The Emerging Role of Aquifers for Water Storage, Treatment and Conveyance

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Abstract

Aquifers are currently used in the United States primarily for water supply purposes. In recent years, aquifer storage recovery (ASR) technology has been developed and implemented widely, utilizing aquifers for cost-effective water storage. Experience with these ASR systems has demonstrated that aquifers are also capable of providing treatment of the stored water for many constituents of great interest to U.S. water managers and utilities. Conveyance of water from points of recharge to points where the water is needed for recovery, is also beginning to be practiced in some areas. Accordingly, a new paradigm is needed that recognizes the ability of aquifers for water storage, treatment and conveyance. Changes in our regulatory framework are needed to accommodate this new paradigm.

Introduction

Aquifers are increasingly used globally for water supply and, to a lesser extent, wastewater disposal. They are also used for thermal energy supply and storage in some areas, and to a minor extent for water conveyance. With rapidly increasing use has come the corresponding problems of water level declines, salt water intrusion, contamination and subsidence, all of which tend to reduce aquifer capacity at a time when demand for this relatively low cost water source is increasing. In particular, many coastal areas around the world are experiencing serious water management challenges as a result of

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overexploitation of aquifers. As a result, attention is turning to artificial recharge of these aquifers to protect them, restore their capacity, and control subsidence.

Artificial recharge in some areas can be achieved through surface methods such as shallow basins and stream channel improvements. Where technically feasible and operationally viable, this is usually the least cost approach for getting water into the ground since pretreatment requirements are relatively minor and the cost of surface recharge facilities is often relatively small. However such areas where surface recharge is viable are the exception. Typical constraints include high land costs, inappropriate subsurface hydrogeology or geochemistry, long pipelines to areas with suitable hydrogeologic characteristics, inadequate control of overlying land use to protect the stored water from contamination, site hydraulic constraints due to mounding of the water table, and competing needs for operation of recharge facilities to meet recreational, aesthetic and other requirements. Consequently most new artificial recharge operations are relying upon wells to introduce the recharge water into the target aquifers. Since injection wells have historically tended to plug, most new recharge wells are utilizing aquifer storage recovery (ASR) technology. Developed during the last 25 years within the United States, ASR application has been expanding rapidly, reflecting its proven performance, low cost relative to other water management options, and environmental benefits. Currently at least 38 ASR systems are operational and fully permitted within the United States and at least 50 more ASR systems are in various stages of development.

ASR is defined as the storage of water in a suitable aquifer through a well during times when water is available or when water quality is most acceptable, and recovery from the same well during times when the water is needed, or at times when water quality from other sources is poor.

ASR systems are operating in at least 14 states and range in recovery capacity from about 4 megaliters per day (Ml/D) (one million gallons per day (1 MGD)) to over 400 Ml/D (100 MGD). Storage zones range in depth from as shallow as 60 m to as deep as 900 m. Aquifer lithologies include sand, clayey sand, sandstone, limestone, chalk, dolomite, basalt, and glacial drift. Native water quality in the storage zones includes fresh water, brackish water and one technically successful ASR site, not currently operational, in a seawater aquifer. Most ASR sites have one or more water quality constituents in the native groundwater that render the native water unsuitable for direct potable use except following treatment. Such constituents include iron, manganese, fluoride, chloride, total dissolved solids, nitrates, hydrogen sulfide, radium, gross alpha radioactivity, and other constituents. Based at least partly upon success in the United States, ASR technology is now being applied in England, Australia, Israel, Canada and Taiwan and is under development in Kuwait, Qatar and probably other countries.

In the United States, most ASR systems to date store treated drinking water. The cost to treat water to this higher standard is greater than that for surface recharge systems. The water is stored and recovered from the same well and is utilized to meet peak day, long-term or emergency water needs, usually without the requirement for retreatment of the recovered water, other than disinfection. Consequently the capital cost for ASR systems to place water into storage and recover it to meet drinking water needs is usually much less than the alternative costs for providing extra treatment and conveyance facilities capacity. Water is stored during times of the year when source water is available at rates exceeding system demands, using spare water treatment plant capacity to treat the water prior to recharge. It is then recovered to help meet peak, emergency and other demands. There are few, if any, adverse environmental effects since land use is minimal and water use occurs typically during wet weather periods when flows are greatest.

