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The Resource for Semi-Arid Hydrology

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Aquifer Recharge, Storage, and Recovery

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A few thoughts about a good team:

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Back in 1999, we assembled our new company on one guiding principle: that the value of our services would equal the sum of our staff.

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Joining founding partners (from left) Doug Bartlett and Marvin Glotfelty as Principals of Clear Creek Associates in Phoenix are:

Thomas R. Suriano, R.G., joined Clear Creek in 2006, bringing twenty-two years of experience managing environmental and water resources projects.

Donald P. Hanson, R.G., joined Clear Creek in 2000 and has twenty-two years of experience managing environmental and water resources projects.

And in Tucson:

Michael L. Alter, R.G., joined Clear Creek Associates at its inception in 1999 as head of the Tucson office and brings thirteen years of experience consulting on environmental and water resources projects.

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Southwest HYDROLOGY

The Resource for Semi-Arid Hydrology

A bimonthly trade magazine for hydrologists, water managers, and other professionals working with water issues.

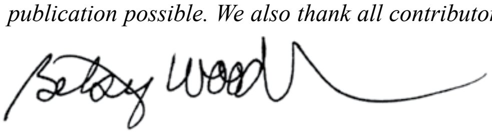
From the Publisher

Does your region have extra water now that you want to save for later, when there might be a drought? You could keep it in a reservoir if you have access to one, but you'll lose some of the water to evaporation. Or you could let it seep into the ground or inject it down a well to an aquifer, and plan to pump it back out when you need it. Your biggest problem may be figuring out what to call this process: in preparing this issue, we discovered strong and diverse opinions on terminology, especially among experts. Not all will agree with our decision (see page 16 sidebar), but we believe "aquifer storage and recovery" most clearly describes what we're talking about.

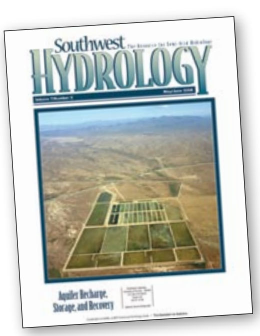
Did you pay someone for your Southwest Hydrology *subscription, or receive it as a "gift"? Say it ain't so! We recently learned that some unscrupulous entities are offering* Southwest Hydrology *subscriptions for around $10/year and pocketing the money.* Southwest Hydrology *is FREE! We are taking steps to stop this activity; if you paid, please let us know.*

Thanks to all of you who responded to our online survey, which was sent to the roughly 4,300 subscribers for which we have valid email addresses. We received some excellent suggestions, many of which we hope to implement in future issues, and learned a lot about our readers. We will provide more on the results in the next issue. Bottom line: most respondents are quite satisfied with Southwest Hydrology *and are also happy in their jobs. And more than half usually or always read this letter—not just my mother!*

We thank our newest sponsor of Southwest Hydrology*: Salt River Project. They, along with existing sponsors (see page 9) and our advertisers, help make continued free publication possible. We also thank all contributors to this issue.*



Betsy Woodhouse, Publisher



The Vidler Recharge Facility, about 90 miles west of Phoenix, recharges Central Arizona Project water through some 460 acres of infiltration basins. The water will be recovered in the future by Vidler or its buyer, for currently undetermined use(s).

Southwest Hydrology

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Inside This Issue

Departments

Aquifer Recharge, Storage, and Recovery

In this issue we define the deliberate recharge and temporary storage of "excess" (unneeded) water in an aquifer, with the intent of recovering that water for future use, as aquifer storage and recovery (ASR). The technique is increasingly being used as a water management tool. The implementation of ASR projects varies widely in the type of water used, method of recharge, aquifer type, and engineering of the project, as described in these feature articles. Furthermore, water quality changes resulting from mixing two different waters must be considered, as well as regulatory and policy constraints. And do you really get that water back? Read all about it…

*Publishing **Southwest Hydrology** furthers SAHRA's mission of promoting sustainable management of water resources in semi-arid regions.*

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New Directions in Water Policy: WRDA 2007

***Gerald E. Galloway** – Dept. of Civil and Environmental Engineering, Univ. of Maryland and **Ari M. Michelsen** – Texas AgriLife Research Center, Texas A&M Univ.*

Since 1976, the U.S. Congress has authorized the construction of water resource projects by the Army Corps of Engineers through the periodic passage of water resource development acts, which also promulgate water resource policies and programs.

Last October, Congress sent the Water Resource Development Act of 2007 (WRDA 2007) to President Bush. It authorized more than 900 projects, studies, and programs. Citing the large number of projects and total cost of near $23 billion, the President vetoed it. Congress overrode the veto and WRDA 2007 was enacted. It was hailed as a move to address significant infrastructure problems across the country and to reform some of the policies and procedures under which the Corps carries out its activities.

Objectives Expanded

For 25 years, the defined water resource development objective of the Corps and other water-related agencies had been national economic development (USWRC, 1983), with little recognition of environmental and social costs and benefits or regional economic development. WRDA 2007, in contrast, states that "all water resource projects should reflect national priorities, encourage economic development and protect the environment," with attention to minimizing adverse impacts and vulnerabilities in floodplains or flood-prone areas; and protecting and restoring the functions of natural systems.

Policy Changes

Principles and guidelines: WRDA 2007 requires the Secretary of the Army, within two years, to revise the principles and guidelines used to formulate, evaluate, and implement water resources projects by specifically considering: best available economic principles and analytical techniques; public safety; environmental justice issues and nonstructural approaches to water resources development and management; potential interactions of a project with other projects and programs within a region or watershed; and evaluation methods that ensure the projects are justified by public benefits.

Flood vulnerability: WRDA 2007 requires the President to submit a report to Congress describing the vulnerability of the United States to damage from flooding, including the risk to human life and property. The report must also compare risks faced by different regions of the country, assess how well existing programs address priorities for reducing flood risk and the extent that they might encourage development and economic activity in flood-prone areas, and recommend ways to reduce and respond to flood risks.

Economic and risk evaluations: The Secretary of the Army now must assess all project feasibility reports for cost-effectiveness and compliance with federal, state, and local laws. The Secretary is further directed to adopt a risk analysis approach to project estimates. For flood damage reduction projects, the residual risk of flooding and the loss of human life and safety must be calculated, as well as upstream and downstream impacts of the project. WRDA 2007 also requires benefits and costs of structural and nonstructural alternatives to be evaluated equitably, an idea long promoted by the environmental and floodplain management communities.

Independent review: For projects deemed controversial or with a total estimated cost greater than $45 million, or when requested by the governor of an affected state, WRDA 2007 requires review by an independent panel of experts to assess the adequacy and accountability of the economic, engineering, and environmental methods, models, and analyses used by the Chief of Engineers.

A Step Forward

Over the last seven years there has been considerable debate in Washington about how to improve the way water resource projects are developed and implemented. WRDA 2007 addresses many of these issues and requires numerous actions by the President, Secretary of the Army, and the Corps' Chief of Engineers to meet the intentions of the legislation. Unfortunately, in many cases, these efforts require funding, and little funding has been appropriated so far.

While far from a perfect solution to a complex problem, WRDA 2007 represents a major step forward. The response by the federal government over the next 12 to 18 months will indicate how well these congressional policy changes and activities are brought into play.

Contact Gerry Galloway at gegallo@umd.edu.
Contact Ari Michelsen at a-michelsen@tamu.edu.

Reference

U.S. Water Resources Council (USWRC), 1983. Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies, GPO, Washington, D.C.


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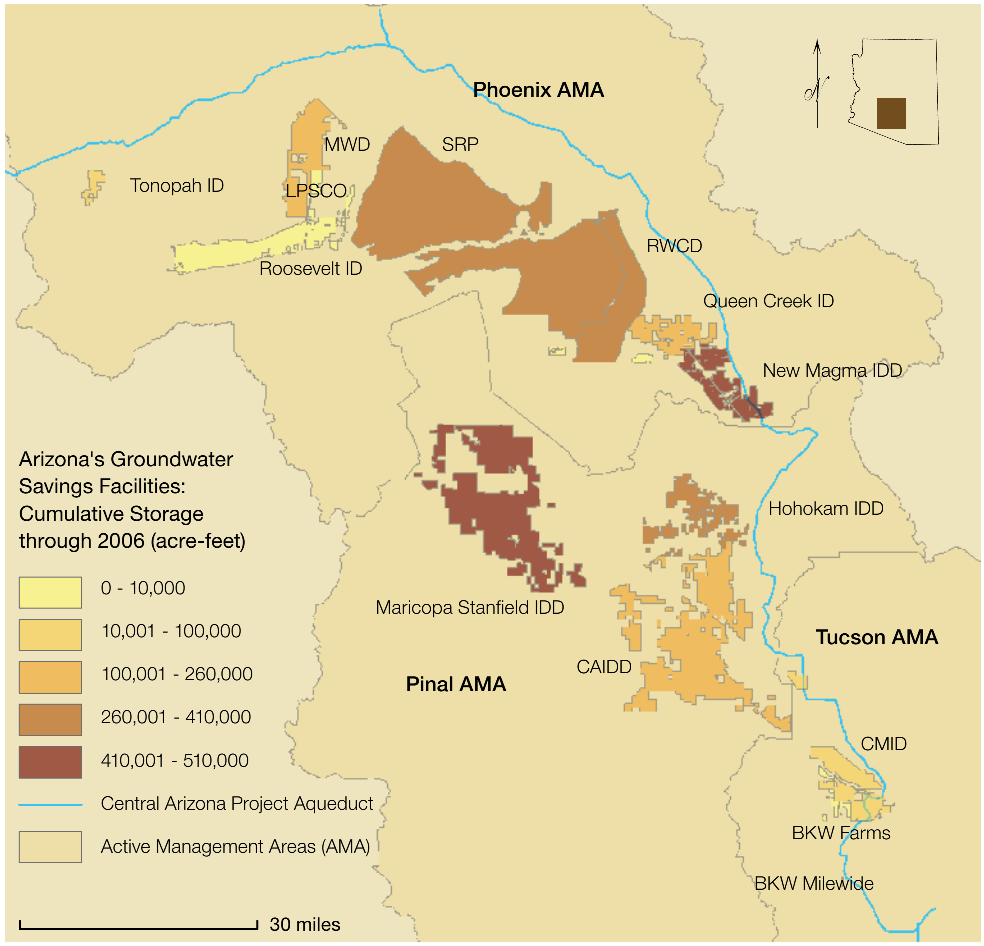
Arizona's Groundwater Savings Program

Sharon B. Megdal – *Water Resources Research Center and* **Taylor Shipman** – *Agriculture and Resource Economics, University of Arizona*

One of the more interesting and sometimes debated elements of Arizona's Groundwater Storage and Recovery Program is the Groundwater Savings Program (GSP). The program was developed when Arizona was struggling to utilize its Central Arizona Project (CAP) water. Agricultural water users rejected the use of CAP water due to its high cost relative to groundwater. Yet, the higher the ratio of agricultural to municipal use, the lower were Arizona's CAP repayment obligations to the federal government, according to the formula used at the time. By the early 1990s, it was clear that both the municipal and agricultural sectors would benefit from a program designed to increase agricultural use of CAP water.

Partnerships Are Key

Sometimes called indirect recharge or in-lieu recharge, the GSP allows storing entities to accrue groundwater storage credits when surface water or effluent is used for agriculture in place of groundwater. Since 1992, agricultural districts have partnered with entities such as municipalities, other water providers, the Central Arizona Water Conservation District (CAWCD, the body responsible for delivering CAP water), and the Arizona Water Banking Authority (AWBA, the independent government authority authorized to store CAP water for times of drought). They are able to provide CAP water to farmers at a cheaper rate than what farmers would pay directly, and they gain storage credits when that water is used for agriculture. Through such arrangements, approximately 3.5 million acre feet of CAP water have been used instead of groundwater in groundwater savings facilities (GSFs) in the three central Arizona Active Management Areas (see figure above.)



Three different types of permits—facility, storage, and recovery—are involved in implementing this program, which is administered by the Arizona Department of Water Resources. The agricultural entity holds the facility permit. The storing entity holds the storage permit and accrues the credits that entitle the credit holder to recover the stored water. More than one entity can be a storage partner. Finally, recovery of the water must be accomplished through a well permitted for that purpose.

