in ASR wells and must be removed with periodic back flushing (pumping to waste). The rate of clogging is tracked closely during injection testing so that a redevelopment schedule can be derived. In our opinion, the design injection rate should be less than 75 percent of the pumping rate so that pumping can effectively remove the sediment that is clogging pore spaces and reducing well efficiency. Clogging caused by mineral precipitation reactions is possible. Geochemical modeling during the feasibility phase and monitoring of geochemical parameters during testing will help us determine if this is a concern.

5) *What is the fate of disinfection byproducts resulting from injection of source water containing chlorine?*

Disinfection byproducts (DBPs) are formed when disinfectants used in water treatment (e.g., chlorine) react with natural organic matter (e.g., decaying vegetation) present in the source water. Likewise, introduction of source water containing disinfectants into the aquifer will react with naturally occurring organic carbon to produce DBPs. DBPs include trihalomethanes (THMs), and haloacetic acids (HAAs). A number of epidemiological studies have suggested that there is an association between an increased incidence of some types of cancer and exposure to chlorinated water containing DBPs (U.S. EPA 2000). In December 1998, the United States Environmental Protection Agency (U.S. EPA) published the Disinfectants/Disinfection By-products Rule that requires water systems to use treatment methods to reduce the formation of disinfection byproducts such as THMs and HAAs. In the US, the maximum contaminant level (MCL) for THMs and HAAs is 80 mg/L and 60 mg/L, respectively.

Due to the complex chemistry involved in the formation of DBPs, it is generally difficult to make any definitive conclusions regarding the effects the ASR program will have on DBP formation and distribution. Some studies have shown, however, that implementation of an ASR program will tend to reduce concentrations of DBPs relative to concentrations that are found in the waters used for ASR recharge (Seattle Water Department 1994). While still the subject of ongoing research, there are several potential mechanisms that contribute to the observed decreases in DBP concentrations subsequent to ASR storage, including the following (Pyne 1996):

- Mixing and dilution between the recharge and surrounding groundwater.
- Biological mechanisms whereby some classes of DBPs will be removed more favorably in aerobic conditions while others tend to be removed only after the onset of anoxic conditions in the aquifer.
- A reduction in DBP precursors during ASR storage as evidenced by declining total organic carbon (TOC) concentrations.

Injected chlorine has been observed to be consumed in a matter of a few days of storage in the aquifer and HAAs degrade in a matter of several weeks. A recent study conducted by the United States Geologic Survey (USGS) indicates that THMs are not degraded under oxidizing conditions in shallow aquifers but instead accumulate in the aquifer matrix.