With the growing success of ASR, attention has focused on whether it is advantageous to also store water from other sources. In water short areas, this is increasingly with storage of reclaimed water during wet weather and other times when irrigation demands are reduced. At some locations, ASR wells are used for storage of water from an overlying or underlying aquifer during periods of low demand, with recovery of the water from both aquifers during periods of high demand. This may be due to water quality differences between the two aquifers, or due to regulatory constraints upon net withdrawals from one of the aquifers. At other locations, ASR wells are used for storage of water from one location in an aquifer where water is fresh, to another location in the same aquifer where water quality is unsuitable for potable purposes but there exists a need for recovery of fresh water. Finally, ASR wells are beginning to be utilized in the United States for storage of high quality, partially-treated surface water. This approach has immense potential value for areas where construction or expansion of surface reservoirs is deemed unacceptable as a water management tool. In such areas, ASR wells can reduce, and in some situations replace, the need for surface storage capacity. Usually an ideal situation is one in which ASR wells are integrated with operation of a surface reservoir that may be reduced in size and volume. The much larger storage volumes usually available underground are then combined with the much larger ability of a surface reservoir to capture and store peak flows for later transfer into ASR storage.

While many technical issues have been addressed and resolved during the past 25 years, some issues remain. Other issues and constraints are being identified as the ASR technology is applied to an ever-widening range of applications. Principal among the constraints is the notion in the United States that once the water passes the wellhead during recharge, no credit for further natural treatment in the aquifer is allowed by regulatory agencies. This highly conservative position, which necessitates treatment to meet drinking water standards prior to recharge, is the principal focus of this paper.

The Underground Injection Control Regulatory Framework in the United States

Some typical examples of the current dilemma are useful to illustrate the issue.

In Miami-Dade county, Florida, water from the shallow unconfined Biscayne aquifer is the only source of water supply. This water is treated to remove color, iron and bacteria, and is then sent to distribution. During times when demand is below peak levels, up to about 57 Ml/D (15 MGD) of water from this aquifer, prior to treatment, is pumped into adjacent ASR wells for storage in a brackish, limestone artesian aquifer at a depth of 260 m to 400 m (850 to 1300 feet). Total dissolved solids concentration of water in this deeper aquifer is about 4000 mg/l. During heavy rainfall periods, water from the Biscayne aquifer may contain coliform bacteria at concentrations up to as high as 6 mpn/100 ml, compared to drinking water standards that provide for concentrations as high as 4 mpn/100 ml. Extensive experience in Florida and elsewhere demonstrates that coliform bacteria die-off rapidly, particularly at temperatures and salinities occurring in the storage zone at this site. Nevertheless the ASR system has so far waited three years to seek regulatory agency approval to recharge water during the wet periods for which the system is designed. It is currently operational but can only recharge water at times when rainfall is less than 19 mm/day (0.75 inches/day). Recovered water is sent to the treatment plant prior to distribution.

In Oak Creek, Wisconsin, water from Lake Michigan is treated with conventional filtration treatment prior to distribution. This is excellent quality source water with very low concentrations of organics. After disinfection, trihalomethane concentrations average about 18 ug/l, well below the current standard of 100 ug/l and the planned future standard of 80 ug/l, subsequently expected to drop to 60 ug/l. Two separate existing state standards are being considered in Wisconsin, one of which is more strict than the federal standard. With this more strict approach, individual trihalomethane constituents would be regulated such that total trihalomethanes cannot exceed about 8 ug/l. ASR facilities have been constructed and tested, and have demonstrated that trihalomethane concentrations reduce with time, with the brominated species reduced or eliminated first and chloroform last. This has been documented at several other ASR sites (AWWA Research Foundation, 1996), showing elimination of disinfection byproducts in ASR wells in typical periods of a few weeks of storage, primarily due to subsurface bacterial reactions and also due to mixing. Geochemical reactions may augment the rate of DBP reduction at some sites. At issue in Wisconsin is the point at which the standards would apply, either at the wellhead during recharge, the wellhead during recovery, or a location at the edge of a management zone around the well within which subsurface treatment mechanisms are allowed to occur. A policy decision by the state has been under consideration for several years.