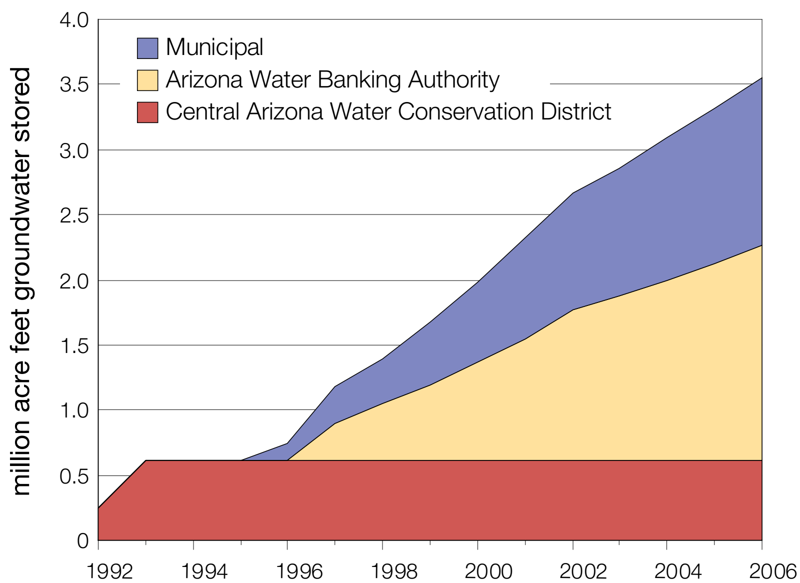
Benefits and Concerns

Storage at GSFs has the advantage of lower costs. The storing entity usually pays only a portion of the CAP water costs, with the agricultural user picking up the rest. In most cases, there is no facility charge associated with storing groundwater at the site. Contrast this with storage of CAP water at underground storage facilities (USFs), at which the storing entity pays the entire cost of the water to be stored in addition to a charge paid for use of the USF. Recovery considerations can be advantageous at GSFs as well. For an agricultural district, a GSF's area of hydrologic impact, where recovery well permits can be administratively easier to obtain, is the entire district.

Concerns about GSFs have mainly centered on the perpetual groundwater use rights of agricultural water users in the Active Management Areas. Should affordable CAP water no longer be available, the agricultural entity has the right to return to groundwater use and benefit from the higher water levels resulting from not having pumped the groundwater while using CAP water. There are also questions about the water management implications of recovery outside the area of hydrologic impact, potentially resulting in recovery at significant distance from the storage. (This concern is not unique to the GSP.) The chart (above right) shows that much of the GSF storage has been on behalf of CAWCD and the AWBA, with planned recovery occurring in the future and perhaps outside the area of hydrologic impact. Because recovery plans have not yet been developed, the potential hydrological disconnect between storage and recovery is a concern.

What is unarguable about the GSP is that this voluntary water exchange mechanism benefits the participating entities while furthering Arizona's water management objectives. Over 3.5 million acre-feet of CAP water has been used in lieu of pumping an equivalent amount of groundwater using this low-cost mechanism. The program enables municipal water providers to utilize CAP water indirectly and inexpensively to comply with regulatory requirements for use of renewable supplies. It is a low-cost alternative for the AWBA. Farmers benefit from water costs below what they otherwise would incur, courtesy of their groundwater savings partners. The popularity of the groundwater savings program is based on the simple economic principle that voluntary transactions yield mutual gains.

For more information, see Artificial Recharge, A Multi-Purpose Water Management Tool, Arroyo, *Winter 2007 at ag.arizona.edu/azwater/arroyo/. Contact Sharon B. Megdal at smegdal@cals.arizona.edu.*



Cumulative storage in Arizona's groundwater savings facilities, by type of storer.

Southern California Water Scarcity Affecting Growth?

In February, Metropolitan Water Board (MWB) in Southern California adopted a region-wide plan for sharing water during shortages that will guide the equitable distribution of water among its 26 member public agencies. The plan considers member agencies' dependency on MWD water and alternative sources of supply, and assesses "penalty rates" that increase as agencies exceed their allocations. Previously, MWB had determined allocation solely on "preferential rights" which were based on an agency's financial contribution.

Recent court-ordered reductions of water deliveries from the Sacramento Delta and ongoing drought were important factors in MWB cutting supplies to its local water districts by up to 30 percent in early January, said the *Riverside Press-Enterprise*.

In response to the new plan, one of the affected member agencies, Eastern Municipal Water District (EMWD), placed new retail and community developments in western Riverside County on hold in January, saying it could not yet guarantee water for a warehouse proposed for Moreno Valley and a $300 million hotel and retail complex in Murrieta, according to the *Press-Enterprise*. Seven other developments were already on hold because their water supply could not be assured.

A 2001 bill passed by the California legislature requires major developments to get "will-serve" letters from their water providers before they can proceed with construction, assuring a supply for 20 years. The delays of new developments are considered the first time the law has had such an effect.

"It's a new paradigm," said EMWD Board Member Randy Record. "It's not water saying 'we're here for you,' but 'You have to do this for us,'" reported the *Press-Enterprise*.

Visit www.pe.com and www.mwdh2o.com.

New Mexico Senate Considers Regulation of Deep Aquifers

Just as developers are realizing the potential of using deep, brackish groundwater—currently unregulated—to support growth in New Mexico (see *Southwest Hydrology*, March/April 2008), legislators began thinking that regulation of that resource is warranted. Senator Carlos Cisneros of Questa introduced SB 262 to the New Mexico legislature earlier this year, calling for regulation of aquifers having "reasonably ascertainable boundaries" with upper surface 2,500 feet or more below the ground and dissolved solids concentrations greater than 1,000 parts per million.

Deep groundwater produced during oil and gas exploration or geothermal projects is already regulated through the New Mexico Energy, Minerals, and Natural Resources Department (EMNRD), although SB 262 proposed additional restrictions.

The bill did not pass, having faced opposition by EMNRD and the State Land Office, according to the *Santa Fe New Mexican*. However Cisneros told the newspaper that he plans to evaluate the opposing arguments and return with a new version of the bill in 2009. Supporters said that significant amounts of groundwater pumping at any depth should be monitored by the state engineer. For now, the developers are getting busy…

Visit www.nmsenate.com and www.santafenewmexican.com.

HydroFacts

Term most widely used internationally for recharging, storing, and recovering water from an aquifer:	Managed Aquifer Recharge (MAR)
Number of wells in Chennai, India (formerly Madras, pop. 7.5 million) used to recharge rainfall from mandatory rooftop harvesting systems:	400,000
Density of wells in Chennai:	15/hectare, or 6/acre
Source: Steve Gorelich, Stanford University	
Estimated capacity of recharge facilities, by recharge methodology, in cubic meters:	
vadose zone wells (per well)	1,000 - 3,000
recharge & recovery wells (per well)	2,000 - 6,000
recharge basins (per hectare per day)	1,000 - 20,000
Estimated life cycle for recharge facilities, by recharge methodology, in years:	
vadose zone wells	5-20
recharge & recovery wells	25-50
recharge basins	> 100
Source: Prospects for Managed Underground Storage of Recoverable Water, NRC 2008	

New Mexico and Texas Bury the Hatchet

Irrigation districts in Doña Ana County, New Mexico, and El Paso, Texas, have reached what Elephant Butte Irrigation District (EBID) Manager Gary Esslinger calls "a monumental agreement" on the apportionment of water from the Elephant Butte Reservoir, according to an *Associated Press* report in the *Las Cruces Sun-News*.

In February, the districts, which together comprise the Rio Grande Project, agreed to drop their separate lawsuits over water rights, following a 29-year dispute, said the *AP* report. El Paso County Improvement District No. 1 had claimed that unregulated groundwater pumping by New Mexico farmers was cutting into their share of reservoir water. Under the agreement, EBID will guarantee delivery of the El Paso districts' water to the state border, and the New Mexico farmers can continue to pump groundwater as long as the El Paso delivery requirements are met.

Visit www.lcsun-news.com.

Division Over Rio Grande Waters

A 1944 treaty that equally apportions Rio Grande waters to Mexico and the United States is proving inadequate to resolve disputes on both sides of the border. Under the treaty's terms, water allocations to Texas farmers were severely curtailed from 1992 to 2002 because of low waters in the shared Amistad and Falcon reservoirs, with Mexico accumulating a deficit of 1.5 million acre-feet by the end of that period. The debt has been gradually repaid through water transfers from the dams every five years.

Farmers in northeastern Mexico are hurting and unhappy from the latest transfers, reported *Reuters*, and lawmakers in Tamaulipas have asked the Mexican Supreme Court to rule on whether the most recent transfer, in 2007, was lawful. The farmers claim their harvests are ruined and farms must be abandoned every time a transfer is made. They argue that water from six western Mexican tributaries to the Rio Grande should be used instead to reduce the deficit, according to *Reuters*.

Meanwhile, the state of Texas has joined farmers, ranchers, and irrigation districts in continuing to seek redress from Mexico for uncompensated damages racked up from 1992 to 2002. Because individuals cannot sue Mexico or the United States under the 1944 treaty, the farmers sued Mexico for $500 million through a tribunal of the North American Free Trade Agreement in 2004. The case was thrown out because NAFTA ruled it did not have

continued on next page

jurisdiction. The farmers are particularly frustrated by the U.S. State Department's last-minute decision to side with Mexico, according to the *Associated Press*.

AP reported that the farmers planned to take their case to a Canadian judge to decide whether they received a fair hearing. They are seeking a decision from a Canadian judge because both sides had agreed to arbitration at a neutral location if the issue could not be resolved.

Visit www.ap.org and www.reuters.com.

Oil Shale Development a Threat to Colorado's Water?

International oil companies have substantial and growing water rights on the Western Slope of the Rocky Mountains and could be planning to use the rights for oil-shale development, according to an article in the *Durango Herald*. Evaluating potential impacts of industry development on the Colorado River is difficult because of a lack of studies on oil shale production and water needs. Most studies are vague, 20 years old, and do not reflect new in-situ development techniques.

But three major oil companies—Shell, Chevron, and EGL—recently obtained leases to demonstrate their in-situ methods on 160-acre parcels in Colorado. The technique requires water to process the shale oil, control dust, and wash leftover oil from underground formations.

According to the *Herald*, while Chevron has the biggest water rights in Colorado, Shell has done the most aggressive purchasing in the last five years, including a ranch in northwest Colorado with three large reservoirs, a land swap for Piceance State Wildlife Area, and an area west of Grand Junction adjacent to a coal mine. Shell is not divulging whether the purchases are for its oil-shale research project, the newspaper said.

The prospect of substantial oil-shale development has some legislators and environmentalists worried, said the *Herald*. Potential water use estimates range up to 500,000 acre-feet per year. Colorado currently uses around 2.1 million acre-fee per year from the Colorado River Basin. The state's entire allocation of Colorado River water is 3.8 million acre-feet—a figure most water experts consider will never be available because of climate fluctuations and change.

A Shell spokesperson, Jill Davis, believes concerns are exaggerated. She estimates production of oil from shale would take two to three barrels of water per barrel of oil produced and believes that work force, air quality, the oil market, and water supplies will all be factors limiting the industry's size, according to the article.

Visit www.durango.herald.

EPA Calculates $202 Billion Bill for Infrastructure

A recent report from the U.S. Environmental Protection Agency estimates $202.5 billion in capital investment is needed nationwide to control wastewater pollution for up to a 20-year period. EPA conducts the Clean Watersheds Needs Survey every four years; the new report is based on a 2004 survey. The estimate includes $134.4 billion for wastewater treatment and collection systems, $54.8 billion for combined sewer overflow corrections, and $9 billion for stormwater management.

The report provides information about pollution control needed to meet the environmental and human health objectives of the Clean Water Act. The figures represent documented wastewater investment needs, but do not account for expected investment and revenues. Wastewater treatment utilities pay for infrastructure using revenue from rates charged to customers and may finance large projects using loans or bonds.

State and federal funding programs, such as EPA's Clean Water State Revolving Fund program, are also available to help communities meet their wastewater pollution control needs. The needs in this survey represent a $16.1 billion (8.6 percent) increase over the 2000 survey report. The increase is due to population growth, more protective water quality standards, and aging infrastructure.

Visit www.epa.gov/cwns/.

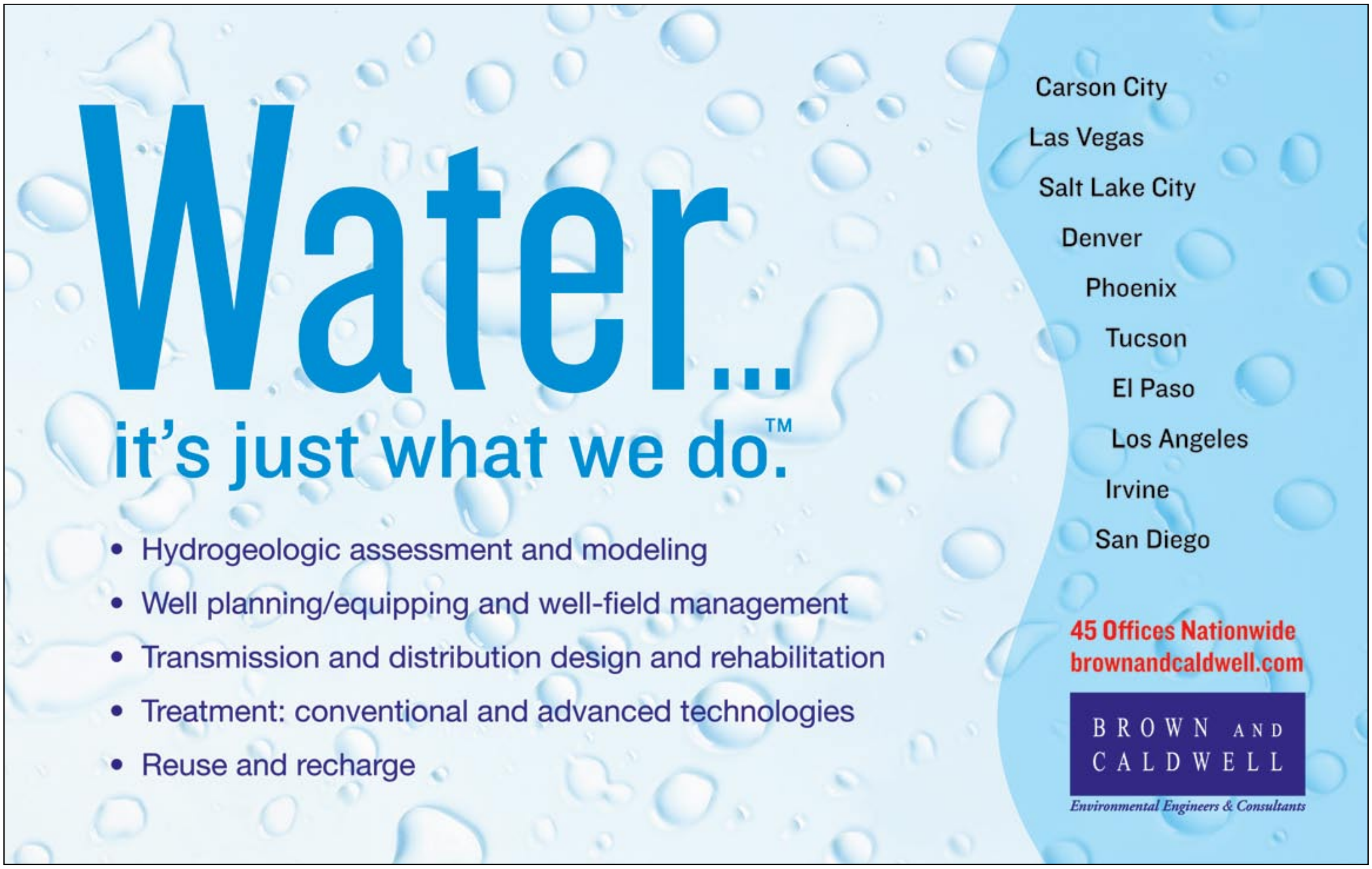
Los Angeles Reservoirs Experience Bromate Spike

Late last year, Los Angeles Department of Water and Power (LADWP) officials discovered unusually high concentrations of bromate in two reservoirs within its water distribution system. The reservoirs, which collectively held 600 million gallons of water, were immediately isolated from the rest of the system. According to the *Los Angeles Times*, bromate concentrations measured in October were 68 parts per billion (ppb) and 106 ppb in the two reservoirs. The U.S. EPA drinking water standard for bromate is 10 ppb calculated as an annual average of monthly measurements. Because the problem was addressed soon enough, no violations occurred.

Bromate is a suspected carcinogen that may cause adverse health effects after long-term exposure. It is known to form as a disinfection byproduct in public water systems when water containing naturally occurring bromide is purified using ozone. The LADWP reservoirs were being filled with local groundwater, and according to the agency's report, bromate formed unexpectedly when the reservoir water was treated with chlorine and exposed to sunlight. This was the first time such an occurrence had been observed.

After using some of the reservoir water for nonpotable uses, LADWP planned to drain and thoroughly clean the reservoirs. They are slated to be back in service by this summer.

Visit www.ladwpnews.com and latimes.com.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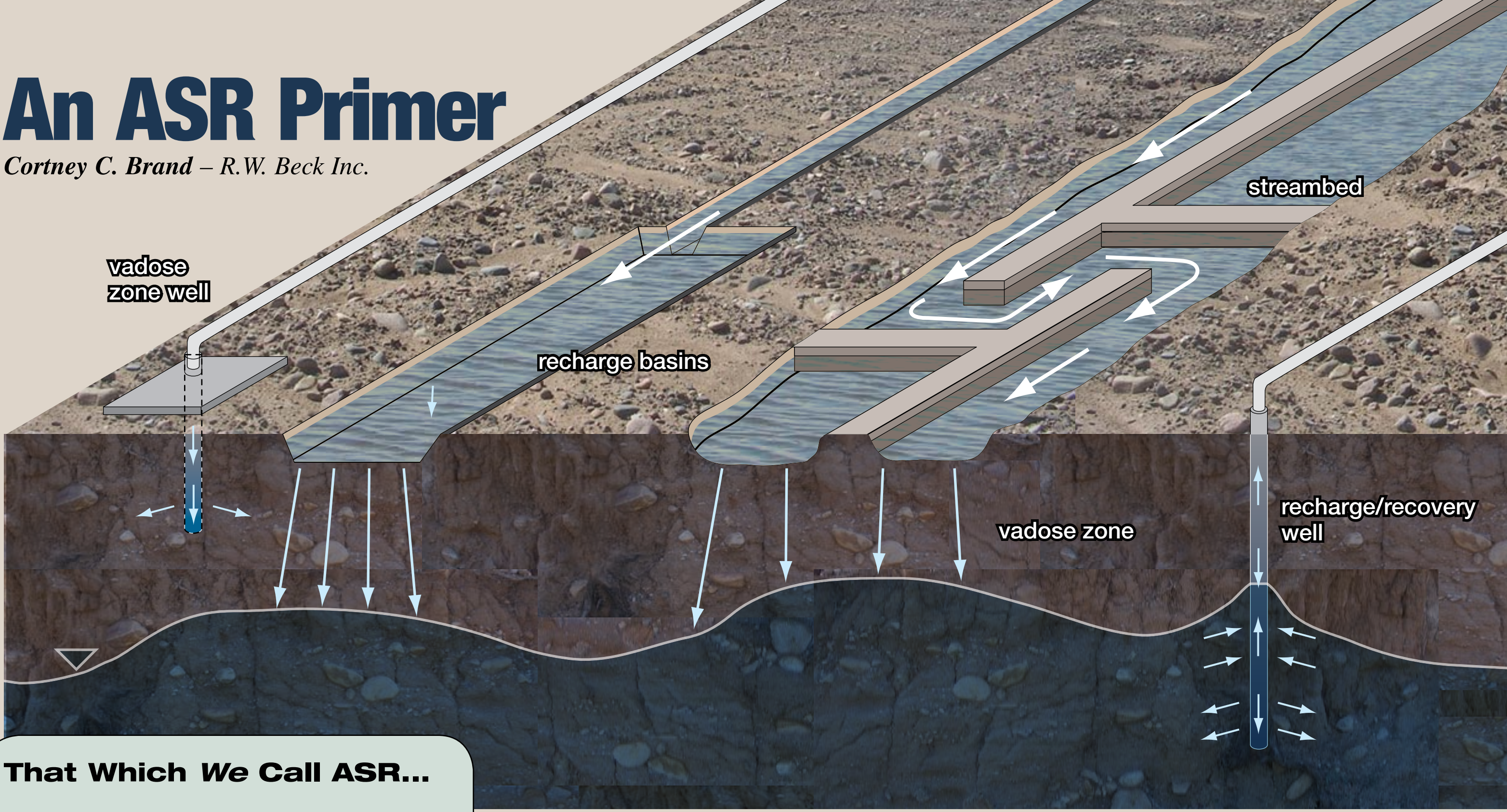


That Which *We* Call ASR…

…others may not. In preparing this issue, *Southwest Hydrology* polled numerous experts for the best term to describe the process of recharging aquifers (by a variety of means using a variety of source waters), storing water (for short to long periods), and then recovering water (from the same or other wells). We received many opinions and no clear consensus. The top candidates, none of which include "recharge," "storage," *and* "recovery," are:

Aquifer Storage and Recovery (ASR): To some, this means strictly recharge and recovery from the same well. Others believe it is the most widely recognized term—at least in the Southwest—to refer broadly to all forms of aquifer recharge, storage, and recovery.

Managed Aquifer Recharge (MAR): Has the greatest international use; less common in this country. The original definition referred to intentional banking and treatment of water in aquifers.

Managed Underground Storage of Recoverable Water (MUS): Introduced in 2008 by NRC's Committee on Sustainable Underground Storage of Recoverable Water to define "purposeful recharge of water into an aquifer system for intended recovery and use as an element of long-term water resource management."

Southwest Hydrology is using the broad definition of ASR.

Most water resources professionals have heard of ASR, or aquifer storage and recovery, but it can mean different things to different people. ASR can mean artificial recharge, groundwater recharge, managed aquifer recharge, underground water storage, conjunctive use, or a combination thereof. For purposes of this and accompanying articles, ASR is a water management technique that encompasses the *purposeful recharge and temporary storage of water in an aquifer with the intent to recover all or a portion of the water from the same aquifer in the future*. Without the intent to, or act of, recovering recharged water it is simply groundwater recharge.

ASR is thought to have originated several hundred years ago in the Kara Kum Plain of Turkmenistan and in Western India (Pyne, 1995), but is now conducted in some form on every continent except Antarctica. The motivators and potential benefits of ASR vary based on geography, hydrology, water chemistry, and water policies/laws. A majority of the Southwest is arid or semi-arid, susceptible to drought, and characterized by declining groundwater levels, unreliable surface water supplies, and overappropriated rivers. As a result, the capture and storage of water when it is available is critical to sustainable water management. The traditional approach has been to store water aboveground by constructing dams and reservoirs. The benefits of aboveground storage include rapid fill and release, large storage capacities, straightforward measurement and management, and opportunities for recreation. However, escalating costs and environmental permitting requirements associated with surface reservoirs, as well as declining availability of land and suitable sites, have driven water professionals to explore ASR as an alternative.

Implementing ASR

Where feasible, storing water underground can save money, increase yields, mitigate the impacts of drought, firm up surface water supplies, improve water quality, and avoid evaporative losses. The necessary ingredients are 1) an aquifer of suitable character, 2) source water of suitable quality, 3) the means to transmit the source water into the aquifer, and 4) the means to recover it. ASR can be accomplished in bedrock, alluvial, or limestone aquifers as long as the formation can receive, store, and transmit water without adversely impacting native groundwater or source water quality.

There are myriad configurations and methods of implementing ASR, and the inherent variability of natural systems necessitates site-specific solutions. Suitable source waters can include surface water diverted from streams, stormwater runoff, remediated groundwater, reclaimed water, and industrial-process water. Water can be transmitted into an aquifer using nonstructural means such as natural drainages or structural means such as impoundments, basins, trenches, injection wells, vadose zone wells, or combinations thereof. Some ASR systems, because of the nature of the water source, require aboveground storage to capture and hold water before it can be transmitted underground. Water recovery is typically accomplished through wells; however, some ASR systems utilize natural discharge of groundwater to a stream as a virtual means of recovery.

ASR is practiced by governmental entities and water utilities throughout the Southwest. Some familiar examples include Scottsdale, Tucson, Orange County, Las Vegas, El Paso, Salt River Project, Central Arizona Project, and Metropolitan Water District of Southern California (MWD). Most of these entities utilize the vast storage capacity available in alluvial-fill basins. In contrast, entities situated along Colorado's Front Range, including Highlands Ranch and Colorado Springs, utilize deep bedrock aquifers of the Denver Basin. The City of San Antonio utilizes the Edwards Aquifer, a cavernous limestone formation. Other examples of ASR include water conservation districts in the San Luis Valley and the lower South Platte River in Colorado, the Wintergarden region of south Texas, and the Jordan Valley Water Conservancy District in central Utah. As illustrated in the table below, these projects vary in their objectives, water sources, aquifer characteristics, and means of recharging and recovering water.

Challenges to Overcome

Although the potential benefits of ASR are numerous, ASR also poses significant challenges. These primarily revolve around issues of water quality; water recovery; the management, monitoring, and accounting of recharged water; water rights; and source water availability. These challenges are geographically dependent due to interstate and intrastate variations in water administration, local hydrology, and aquifer characteristics.

ASR is typically accomplished using water derived from a source other than the receiving aquifer. Waters from different sources can have different chemistries, pH, temperatures, and redox conditions. Mixing dissimilar waters underground and exposing aquifer materials to non-native water can drive geochemical reactions that alter water chemistry. Some potential impacts include dissolution of arsenic compounds and precipitation of clays. Water quality changes can also occur as water percolates through the vadose zone and encounters evaporite deposits or leaching zones underlying agricultural areas. Recharged water can acquire salts and nitrogen compounds as it percolates to groundwater, degrading source water and groundwater quality.