In Hillsborough and Manatee counties, southwest Florida, heavy groundwater production for agricultural and urban uses has caused salt water intrusion, lowered lake levels and a substantial long-term decline in the potentiometric surface of the Floridan aquifer, which provides groundwater in this area. Several ASR projects have been constructed and others are in various stages of development, with the objective of making more efficient use of seasonally available water supplies during the rainy season. Among the planned projects are two that would store reclaimed water at one site, and high quality, partially-treated surface water at the second site, both located near the edge of the saline water interface. In each case, interpretation of current regulations is that these facilities may have to be located where the aquifer is already intruded with salt water, in order to "protect" future potential users of this brackish water along the coast. Such a location would drive brackish water inland at each site, contaminating existing freshwater wells. Location further inland where the aquifer is relatively fresh, thereby pushing salt water back toward the coast, is severely hampered by current federal regulations designed to protect as "underground sources of drinking water" any aquifer containing water with a TDS concentration under 10,000 mg/l. At one of these two sites, the opportunity may exist to recharge substantial quantities of water during the wet season, allowing the aquifer to convey this water to other groundwater users in the region and thereby helping to restore aquifer water levels. However regulations do not currently allow subsurface conveyance from one permitted water user to another permitted water user in this inexpensive manner. Partly as a result there is little financial incentive for existing users to work together to arrange a regional solution to their future water needs.

Arsenic is presently regulated at 50 ug/l in drinking water supplies, however in the immediate future this standard is expected to drop to 10 ug/l, effective 2004. At an unnamed Florida location, initial ASR operations indicated that, although not present at significant concentrations in either the recharge water or the native groundwater, arsenic was present in the recovered water at elevated concentrations. After 17 years of Florida operational ASR experience without any arsenic-related issues, this was a considerable surprise. Subsequent intensive investigations showed this to be a transitional phenomenon, occurring at the beginning of cycle testing or initial operations but disappearing after a few cycles of operation. The mechanism for natural attenuation is believed to be due to initial solution of arsenic originating in pyrite and/or other minerals in the aquifer under changing pH and Eh conditions in the aquifer close to the well, followed by adsorption of the arsenic on ferric hydroxide floc forming in the aquifer matrix, at pH levels that may need to be controlled in the recharge water to prevent desorption from the floc. Sampling from most of the long-term operational ASR sites in Florida did not indicate any detection of arsenic at significant concentrations., suggesting that either this was a relatively isolated experience reflecting unique local circumstances or, more likely, that this was due to rapid attenuation of arsenic from minerals naturally present in the aquifer at all or most ASR sites in Florida. ASR testing at this particular site is continuing, with extensive monitoring, retreatment of the recovered water and other measures designed to ensure no adverse environmental, public health or water quality impacts. However satisfactory resolution of the associated regulatory policy issues is vitally important since federal law is clear in providing that recharge activities shall not create a situation where other nearby well owners have to treat water from their wells in a manner different than what they would normally have to provide, due to arsenic potentially in solution in the aquifer as a result of recharge activities. While this position is understandable, it does not provide for natural attenuation of arsenic in the aquifer that has been demonstrated to occur within a short distance from the ASR well.