The increased use of reclaimed water for ASR has created an emerging water quality issue posed by pharmaceuticals and endocrine disrupting compounds. These contaminants occur in wastewater at very low concentrations and are not effectively

see ASR Primer, page 32

Entity / Project	Objective	Water Source	Aquifer Type	Recharge Method	Recovery Method
Arizona					
City of Scottsdale	store excess surface water and stormwater runoff	treated CAP water, reclaimed water	alluvial basin	direct injection wells, vadose zone wells	production and dual-use wells
Salt River Project	store excess surface water	CAP water, surface water (Salt and Verde rivers), reclaimed water	Salt River alluvium	basins	to be determined
Central Arizona Project (CAP)	store excess surface water	CAP water	alluvial basin	basins	to be determined
Tucson Water	treat and store surface water and reclaimed water	CAP water, reclaimed water	alluvial basin	basins	production wells
Vidler Recharge Facility	store surface water	CAP water	alluvial basin	basins, vadose zone wells	to be determined
California					
Orange County Water District	long-term storage, groundwater replenishment	surface water (from MWD), stormwater runoff, reclaimed water	alluvial basin	direct injection wells, in-lieu, basins	production wells
Coachella Valley	long-term storage, groundwater replenishment	surface water (from MWD), All-American Canal	alluvial basin	in-lieu, basins	production wells, water transfer
Texas					
City of El Paso	recharge aquifer and store water	reclaimed water	alluvial basin	direct injection wells, basins	production wells
City of San Antonio	store seasonally available Edwards Aquifer water	groundwater	alluvial basin	direct injection wells	production wells
Wintergarden Groundwater Conservation District	enhance recharge to the Carrizo aquifer	stormwater runoff	sandstone	impoundments, passive wells	production wells
Colorado					
Centennial Water & Sanitation District	store excess surface water	surface water (S. Platte River)	sandstone	direct injection wells	production and dual-use wells
Colorado Springs Utilities	store excess surface water	surface water (Colorado River)	sandstone	direct injection wells	dual-use wells
Lower South Platte Water Conservancy District	streamflow augmentation, wildlife recovery	surface water (S. Platte River) and alluvial wells	S. Platte River alluvium	basins and ditches	accretion to river
Nevada					
Las Vegas Valley Water District	store excess surface water	surface water (Colorado River)	alluvial basin	direct injection wells	production and dual-use wells

Examples of ASR projects in the Southwest. Note: CAP water is untreated Colorado River.

Hydrogeology and ASR Design

Greg Bushner – *Vidler Water Company*

Today there are many choices for the design and operation of an aquifer storage and recovery (ASR) facility, since such facilities can serve a variety of needs. An ASR facility has the capability to recharge, store, and recover all or a portion of the source water recharged regardless of the recharge method. It might consist of shallow or deep infiltration basins, vadose zone wells, direct injection wells, wells that can both inject and recover water, or a combination thereof.

Evaluating Land and Water

The selection of a facility initially is driven by the available source water, available or needed land, and the planned end use of the water. What is the source water? It may be wastewater effluent, seasonal surface water, vested or certificated water rights, or another water source. Once identified, its chemistry must be evaluated to determine if it will need pretreatment or if the quality is adequate for the project method.

Next, how much land is needed and of what type? A vadose zone, injection, or dual-use (recharge/recovery) well in an urban setting has a significantly smaller footprint than an infiltration basin; however, the unit land cost may be much higher. How will the facility design be incorporated into the available land or vice versa? Is the land undeveloped or has it been disturbed?

Finally, what is the end use of the stored water—what type of recharge/recovery cycle will be needed? How long will the water be stored before it is recovered, and how will it be accounted for until it is recovered? Answering these questions will guide the project design and budget through the next phases of project planning. A life-cycle cost analysis is also useful to determine the appropriate recharge method and its application to a specific project and water source.

Now the Hydrogeology

No matter what type of recharge method is decided upon, all ASR projects require characterization of the hydrogeologic conditions in the vicinity of the project site. This begins with identifying the land use and land owners, and any existing wells and their use, proximity to the project site, water source, conveyance options, and water quality.

Baseline hydrologic data are critical to predict future impacts from the project. These data should include a water-level-elevation contour map showing direction of groundwater flow and hydraulic gradient, and determination of storage capacity or transit capacity of the vadose zone. Are water levels at surrounding wells increasing, decreasing, or both? Areas of subsidence should be mapped relative to the project location. Baseline groundwater chemistry data should be collected if they are not already available, and constructing one or more project monitoring wells may be warranted.

Data Needs

Depending on the type of recharge method to be used, additional hydrogeologic data may be needed. Infiltration basin facilities require a detailed investigation of the surficial soils and vadose zone. Soil samples should be analyzed for lithologic characteristics such as grain size, distribution, intrinsic permeability, residual moisture content, and pore-water chemistry. A similar investigation should be conducted in the vadose zone through use of soil borings strategically located to represent site conditions for the project area. The goal of this investigation is to identify positive attributes of the soils and vadose zone, such as high porosity and permeability that would be conducive for a particular recharge method, as well as negative attributes such as the presence of subsurface impermeable layers or

Aerial view of the Vidler Recharge Facility, a privately-owned project in western Arizona that contains over 460 acres of surface infiltration basins. Photo: Kenney Aerial contaminants. Site-specific tests using infiltrometers should be conducted, as well as field-scale infiltration tests to determine initial and long-term infiltration rates for use as facility-design parameters. Borehole percolation tests may also be used to develop a vertical hydraulic conductivity profile of the vadose zone.

Initial infiltration rates for recharge through basins in Arizona have been found to range from about one foot per day to more than 12 feet per day, depending on site conditions. However, these rates may decrease by one-half to two-thirds during actual facility operations. Initial testing and site characterization are important for determining project feasibility, but only long-term project operations provide true infiltration rates that determine the project's viability.

Sampling and chemical analysis of pore water and soils can identify potential constituents that, once the facility is in operation, could migrate due to water infiltration. For example, nitrates are known to occur in pore water of undeveloped arid soils. Operation of an ASR facility might mobilize them, resulting in a concentration of nitrates at the groundwater interface. Knowing the potential for migration of a constituent prior to facility construction is beneficial so that other alternatives, such as use of a different recharge method, can be considered.

Test to Target

Similar data should be collected to identify target injection zones for vadose zone wells, if that recharge method is chosen. For direct injection and dual-use wells, standard hydrogeologic characterization of the aquifer system is needed. This includes a lithologic description of the drill cuttings and a full suite of geophysical logs. In addition, aquifer testing and determination of hydraulic properties, including transmissivity, storage coefficients, and hydraulic conductivity should be conducted once the well is constructed and the aquifer water chemistry analyzed. Monitor wells should be installed as part of this effort, initially to determine the viability of the aquifer system, subsequently for use during the testing of the injection/dual-use well, and finally during facility operations to monitor water level and chemistry, and as a regulatory point of compliance if needed. Regardless of the recharge method used, the receiving aquifer system needs to be understood so that the potential effects of recharge to the system can be discerned.

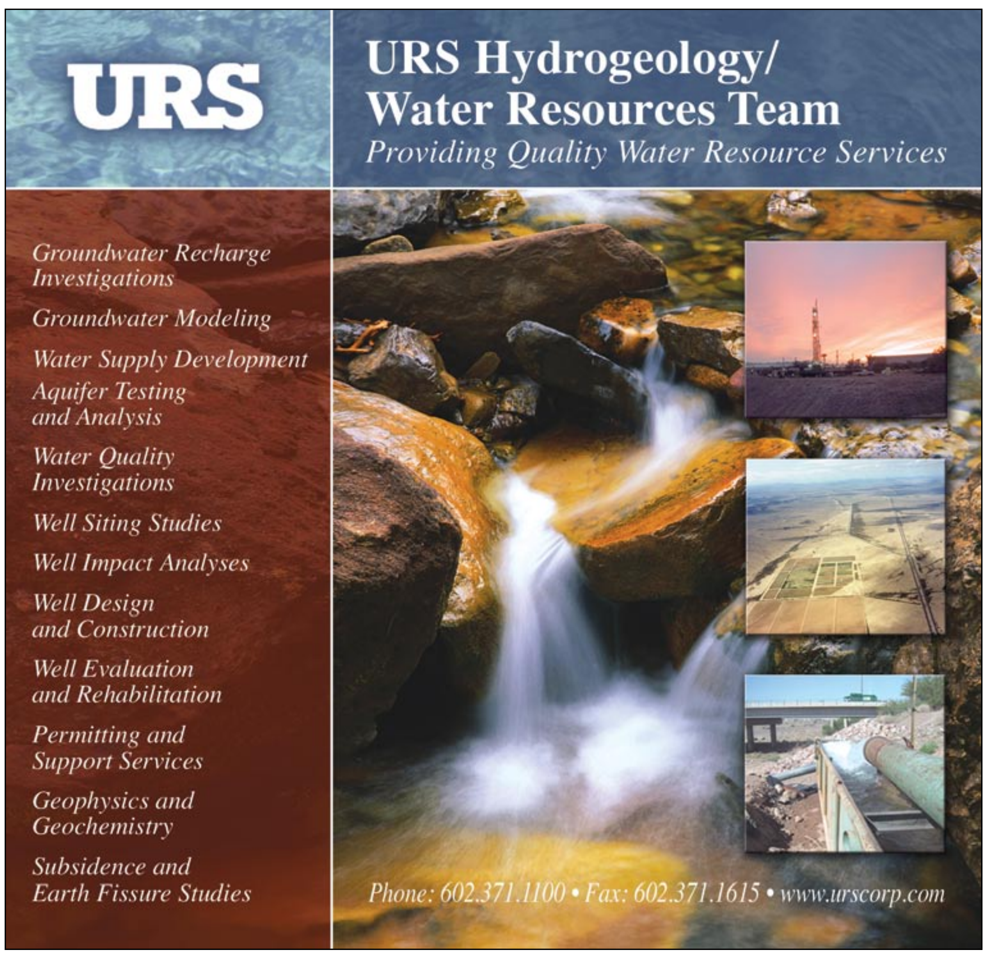
The development of baseline hydrologic data is critical to predict future impacts from the project.

Plan on Maintenance

Maintenance and operational issues for ASR facilities include mechanical plugging such as air entrainment, conveyance system dry-ups or maintenance, and other issues including biofouling. Biofouling is an all-encompassing term that pertains to all organisms that can cause a reduction of infiltration or injection rates. Correct identification of biofouling agents is imperative in order to devise an effective treatment plan. Biofouling can also occur in the form of algal mats or clogging layers in basins. Maintenance of affected facilities would include dry-outs and scarification of the basins to remove clogging materials, and well development or redevelopment for vadose zone, injection, and dual-use wells.

Careful thought and planning are necessary to develop a successful ASR project. Source water characteristics and amount and type of available land guide the initial design and type of recharge facility to be constructed. But hydrogeologic characterization ultimately determines the feasibility of the project, the design criteria, and the project's long-term viability.

Contact Greg Bushner at GBushner@vidlerwater.com.



ASR and the "Big Picture"

Cat Shrier – Watercat Consulting LLC

Hundreds of water providers throughout the United States are already using some form of well or surface recharge for managed underground storage (MUS, called aquifer storage and recovery [ASR] in this publication) as an integral part of their water supply management. The Congressional Water Caucus recently identified "groundwater banking" as a priority for U.S. water policy.

Yet as a 2008 National Research Council (NRC) report reveals, little quantifiable, reliable information is available regarding total amounts of water stored underground, subsurface storage locations, or available storage. Nor are there widely accepted metrics for assessing storage suitability, economic and financial costs and benefits of ASR, or ways to compare and combine surface and subsurface storage alternatives for conjunctive (joint groundwater and surface-water) management. This lack of information, along with inconsistent regulatory guidance, creates challenges for individual providers considering ASR, but is also a problem for planners considering the bigger picture: How can we apply and integrate ASR into conjunctive water management to address regional and national or federal priorities?

On March 19, 2008, NRC hosted a forum in Washington, D.C., to discuss institutional issues of managed underground storage such as science- and risk-based ASR policy and regulations for water supply and protection of health and the environment; and monitoring, management, and planning. Held in partnership with the Ground Water Protection Council, National Ground Water Association, and Groundwater Resources Association of California, the forum attracted speakers and participants from more than 25 states and three federal agencies. Some points and questions raised at the forum follow.

Public and Policy Maker Education

Education was widely recognized as a critical component for ASR to be perceived and accepted as a mainstream tool for water management. The Southwest has generally higher water knowledge than other regions, and most western states have ASR-specific permitting regulations. However, nationally and federally, the concepts, challenges, and benefits associated with ASR have been poorly communicated to policy makers and the public, making it hard to gain public trust.

Efforts to address policy and management aspects often become bogged down over technical details and debates over terminology—such as whether to use "ASR" or "MUS"—or derailed by characterizations of ASR as an experimental and untested technology in spite of its widespread use. Many water managers discount ASR, saying "We use surface water, not groundwater."

Groundwater organizations have taken the lead on organizing ASR symposia and developing educational materials—but since most ASR system supplies are surface water, is ASR really just a groundwater issue? Policy makers and the public usually understand water only in surface-water terms. What metrics and educational tools could help translate ASR benefits and constraints into terms that fit a surface-water paradigm?

UIC and Groundwater Protection

The biggest direct federal involvement in ASR comes from the U.S. Environmental Protection Agency's Underground Injection Control (UIC) program. ASR wells are "Class V" wells, a catch-all category mainly for permitting waste disposal. UIC is implemented by states if EPA grants them primary enforcement responsibility, or by regional EPA offices. EPA headquarters is completing an internal review on how ASR works, but has not provided states or regional agencies with guidance on UIC interpretation, resulting in inconsistent permitting approaches.

UIC-related questions raised in the NRC report and forum include: 1) Do residence-time requirements reflect site-specific conditions for different constituents? 2) Are state interpretations of "antidegradation" preventing ASR development in cases where the risk is remote of impacting other groundwater users pumping from an underground source of drinking water and where the benefits to the water supply—and even water quality—are high? 3) Do primary drinking water standards need to be met at the wellhead or at the edge of a limited zone of conditioning?

State agencies, regional EPA staff, and water providers at the forum saw no need for new regulations, and stressed that permit requirements must be specific to site conditions, operations, and risk of adverse interactions between the stored water and water in the aquifer. However, they requested federal guidance for more consistent interpretation of UIC and funding to develop approaches for ASR permit application review.

Federal Support

While water supply issues are handled at the state level, federal agencies have long been involved in ASR, from the U.S. Geological Survey's post-World War II groundwater recharge studies to the U.S. Bureau of Reclamation's Ground Water Recharge Demonstration Projects of the 1980s, a major catalyst for western ASR development. The proposed SECURE Water Act would increase the activities of USGS and Reclamation related to water resources data and water availability, including groundwater. Will these studies consider use of aquifers not just as groundwater reserves but also as potential underground storage zones?

The U.S. Army Corps of Engineers' (Corps) Water Resources Principles & Guidelines (P&G), which provide standards for evaluating water resources management alternatives and planning, are being reviewed and updated (see page 8). Colorado, Utah, and Oregon have developed metrics for evaluating potential underground storage areas, as has the

Corps Central Everglades Restoration Plan. Individual water entities such as South Metro (Colorado) Water Authority and the cities of Phoenix and Beaverton, Oregon, have developed methods for comparing benefits and costs of storage options, supporting more integrated planning approaches. When agencies such as Corps and Reclamation are developing basinwide and regional water plans to meet national priorities, such as ensuring water is left in streams to preserve habitat, will all opportunities for storage (surface and underground) and considerations of conjunctive water use be incorporated as critical components for optimal water management?

Other federal agencies, such as those that own land with potential recharge sites or are involved with water-intensive activities, also are interested in underground storage. In Colorado, the National Resources Conservation Service and U.S. Fish and Wildlife Service have funded and supported projects on state wildlife areas and private lands where recharge ponds for stream augmentation provide habitat benefits. The U.S. Department of Energy is currently exploring increased use of treated effluent and water produced during energy extraction. In Wyoming, water providers have completed pilot studies on produced-water ASR. Will federal agencies consider and incorporate underground and surface storage options and conjunctive management for federal activities involving water storage?

Building a National Network

The NRC forum was the first national meeting on ASR institutional issues. Water providers and state agencies from across the country want this dialogue to continue with the benefit of widely accessible statistics, metrics, policy and facility profiles, and case studies. A national network of ASR water providers, agency personnel, and other stakeholders is being considered, which would work with existing water education organizations and associations that consider ASR an issue of interest to their members. The network could improve communication between ASR systems and regulatory programs, make reliable information more widely available, develop statistics on national ASR use, and further national dialogue on policy, permitting, and planning.

Contact Cat Shrier at cat@watercatconsulting.com.
Read or purchase NRC's "Prospects for Managed Underground Storage of Recoverable Water" (National Academies Press, 2008) at books.nap.edu/openbook.php?record_id=12057&page=R1.

VIEW THE WEBCAST of NRC's March 19, 2008 ***Forum on Policy, Regulatory, and Economic Issues Associated with Managed Underground Storage of Recoverable Water*** for no charge until June 30. Link through these partner organizations:

- National Ground Water Association (*www.ngwa.org*)
- Groundwater Resources Association of California (*www.grac.org*)
- Ground Water Protection Council (*www.gwpc.org*)

ASR from a Legal Perspective

***Denise D. Fort** – University of New Mexico School of Law*

Drought, population growth, groundwater mining, and a host of other challenges are accelerating the search for new approaches to water supplies. One promising approach already utilized throughout the United States is using groundwater aquifers for storage and retrieval of waters. I served as a participant on the National Research Council's panel on managed underground storage (here termed aquifer storage and recovery, or ASR) and found the topic to be a rich one for consideration by institutional researchers, because the practice raises an array of legal questions.

The regulatory structure for ASR is complicated because the legal arrangement for managing water historically has separated water quality and water quantity, as well as groundwater and surface water. Several water quality schemes may apply to ASR projects. In certain circumstances authority is divided between the federal and state governments, and states vary in how stringently they regulate these projects. The water quality questions may pale in comparison to the water quantity issues. Water allocation is primarily a matter of state control, but states vary in how they view the right to store and withdraw water. Ownership and control of aquifer storage raise yet other legal issues.

Water Quality

The regulatory system for protection of water quality depends on how ASR projects are undertaken. In general, protection of the groundwater aquifer is regulated by states, and therefore standards vary. Protection of wellheads of drinking water systems is a matter of federal law, administered by the states. States may in fact provide a higher degree of protection for aquifers than required by federal law.

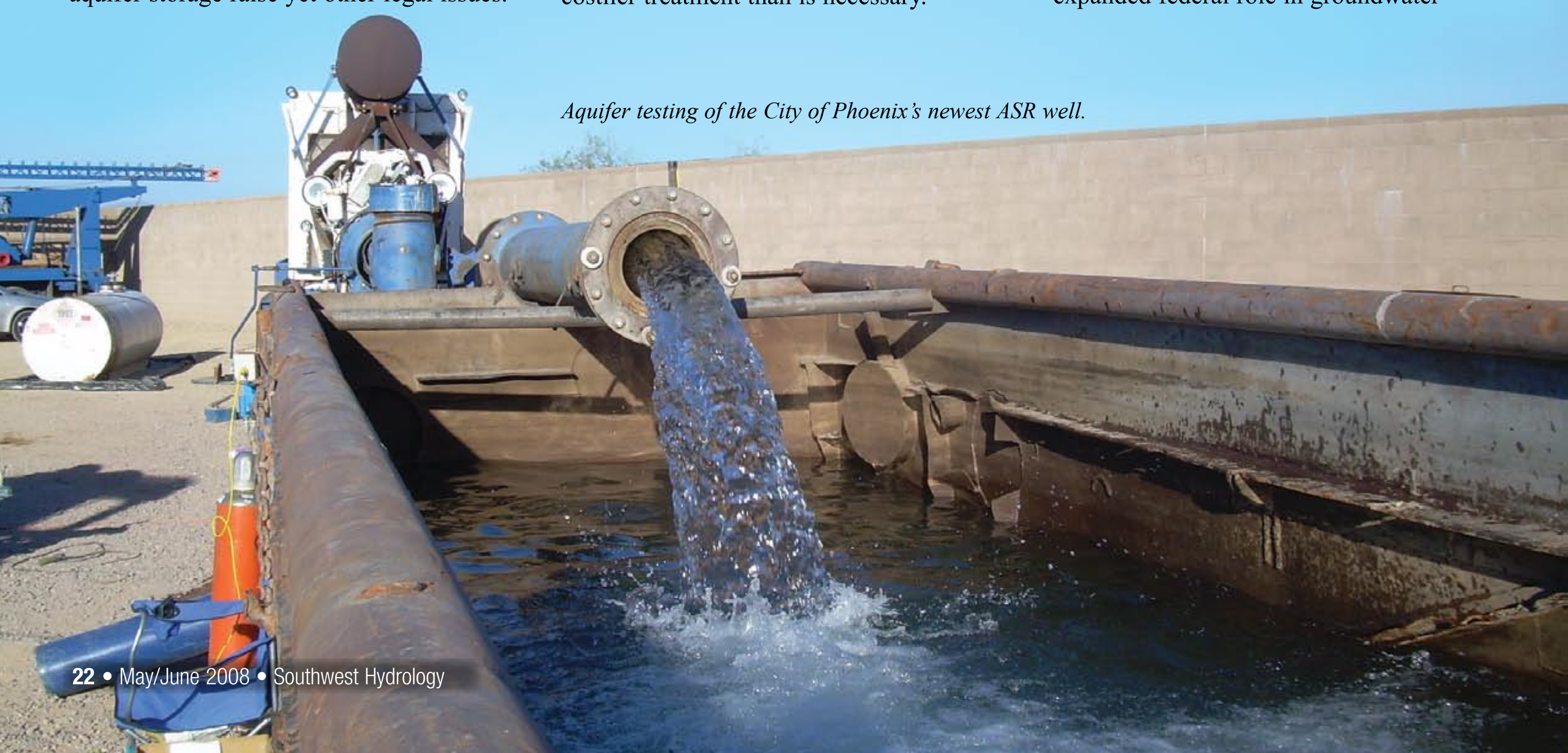
The greatest sources of regulatory conflict seem to be over the degree of protection required for aquifers. If a state prohibits any degradation of an aquifer, this puts a costly burden on an ASR project developer. From a pragmatic perspective, the question is whether it is preferable to require a high degree of treatment before injection/infiltration, or after water is withdrawn.

Have most states sufficiently weighed the water resource and pollution risks and benefits of ASR projects against the long-term protection of aquifers? Probably not, since such projects still are relatively novel. In fact, nondegradation of aquifers may be a standard that prevents projects from going forward that offer greater benefits than risks, and causes costlier treatment than is necessary.

Federal involvement in ASR projects is relatively limited. Insofar as projects are conducted through injection wells, federal UIC (Underground Injection Control) regulations apply, either through the U.S. Environmental Protection Agency or state-delegated programs. Recharge through infiltration is not regulated by the EPA, although permits may be required for the discharge to surface water (National Pollutant Discharge Elimination System permit) and for alterations to streambeds (Section 404 of the Clean Water Act). The distinction appears to be an accidental consequence of the federal regulatory structure, and not a statement about which type of project presents greater risks to aquifers. The federal UIC program is a narrow groundwater protection program directed at a particular source of groundwater pollution, the injection of wastes into groundwater.

Another policy question is whether the federal government should be more involved in regulation of these projects, or less. The current federal role seems to be as a backstop for inadequate state regulation, but only for certain types of projects.

In general, one could argue for an expanded federal role in groundwater



Aquifer testing of the City of Phoenix's newest ASR well.

protection because so many sources of groundwater pollution are inadequately regulated by either federal or state governments. Pollution from mining, energy production, and agriculture, for example, can be politically difficult for states to regulate when they are competing to attract such industries. States do not compete for ASR projects, however, and I am aware of no evidence that the states are failing to adequately regulate them. Furthermore, groundwater pollution risks posed by ASR projects appear minimal compared to many other projects, thus they would seem to offer a good opportunity to allow states to function as the "laboratories of democracy."

Water Quantity

State control over the use of water is well-established. Federal issues do arise, as for example, when federal funds are used for an ASR project, or where federally owned water rights are proposed as the source water. However, each state's water regime varies, and some states do not clearly address the water rights issues raised by projects.

ASR projects must own or have a right to control the water that is used for recharge. Effluent, one possible source water, is not necessarily owned by the entity that wishes to recharge the aquifer. Critical questions about control of the aquifer are whether the project can use aquifer space for storage and whether the recharger has control of the water that it has put into the aquifer. Generally, a state government would expect to be able to use an aquifer for storage without a clear legal basis to do so, but the use of aquifer storage space becomes a thorny legal problem when there are multiple entities pumping groundwater in the aquifer. The legal questions would be most pointed if a commercial entity proposed such an operation in an aquifer. In any event, the right to use the capacity of an aquifer for storage will have to be resolved by statute or under the common law.