As these examples suggest, the regulatory framework for ASR in the United States is awkward, at best. At the federal level, it was implemented almost 20 years ago to protect aquifers from contamination through well injection wastewater disposal practices and was not designed with consideration of ASR projects for storage and recovery of high quality water. At that time ASR hardly existed as a practice. Federal regulation has been delegated to most of the states, an increasing number of which are now developing supplemental ASR legislation to meet their own unique needs and opportunities. Under this federal and state regulatory framework, recharge water currently has to meet federal primary drinking water standards at the wellhead during recharge in order to gain federal approval. An exemption process is provided, however experience to date suggests that this process is extremely time consuming, expensive and of uncertain outcome. By definition, treated drinking water ASR systems meet this criterion. However ASR systems proposing to store partially-treated surface water, or groundwater from shallow aquifers, will probably violate coliform bacterial standards unless disinfection is provided, even though natural disinfection occurs in the aquifer. Reclaimed water ASR systems may violate nitrate or nitrite standards, or disinfection byproduct standards, unless they alter their treatment processes to denitrify the reclaimed water or to add ammonia for control of trihalomethane concentrations. Extensive experience supports denitrification and trihalomethane reduction natural processes in the aquifer around ASR and injection wells.

A New Paradigm for Aquifer Management

In the future, aquifers should be used primarily for storage, treatment and conveyance of water from a variety of sources, taking full advantage of their ability to provide large storage volumes; to provide treatment for many constituents through natural bacterial, geochemical and physical processes, and also to convey water inexpensively from a point of recharge to locations where it is needed for recovery. Some pretreatment of the water prior to recharge will probably be required. Such aquifer recharge practices should be consistent with overriding needs for protection of these aquifers from contamination and for protection of public health, groundwater quality and the environment since many constituents in surface water and reclaimed water may not be amenable to subsurface treatment with natural processes.

This would be a new paradigm for water management. In different parts of the world, aquifers are used for different purposes, and are regulated within different constraints, reflecting local needs, perceptions and opportunities. In the United States, aquifers are used for storage and, in a few areas for conveyance, however with the exception of surface recharge systems into shallow, unconfined aquifers, their use for treatment purposes is essentially prohibited under federal Underground Injection Control (UIC) regulations promulgated by the Environmental Protection Agency (EPA) in 1981 pursuant to the 1974 Safe Drinking Water Act. Implicit in U.S. regulations is that treatment in the vadose zone is accepted whereas treatment in underlying confined aquifers is assumed, incorrectly, to not occur.

This is in contrast to artificial recharge practice in the Netherlands, for instance, where for more than fifty years the water supply for Amsterdam has been diverted from the Rhone and treated to remove particulates, then conveyed to the Dunes area of coastal Holland and post-treated by natural filtration through sand aquifers to achieve disinfection. In recent years this practice has shifted from surface recharge basins in the Dunes to recharge wells, with water recovered from separate recovery wells. Aquifers in the Netherlands are used for water supply and also for water treatment. It is only recently that these aquifers have been considered also for water storage in addition to treatment. No ASR wells are yet operational in the Netherlands, however testing has commenced at one pilot ASR system.

In the area around Adelaide, Australia, eight ASR systems are operational, storing partially-treated surface water and reclaimed water in brackish, limestone artesian aquifers. This is a very water short area, within which seasonally-available water supplies are of vital importance for aquifer recharge. The goal of creating useable, freshwater aquifers is deemed to be more important than the potential for contamination of these brackish aquifers through addition of coliform bacteria, for example. Pretreatment of the recharge water is practiced, but not necessarily to drinking water standards. To date in Australia, no drinking water ASR systems are believed to be operational.