Another set of legal concerns arises from how to protect the investment in the water that has been recharged without harming other entities that may be extracting water from the aquifer. Where multiple entities utilize an aquifer,

The greatest conflicts seem to be over the degree of water quality protection required for aquifers.

explicit legal guidance or contracts among the groundwater users would be necessary. Finally, there are potential liability concerns should a project cause impairment of another's water rights.

This list of legal concerns might seem daunting and a testimony to the desirability of statutory and regulatory schemes that respond to the particular issues raised by ASR projects. Despite the complicated nature of these projects, the NRC report contains discussions of how institutional challenges have been overcome in different jurisdictions.

Future Looks Favorable

Water projects always are complicated, requiring knowledge of both written and unwritten rules and the capacity to ease the way through innumerable barriers. ASR projects are viewed as extraordinarily complex by some, but the successful implementation of these projects suggests that these barriers can be overcome. There are no comprehensive studies of how many technically worthwhile projects failed due to institutional barriers.

A number of factors favor the future of ASR projects. Organized opposition to them by citizen organizations seems to be lacking, except when treated wastewater is proposed for drinking water reuse. Among the choices for water storage, ASR appears to be one of the most benign, since storage underground does not affect river function and it decreases evaporation losses. ASR may even provide ancillary environmental benefits. Environmental risks exist, but perhaps have been better addressed than many others associated with water, such as unregulated pesticide runoff, the effects of oil and gas operations, and even leaking septic systems. A well-thought-out regulatory system, providing appropriate information about risk, opportunities for public participation, and appropriate regulation should allow this technology to be utilized.

State governments should consider adopting regulatory regimes that specifically address the issues raised by ASR. Doing so lessens transaction costs and provides a more tailored review of issues that arise with respect to these projects. I suggest that it is appropriate for the federal government to assist by providing research funding and for state governments to cooperate in devising templates for regulation, within the constraints of each state's unique water code.

Contact Denise Fort at fortde@law.unm.edu. Read or purchase "Prospects for Managed Underground Storage of Recoverable Water" (National Academies Press, 2008) at books.nap.edu/openbook.php?record_id=12057&page=R1.

Photo: Gary Gin

Water Quality Changes During Subsurface Storage

Peter Fox *– Arizona State University*

While underground storage of water offers many benefits, transformations in water quality resulting from the recharge of one type of water into an aquifer of different composition warrant attention. The primary constituents of concern that may be introduced into or form in storage systems include organics and pathogens; nutrients and inorganics can also cause problems. These constituents may be broken down, mitigated, or otherwise changed through chemical, biological, adsorption, dilution, or filtration processes that take place in the storage zone. The extent to which these processes occur depends on the compositions of the two water types and the subsurface conditions.

Time, Surface Area Are Factors

Some water quality transformations occur rapidly, such as those that result from changes in oxidation-reduction (redox) conditions or chemical interactions between the injected water and the aquifer. These reactions may not only change the water quality but also impact the hydraulic capacity of injection wells.

Other transformations, such as the biodegradation of trace organic compounds, often occur slowly; sufficient time is required to achieve the full benefits of aquifer storage. For example, with enough time, natural attenuation processes can improve the quality of stored water to that approaching native groundwater.

Alluvial aquifers, comprised mostly of sand and gravel, contain abundant surface area, which permits plenty of contact with the water traveling through it. This surface area mediates many biogeochemical reactions that can improve water quality. Such water quality transformations are less likely in fractured and karst aquifers where preferential flow through cracks and fissures limits contact between the water and aquifer material.

A select group of SOCs has been found to persist in the subsurface, and the list is growing.

Flowpaths also affect transformations during subsurface storage. Flowpaths surrounding dual-purpose wells—used for both injection and recovery—have highly variable travel times and the most unpredictable effects on water quality. Subsurface storage systems with different recharge and recovery points can have defined flowpaths and associated travel times. Such systems have more consistent and predictable water quality transformations.

Oxygen Matters Also

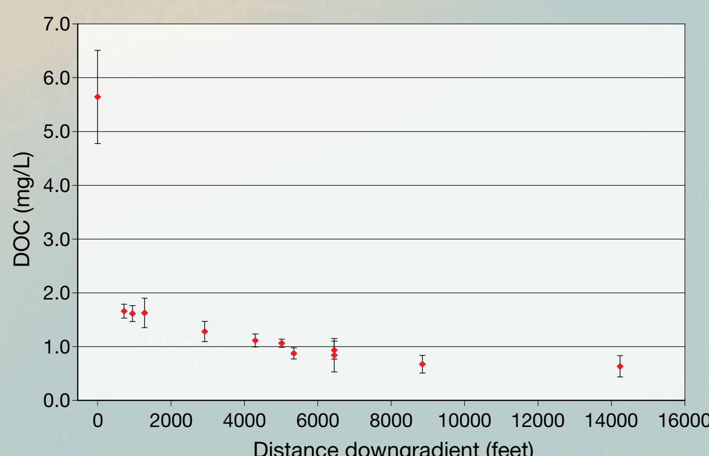
Many organics, nutrients, and pathogens of concern can be removed in the subsurface through biological mechanisms. Key factors that affect biological removal during subsurface storage include the biodegradable organic carbon content of the recharge water and redox conditions of the aquifer. Therefore reverse-osmosis-treated water, lacking organic carbon, does not support significant biological removal. In fact, trace constituents such as N-nitrosodimethylamine (NDMA) have been shown not to attenuate during the injection of reverse-osmosis-treated water, unlike in other recharge systems.

Most biological transformations will occur whether or not oxygen is present, however, some organic compounds require a specific electron acceptor to degrade. Many chlorinated organic compounds, such as trihalomethanes, degrade faster under conditions where oxygen is low or absent. Finally, recharging waters high in oxygen demand will create anoxic conditions and increase the potential for the dissolution of mineral iron and manganese.

The Organic Players

Three types of residual organic materials undergo transformation: natural organic matter (NOM), which is present in most water supplies; soluble microbial products (SMPs) formed during the wastewater treatment process from the decomposition of organic compounds, and synthetic organic compounds (SOCs) added by consumers and also generated as disinfection byproducts (DBPs) during water and wastewater treatment (Barker and Stuckey, 1999).

Most waters contain NOM; reclaimed waters contain a mixture of NOM and SMPs. NOM and SMPs measured together as dissolved organic carbon have concentrations typically measured in the milligrams per liter range. The primary concern over NOM and SMPs is their potential to form DBPs and stimulate biological growth in distribution systems. Concerns over both human and aquatic health effects are generally associated with SOCs and DBPs, which are measured individually at concentrations of micrograms or nanograms per liter.



Dissolved organic carbon (DOC) concentration is shown as a function of distance for the Mesa (Arizona) Northwest Water Reclamation Plant groundwater recharge basins. Each 1,000 feet of travel equals around six months of travel time. After several years of travel, DOC concentrations are less than 1 milligram per liter, approaching background conditions of the aquifer.

Subsurface Removal of Organics

Organic compounds are removed during subsurface storage by a combination of biodegradation, filtration, sorption, and oxidation/reduction. Biodegradation is the most sustainable removal mechanism for organic compounds during subsurface transport. Concentrations of NOM and SMPs are reduced during subsurface transport as high molecular weight compounds are hydrolyzed into lower molecular weight compounds, which serve as substrate for microorganisms. As NOM and SMP concentrations decrease, their potential for forming DBPs also decreases. Given sufficient surface area and contact time, the stored water may approach the quality of native groundwater with respect to organic carbon content (see figure, below left).

However, a select group of SOCs has been found to persist in the subsurface, and the list is growing as new analytical techniques are developed. In the Netherlands where Rhine River water has been recharged for over a century, recharged groundwater can be dated by the presence of persistent pharmaceutical compounds during the last five decades. The persistence of carbamezapine (an anticonvulsant and mood-stabilizing drug) is so widespread that researchers have suggested its use as a universal indicator of anthropogenic contamination. These compounds are all polar and resist biodegradation, making them both mobile in the aquifer and persistent. In contrast, the steroid hormones and alkylphenols suspected of causing estrogenicity are nonpolar and biodegradable, and have been observed far less frequently in aquifers.

The Fate of Pathogens

Alluvial recharge systems effectively filter bacteria and protozoa, leaving viruses as the major concern for pathogen transport during subsurface flow. In fact, the survival of viruses has been used as travel-time criteria for systems designed for potable water production. In California, the minimum travel time requirement is six months, while 50 and 70 days are required in Germany and the Netherlands, respectively. Higher levels of microbial activity in an aquifer decrease the survival of pathogenic viruses since the viruses are subject to predation. This is one reason for the discrepancy between criteria in different parts of the world.

Nutrients

Recharge systems have limited potential for the removal of nutrients. Biological processes may sustain the removal of nitrogen species under specific conditions. The addition of ammonia in secondary effluent to surface recharge basins can result in significant nitrogen removal since cyclic aerobic/anoxic conditions will result from the use of wetting/drying cycles. The adsorption of ammonia is dependent on the cation exchange capacity of the soils. Some adsorbed ammonia is converted to nitrate under aerobic conditions and the nitrate can be reduced to nitrogen gas under anoxic conditions. Adsorbed ammonia may also serve as the electron donor to reduce nitrate by anaerobic ammonia oxidation. Removal rates of 70 percent have been observed at the Tucson Sweetwater Underground Storage and Recovery system. Direct injection systems may remove some nitrate if the aquifer is anoxic and the potential for ammonia oxidation is low since there is insufficient oxidation. Phosphorous can be removed by precipitation on calcerous soils for time periods that have been estimated to be centuries, but the removal is not sustainable.

Inorganics

Similar to phosphorous, inorganics may be removed by precipitation or as a consequence of changes in their redox state. Most waters, including reclaimed waters, that are used for recharge do not contain inorganics at concentrations that cause concern. As long as the waters applied do not contain elevated concentrations, they should equilibrate with the local geochemical conditions and not pose a problem. However, rapidly changing redox conditions that can occur in dual-purpose wells can create both dissolution and precipitation of naturally occurring iron, manganese, and arsenic. Such conditions can result in well plugging and contamination of recovered water. It is necessary to inject a sufficient quantity of water to create a storage zone that eliminates the recovery of water that is subject to varying redox conditions.

Contact Peter Fox at Peter.Fox@asu.edu.

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What About the "R" in ASR?

Betsy Woodhouse – *Southwest Hydrology, University of Arizona*

Southern Nevada Water Authority ASR well

Getting water into the ground is fairly straightforward: water drains down from a basin or goes down a well. But then what happens to it? Will the water really be there when it's needed? Does it matter if the exact same water is there to recover? Was water actually stored? The answers depend on the goals of the project and the local regulatory framework.

When fresh water is stored in saline or brackish aquifers, common in the Southeast, mixing of the waters is undesirable: the goal is to recover essentially the same water that was recharged. When fresh water is stored in fresh-water aquifers, as is typical in the Southwest, recovering the same water is less critical. The goal of such projects may be to reverse water level declines in the aquifer or to store water long-term for future drought or development.

What Storage Means

From a physical standpoint, water must remain in a location that is definable and accessible for recovery in order to be considered "stored." Rising water levels in wells demonstrate that the volume of water stored in an aquifer is increasing. The Vidler Water Company has been recharging about 30,000 acre-feet per year of Central Arizona Project water in its spreading basin facility in western Arizona since 2000; nearly a 200-foot rise in water levels has been observed. The Southern Nevada Water Authority stores water in a highly transmissive confined aquifer that also is used by other entities. It operates on a seasonal cycle, storing water during the wet months when demand is low (and natural recharge also replenishes the aquifer) and pumping it during dry months. Water levels fluctuate 35 to 40 feet between the two seasons, of which 13 to 18 feet are attributed to artificial recharge.

> *Sometimes recovery of an equivalent mass matters more than getting the same molecules back.*

Permeability tests, tracer experiments (primarily using chloride), and flow and transport models have been used to study the behavior of recharged water in an aquifer. In general, recharged water usually stays in a somewhat coherent mass in the subsurface for a period of time after some initial mixing at the entry zone. How much and how quickly the recharged water mixes with native groundwater depends on parameters such as regional groundwater flow velocity and the dispersivity, transmissivity, and heterogeneities of the aquifer.

If water is stored only briefly or the aquifer is not highly transmissive, the recharged water mass will likely maintain its integrity, permitting recovery of most of the stored water. If the water is stored longer, its mass may eventually dissipate throughout the aquifer, but if the aquifer is well-constrained, storage will still be evident through elevated water levels. If the aquifer is very large or highly transmissive, however, physical storage may be measurable only briefly if at all.

Another Kind of Storage

From a regulatory perspective, storage can simply mean credit for recharging a certain quantity of water which provides the storing entity a right to withdraw water in the future. The water need not stay in any particular location, although ideally it should stay within the groundwater basin. In some states or regions, a storing entity receives an equal amount of credits for withdrawal as was recharged. In other cases, a "tax" may be levied. The Arizona Water Banking Authority takes a five percent "cut to the aquifer" for recharge of Central Arizona Project water in recognition that some amount of water is lost in the aquifer. However, that five percent does not have a scientific basis.

Robert Maliva of Schlumberger Water Services points out that so-called “regulatory storage” can cause problems. Where groundwater use of an aquifer is being limited because of local hydrogeologic concerns such as water levels in wetlands or spring flows during dry periods, the additional pumping during recovery from an ASR system could actually make matters worse. If the aquifer is not sufficiently constrained and recharged, water spreads over a very large area and no long-term local rise in aquifer water level or pressure occurs to compensate for subsequent withdrawals.

Getting It Back

When fresh water is recharged into brackish or saline aquifers, an initial “investment” of unrecoverable water is often necessary to, in effect, clean out space in the aquifer. Recovery ceases when water quality deteriorates. When fresh water is recharged into a fresh-water aquifer, recovery of an equivalent mass matters more than getting the same molecules back—and storage may only be of the regulatory kind.

Recovery can take place on a regular cycle, such as during the annual dry season, or it may simply be part of the long-term plan, such as for future development or drought protection. Many long-term projects in the Southwest have no specific recovery plans yet. In an ASR project under development, the City of Phoenix plans to recharge and recover on an annual cycle, but will only recover slightly more than 50 percent of the 1,900 acre-feet per year that will be recharged, with the remainder used to maintain the aquifer for future needs. For the privately-owned Vidler Recharge Facility, recovery will be initiated at an undetermined time in the future dictated by either sale of some or all of the water credits or Vidler’s decision to build a development itself. Project goals also influence placement of the recovery system relative to the recharge facilities (see sidebar).

On Recovery Efficiency

Recovery efficiency is strictly defined as the amount of useable water that is recovered compared to the volume that was recharged, for a single recharge/recovery cycle in a dual-purpose well. This calculation is typically used where fresh water is stored in a brackish-water aquifer for seasonal use; water is recovered until concentrations exceed a drinking water standard, such as for chloride or total dissolved solids. For fresh-water systems having a well-defined aquifer, a quantity-based recovery efficiency can be estimated using a mass-balance approach and changes in water level elevations.

According to Maliva, too much emphasis is placed on achieving high recovery efficiency, with the implication that a project is wasting water otherwise. But if water is being stored that would have been lost, that in itself is a benefit. As an example, the township of Clayton, Australia, is storing fresh water in a saline aquifer. The recovery efficiency of the project is less than 10 percent, but the system is providing much-needed fresh water at lower cost than other options and is viewed as a success. The system stores excess lake water during wet periods that would otherwise not be put to beneficial use. The water that is recovered comprises a critical component of the town’s water supply during dry periods.

Water Is Lost

No large-scale water storage system is loss-proof. Just as reservoirs lose some amount of water to evaporation, artificially recharged water is undoubtedly not entirely recoverable, although one could argue that at least it remains in its liquid form and goes *somewhere*. Loss to fresh-water aquifers generally is not monitored or calculated. It may not be a problem now when more recharge than recovery is occurring, but when storing entities start cashing in their credits, the importance of knowing where that water went will likely increase.

Is Downgradient Recovery Better Than Upgradient Recovery?

Mark Cross – Errol L. Montgomery & Associates Inc.

Placement of recovery wells relative to recharge facilities varies widely in practice due to differences in recharge and recovery objectives, legal and regulatory constraints, hydrogeologic conditions, and other factors. If the intent is to recover the same water that was used for recharge, recovery wells should be located at or down-hydraulic-gradient from the recharge site. However, if the objective of recharge is simply to increase the amount of water in storage, recovering the same water may not be important and recovery wells need not be located at or downgradient from the recharge site.

The physical benefits of recharge include increased water storage and water-level rise, or at least reduced water-level decline. A common misconception is that these benefits are greater downgradient from a recharge site than upgradient. However, both theory and practice indicate that the benefits of increased storage radiate outward in all directions from a recharge site, depending only on aquifer hydraulic properties (transmissivity, storage coefficient). The magnitude of the water-level rise (or reduced water-level decline) diminishes dramatically with distance from the recharge site. The magnitude of water-level rise does *not* depend on the rate or direction of groundwater movement, only on aquifer hydraulic properties and distance from the recharge site. Thus, if recovering the same water is not important, no advantage is gained by locating recovery wells downgradient from the recharge facility.

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Water Spreading in the Desert

***Mario R. Lluria** – HydroSystems Inc.*

In the late 1980s, the portion of the Central Arizona Project (CAP) aqueduct that conveys water from the Colorado River to Phoenix was completed. At the time, the Salt River Valley lacked sufficient surface storage capacity for Arizona's unused portion of CAP water, and storage in the distant reservoirs of the Salt and Verde rivers was prohibitively expensive. Consequently, the Salt River Project (SRP) and several municipalities agreed to develop a large underground water storage facility. A study funded by the Arizona Municipal Water User Association (AMWUA) identified favorable sites in the Salt and Agua Fria rivers for in-channel groundwater recharge, a method successfully used for many years in the Los Angeles Basin to store water in the underlying alluvial aquifer.

The First Facility: GRUSP

In 1986, the City of Mesa and SRP initiated work on a large water-spreading recharge facility in the East Salt River Valley. Based on the AMWUA study, SRP evaluated a 7-mile-long reach of the lower Salt River immediately downstream of Granite Reef Dam, and found favorable hydrogeologic conditions with no environmental constraints.

Four potential sites were selected, all near the SRP water delivery system and its large-capacity wells, providing the necessary supporting infrastructure. In 1987, Phoenix-area municipalities joined with SRP to select a site, acquire the land, and design, permit, construct, and operate the regional Granite Reef Underground Storage Project (GRUSP). More than 90 percent of the site would be within the Salt River Pima-Maricopa Indian Reservation. Negotiations with the tribal government concluded in 1992 with the leasing of a 350-acre parcel for a period of twenty years. Every five years the land is re-appraised and the rent adjusted according to current value. The main determinant is the value of the land's sand and gravel, which is in high demand. Thus, a steady, substantial rent increase has affected the unit cost of recharge at GRUSP.

The permit process for GRUSP commenced in 1987 and was completed in 1992. Two federal permits were required under the Clean Water Act, one each from the U.S. Environmental Protection Agency and the Army Corps of Engineers. State permits were issued by the Arizona Department of Water Resources (for underground storage) and the Arizona Department of Environmental Quality (for aquifer protection).

Construction and Operation

In 1994, four recharge basins with a total area of 174 acres were completed. Two more added in 1999 increased the area to 225 acres. Originally, CAP water and water from the Salt and Verde rivers were used for recharge; in 2007 reclaimed water was added. The waters are mixed before entering the recharge basins.

One of the most important factors in GRUSP's successful operation is the site's favorable hydrogeologic characteristics. On the periphery of the large Salt River Valley tectonic basin, the site's coarse-grained unconsolidated sands and gravels have high permeability and water storage capacity, producing recharge rates of 2 to 7 feet per day. The storage capacity of the area of hydrologic impact exceeds one million acre-feet. Over 920,000 acre-feet of water have been stored in GRUSP, both short-term and long-term, over its 13 years of operation (Lluria, 1998).

View of the Granite Reef Underground Storage facility in 1995, showing canals transporting CAP water to the facility in the Salt River Valley.

The cost of construction of the GRUSP facility was $1.2 million, with a total project cost at the start in May 1994 of $2.2 million. Ownership of GRUSP is held by SRP and the cities of Chandler, Gilbert, Mesa, Phoenix, Scottsdale, and Tempe. The recharge capacity for each city is based on entitlement, with recharge rights based on percent ownership. Other entities have also used GRUSP; of these, the Arizona Water Banking Authority has accumulated the most water storage credits.

Challenges and Solutions

GRUSP has faced some challenges. All delivery and recharge facilities are constructed of river bed material and are subject to damage during stormwater releases from Granite Reef Dam. Damage caused by such releases are of primary concern because of reconstruction costs, but only three flood events, in the winters of 1995, 2005, and 2008, have occurred so far. Successful mitigation measures have included breaching some of the structures to route flows and minimize erosion.

In 1994, a sanitary landfill was completed one mile north of the GRUSP site. Groundwater mounding under the landfill is controlled by regulating inflow, rotating the operating recharge basins, and increasing the hydraulic gradient away from the landfill by pumping. Evapotranspiration losses are minimized by controlling the vegetation in the delivery and recharge units of the facility.

Benefits Accruing

The principal benefit of GRUSP has been replenishment of the aquifer beneath the East Salt River Valley. The equivalent of 40 percent of the total water storage capacity of SRP's reservoir system for the Salt and Verde rivers has been added to the aquifer for future recovery. As the first ASR project in the Phoenix area, GRUSP was able to store a large volume of CAP water which otherwise would have gone to California. The recharge operation has also improved the quality of groundwater near the site by reducing arsenic and nitrate concentrations. Finally, GRUSP has improved SRP's operational flexibility and the water management practices of several municipalities.

On the West Side: NAUSP

To provide aquifer storage services to the western Phoenix metropolitan area, SRP constructed the New River Agua Fria Underground Storage Project (NAUSP) with four partnering municipalities. Agricultural land was purchased on the eastern bank of the Agua Fria River in its ancestral fluvial system, where favorable hydrogeologic characteristics existed for direct surface groundwater recharge (Paski and Lluria, 2005). The site is on the periphery of a large cone of depression, where considerable land subsidence has occurred and aquifer replenishment is urgently needed (Lluria, 1995).

GRUSP was able to store a large volume of CAP water which otherwise would have gone to California.

NAUSP was completed in March 2007 and stored 21,000 acre-feet of water last year, achieving recharge rates of 1 to 3 feet per day. The facility consists of six off-channel basins with a 126-acre infiltration area. A seventh in-channel basin of 65 acres will be added in 2008. The facility receives water from CAP and the Salt and Verde rivers, plus a small volume of reclaimed water. The waters are blended before recharging. The NAUSP facility is permitted for a maximum volume of 75,000 acre-feet per year, 40 percent of the permit capacity of GRUSP.

During facility development, a few difficulties had to be resolved. The original site in the Agua Fria River channel was abandoned because of its proximity to future gravel mining operations. Topsoil from the agricultural fields had to be removed for construction of the off-channel basins to ensure adequate infiltration rates and eliminate potential agriculture contaminants. The cost of land was high because of its proximity to the recently completed City of Glendale sports center.

NAUSP will provide a much-needed underground storage facility for the area, particularly for the temporary storage of reclaimed water. It will capture flows in the tail end of the SRP system that might otherwise go unused. The recharge activity will improve groundwater quality near the site by diluting the high nitrate concentrations caused by decades of agriculture. Having two recharge facilities, one located near the head of the water delivery system, the other near its terminus, considerably increases the operational flexibility of SRP's water resources management system.

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ASR in Roseville: *Navigating Water Quality Issues*

***Christian E. Petersen** – MWH Americas Inc. and **Kenneth Glotzbach** – City of Roseville*

The City of Roseville, in the Central Valley of California near Sacramento, is studying the feasibility of aquifer storage and recovery (ASR) to maintain water supply reliability during dry periods. An ASR pilot and demonstration project has been underway since 2004 to improve understanding of the hydrogeologic factors affecting well flow and water quality, identify and address regulatory concerns, and evaluate operational considerations associated with augmenting Roseville's water supply with ASR.

Water Supply

The city's current annual surface water supply of 66,000 acre-feet is American River water diverted from Folsom Lake. The city maintains a contract entitlement with the U.S. Bureau of Reclamation for 32,000 acre-feet per year for Central Valley Project supplies and contracts with local agencies for the remaining 34,000 acre-feet per year, some of which is available only in normal and wet years. Roseville may also purchase Section 215 water, released by Reclamation from Folsom Lake in excess of the entitlements

Longer-term testing was needed to understand the fate and transport of DBPs in the subsurface.

and rights of downstream users when it is available, but has not done so yet. Folsom Lake water treated to potable standards at Roseville's water treatment plant is being used for the ASR testing and will also be the supply for the long-term project.

A county policy prevents Roseville from relying on groundwater as a source of supply. Roseville intends to operate its ASR program as a seasonal storage program, but would also like to retain some water in longer-term storage as protection against droughts. ASR is allowed by the county because it does not result in a net take from the basin: the volume of water extracted will not exceed the volume injected and stored in the aquifer.

Testing ASR Feasibility

ASR testing at Roseville is being completed in two phases. First, a short-term pilot test was conducted in 2004 using the Diamond Creek well, which was installed as a dual-purpose injection-recovery well. It is screened from 310 to 450 feet below ground surface in a confined zone of the target aquifer, the Mehrten Formation (see figure, top right), a coarse-grained sand, gravel, and cobble of volcanic origin deposited in a fluvial environment. Three existing wells were used to monitor water level and water quality in the aquifer during the test.