These are three examples, reflecting needs and opportunities for artificial recharge in different parts of the world. It is evident that aquifers may be relied upon for storage, treatment and conveyance. However some public resistance to this paradigm shift may be expected in the United States. Treatment to drinking water standards prior to recharge is usually considered to be of minimal risk. Any relaxation of this criterion is deemed to open up a relatively higher risk of contamination, public health problems and adverse environmental impacts. What is clearly needed is a process by which the risks and benefits can be compared, and a judgement rendered in each case regarding an acceptable tradeoff of risks and potential benefits. Treatment to drinking water standards prior to recharge can be achieved, but perhaps at a high price compared to other viable alternatives with equal or better protection of water resources, public health, groundwater quality and the environment. For example, the unit cost for treatment to drinking water standards may be well in excess of $1.00 per gallon per day of installed treatment capacity, whereas partial treatment is perhaps in the range of one fourth to one third of this cost. Is the public interest best served by requiring that treatment of recharge water be provided to meet drinking water standards to eliminate coliform bacteria and particulates in recharge waters, which will then be stored in brackish aquifers with native concentrations of total dissolved solids up to 10,000 mg/l, when use of the native water would require membrane treatment to render it suitable for potable use? Freshening of the native water with ASR would seem to make it more useful for the same purposes. Partial treatment can also potentially achieve these criteria, but at much lower cost. Initial experience suggests that capital and operating cost savings between the two approaches can be substantial. For south Florida alone, the potential savings is estimated to lie between one and two billion dollars, to meet projected increases in water demand between 2000 and 2020.

The Zone of Discharge (ZOD) for Aquifer Storage Recovery

Consistent with this new paradigm shift would be recognition of a new concept for ASR, namely the Zone of Discharge (ZOD). This is a buffer zone around an ASR well that, in some areas, is referred to as the "AMZ," or "ASR Management Zone." This is defined as a radial distance around an ASR well within which natural treatment processes occur, and are accepted by regulatory agencies as an integral part of water management practices. Compliance with drinking water standards would be evaluated at the edge of the ZOD instead of at the wellhead during recharge. The ZOD would extend from the top to the base of the storage zone. Experience with arsenic and coliform bacteria at selected Florida sites suggests that the ZOD may be typically on the order of a few hundred feet radius around an ASR well.

The ZOD concept has been accepted in some states, such as Utah and Arizona. It is under consideration in other states, such as Florida and Wisconsin. It is a concept that seems to make a lot of sense for water users and taxpayers.

Conclusions

Whether through changes in the Underground Injection Control federal regulatory program administered by EPA, or by changes to various state regulatory programs, or both, it is time to implement a new approach to water resources management in the United States that will help to achieve an efficient, integrated use of surface and groundwater resources while protecting public health, groundwater quality and the environment. With this new approach, aquifers will be considered capable of providing both treatment and storage of recharge water, and in some cases conveyance of this water from where it is most available to where it is needed. Such an approach would be based upon evaluation of risks and benefits of proposed ASR operations, and would accommodate establishment of a zone of discharge around an ASR well. Compliance with applicable water quality standards during recharge would be evaluated at the edge of this zone, and at the wellhead during recovery of the stored water.

References

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Development and Application of a Three-Dimensional Integrated Hydrologic Model of East-Central Palm Beach County, Florida

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Abstract

The city of West Palm Beach, Florida, has developed a reuse program to maximize water conservation that includes an innovative approach for the reuse of treated wastewater and augmentation of the drinking water supply-- a Wetlands-Based Water Reclamation Project (WBWRP). Implementation of the program will provide maximum flexibility for management of all water resources. The innovative technology of indirect potable reuse maximizes water conservation by taking treated wastewater and cleansing it to a very high level through several additional processes, including wetland treatment systems. This process will allow the city to augment their drinking water supply, create valuable wetlands, and protect existing wetland and water supply resources.

To simulate the hydrologic interaction between surface water and groundwater at specific wetland locations within the model area, an integrated hydrologic model was needed. By using the WETLANDS module created by the South Florida Water Management District for use in the USGS MODFLOW, model the quantification of surface water mounding and preferential flow through the wetland sloughs could be accounted. The robust nature of the integrated surface water/groundwater flow model was confirmed by simulating groundwater and surface water elevations measured throughout the area for the period January 1994 through July 1997. The resulting model provided an excellent representation of the surficial aquifer system in east-central Palm Beach County and onsite surface water features. The model was then used for evaluating different pumping and recharge options associated with the WBWRP.

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