Results from the short-term test indicated that ASR is feasible in Roseville, but that longer-term testing was needed to understand the fate and transport of disinfection byproducts (DBPs) in the subsurface. Therefore, Phase II demonstration testing began in November 2005 and was to be completed in May 2008. Water quality and water levels are again being monitored in the four wells. No problems have yet been encountered regarding well plugging associated with solids accumulation or geochemical precipitation in the well.

Enter the Regulatory Environment

Although drinking-quality water might appear to be ideal to store underground, California's water quality regulators saw it differently. The State Water Resources Control Board oversees nine regional water quality control boards (RWQCBs) that develop and enforce water quality objectives and implement plans to protect the state's waters, recognizing differences in climate, topography, geology, and hydrology. This means that regulation of ASR has evolved inconsistently among regional boards throughout the state.

The Roseville ASR project lies within the purview of the Central Valley RWQCB. CVRWQCB determined that the ASR test project would be regulated under a conditional waiver of *waste discharge* requirements, even though the project is using *drinking water that meets all standards*. The problem is the drinking water contains DBPs at levels greater than the groundwater basin water quality objectives. The waiver allows the test project to proceed as long as DBP concentrations remain below EPA's maximum contaminant levels for a short-term, controlled project. The waiver requires:

- estimation of the aquifer volume to be impacted by injected drinking water;
- establishment of a monitoring program to confirm that stored drinking water is contained within that portion of the aquifer defined above;
- reporting of project status and testing results to CVRWQCB every 60 days;
- submission and implementation of contingency plans to clean up or abate unintended impacts on groundwater quality, should the demonstration project result in a violation of water quality objectives beyond the predicted injection front or after the stored water has been extracted; and
- the extraction phase of testing to continue until DBP concentrations are below basin objectives (1.1 micrograms per liter [µg/l] for chloroform).

Results to Date

Results (see MWH, 2008) indicate that ASR in Roseville has two significant water resource benefits including:

- a rise in regional groundwater levels of approximately five feet during the five-month injection period, and

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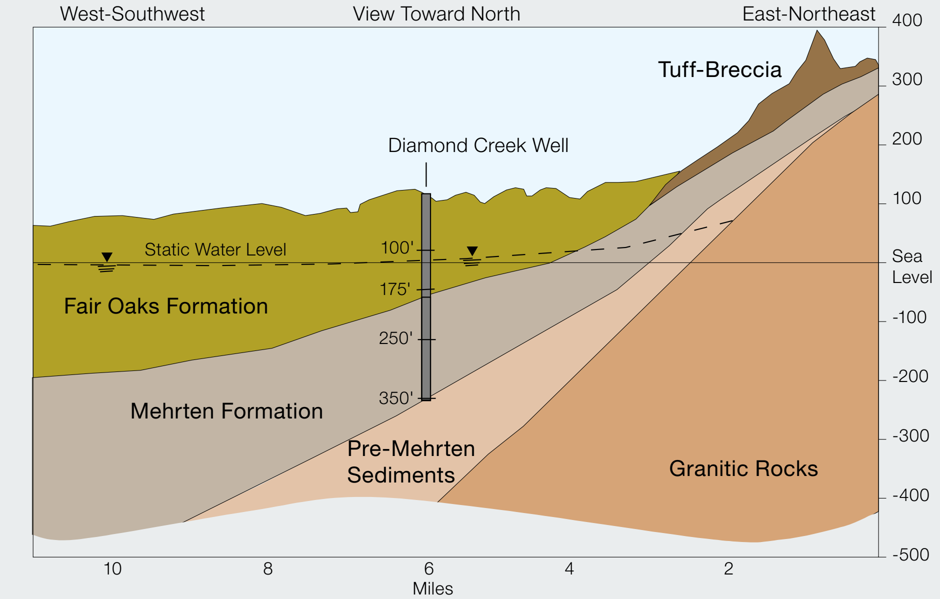

Regional geologic cross-section through Diamond Creek well site. Modified from DWR, 1974.

Changes in concentrations of chloroform (top) and total haloacetic acids (bottom) during demonstration testing in the Diamond Creek well (DCW), three monitor wells (DCMW-1, 91 feet crossgradient of injection; DCMW-2, 193 feet upgradient; and DCMW-3, 402 feet downgradient), and the water treatment plant (WTP), compared to EPA's maximum contaminant level (MCL). Units are micrograms per liter (µg/l). The chloroform plot is nearly identical to that of total trihalomethanes (THM), as chloroform accounts for 90 to 95 percent of THM.

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- a reduction in total dissolved solids (TDS) concentrations in the aquifer from an average of 457 milligrams per liter (mg/l) to 59 mg/l at the beginning of the storage phase, measured at the Diamond Creek Well. The TDS of the water being injected ranged between 47 and 62 mg/l.

The charts on the previous page show the changes in DBP concentrations during each period of the demonstration test. By comparing DBP to conservative constituents such as chloride and fluoride, it appears that haloacetic acids were naturally attenuated in the aquifer during the storage phase of testing: they were not detected after five months of storage. Trihalomethane (THM) concentrations (as represented by chloroform) were reduced during the storage period, but not completely eliminated. The mechanism of THM reduction is not fully understood, but appears to be caused by dilution, again based on correlation with chloride concentrations over the same time period.

Long-Term Plans

Roseville expects to complete the demonstrate test by May 2008 and to have extracted 300 percent of the injected volume in an effort to remove DBPs below basin objectives (chiefly chloroform below 1.1 µg/l). Clearly 100 percent injection followed by 300 percent extraction is not sustainable for long-term operation, but was necessary to comply with the waiver for the testing phase of implementation. Roseville and CVRWQCB now have a better understanding of the water quality implications of a long-term ASR operation.

What's next? Roseville has begun discussions with CVRWQCB management and staff regarding long-term operation of ASR in Roseville and expansion of the program to eventually include up to 12 operating ASR wells over the next three to five years. In striking a balance between the water supply benefit of ASR and the need to protect groundwater quality, it is anticipated that a long-term operational permit will:

- allow a designated portion of the aquifer to be impacted above basin objectives during the operational life of the ASR program;
- establish institutional controls to prevent other beneficial users from accessing the portion of aquifer designated for ASR;
- allow a point of compliance within the aquifer downgradient of the project;
- require a reasonable monitoring program, agreed upon by Roseville and CVRWQCB; and
- likely require that water quality objectives be restored to either pre-project conditions or reasonably achievable conditions at the end of the project.

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ASR Primer, continued from page 17

removed by traditional wastewater treatment processes. Much research is being conducted on the potential health risks associated with introducing reclaimed water to potable aquifers. Lastly, pathogen removal by chlorination can cause formation of disinfection byproducts, such as trihalomethanes, that can persist in some ASR systems (NRC, 2008).

Getting It Back

Recovery is a critical component of any ASR system because the objective is to recover the recharged water, or a nearly equivalent amount, in the future. However, full capture and recovery is not always feasible due to aquifer characteristics and the practical placement of wells. As a result, the potential exists for losing a portion of recharged water. However, water recovery issues can also be political or legal in origin, as when a governing entity intervenes and imposes limitations on the rate or volume of water that can be recovered.

The management, monitoring, and accounting of recharged water are inherently obscure as groundwater is not visible. Therefore, computer models, monitoring wells, and sophisticated accounting systems are employed to accomplish these tasks. Even with these tools it can be challenging to adequately demonstrate control and capture of recharged water. Many western states utilize some form of prior appropriation to allocate scarce water resources. Some states such as Colorado administer groundwater and surface water conjunctively, and others administer these resources discretely. The protection of senior water rights can represent a significant barrier to ASR projects, particularly with respect to accounting and recovery. It must be demonstrated that ASR operations will not cause an out-of-priority diversion of stream flows or native groundwater that is not otherwise replaced.

Source water availability can be the limiting factor for some entities, even when a suitable aquifer and recovery system are available. However, these situations can engender creative solutions such as "borrowing" source water from a surface water provider in exchange for delivering groundwater to the same provider during periods of drought.

ASR is expanding in scope and complexity as more projects are initiated, long-term data become available, monitoring and analytical technologies advance, and the demand for water increases with respect to supply. Not every situation or set of conditions is favorable for implementing ASR, and ASR will not displace the need for surface storage. However, it is a viable alternative and a beneficial water management technique where and when the necessary ingredients exist.

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The Arizona Hydrological Society extends our sincere thanks to the 2007 Symposium Planning Committee, Southwest Hydrology magazine, and SAHRA for their contributions to the 2007 Annual Symposium. Without their efforts, the symposium would not have been such a success.

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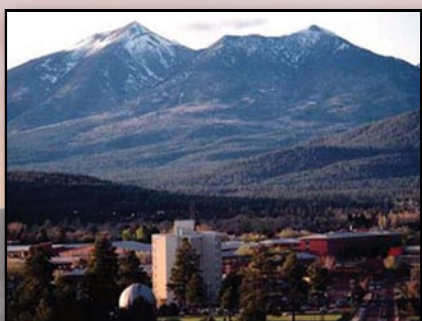

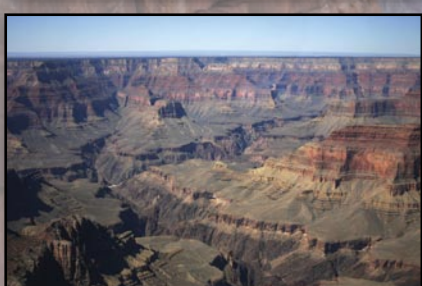

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Dire Predictions for Colorado River Reservoirs

There is a 50 percent chance live storage (water that can be evacuated by gravity) in lakes Mead and Powell will be gone by 2021 if climate changes occur as expected and no changes in water management strategies are made, according to Tim Barnett and David Pierce at Scripps Institution of Oceanography at the University of California, San Diego. Furthermore, the reservoirs have a 50 percent chance of dropping too low to allow hydroelectric power generation by 2017. The researchers performed their analysis using a simple water budget model and reported their findings in a paper accepted for publication in *Water Resources Research*.

The release of the report generated headlines across the country, and some controversy. Among the scientific community, disagreement with the study's approach appears to center on whether the climate prediction models used by the Scripps researchers are sensitive enough at the regional scale to make accurate predictions. The U.S. Bureau of Reclamation recently completed an extensive analysis of Colorado River basin flows, but its researchers based their analyses on tree-ring data to consider the range of historic flows over the last 1,200 years, rather than climate models, which they deemed not scalable to local effects. Disagreement—often colorful—also came from water managers who said the findings are overly alarming: managers would take steps to prevent the dire predictions from coming true.

According to a Scripps news release, the researchers were conservative. They based their findings on the premise that climate change effects started in 2007, even though most scientists consider human-caused changes in climate to have started decades earlier. They based their Colorado River flow on the 100-year average, although actually it has fallen in recent decades and the 500-year average is even lower. Even if water agencies follow their current drought contingency plans, they found, it might not be enough to counter natural forces, especially if the region enters a period of sustained drought or human-induced climate changes occur as currently predicted.

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Visit scrippsnews.ucsd.edu/Releases/?releaseID=876 or www.agu.org (members only).

Mussel Update

You wouldn't think mussels that move at a snail's pace would be able to cross the country like birds and reproduce like rabbits, but it appears that is what's happening. It was only in January 2007 that the first quagga mussels west of the Mississippi River were confirmed in Lake Mead (see *Southwest Hydrology*, Jul/Aug 2007 and Nov/Dec 2007). But in the last several months, news of the invasion has become worse: the prolific quaggas that clog pipelines and machinery and upset ecosystems appear to be thriving in the Colorado River Basin, and their cousins, the zebra mussels (both genus *Dreissena*), has also invaded the West.

In February, the *Las Vegas Review Journal* reported that the quaggas in Lake Havasu and other reservoirs are reproducing three times faster than those in the Great Lakes area, at a rate of six times per year rather than two, according to Bureau of Reclamation quagga coordinator Leonard Willett. He estimated the cost to manage the mussel population and maintain operations in Hoover Dam alone could reach $1 million per year.

Without control, quaggas can clog cooling pipes, causing turbines to overheat, said the newspaper. Control options under consideration are a soil bacterium that targets quaggas (still in development), filters, chemicals such as chlorine, and ultraviolet light. However, most of those approaches require that discharge permits be obtained, noted the article.

The warmer temperatures of Colorado River reservoirs, combined with plentiful food, calcium, and dissolved oxygen appear to be helping the mussels thrive, Willett told the *Review Journal*. He also noted that quaggas seem to prefer flat, stainless-steel structures in relatively slow-moving water to colonize; they dislike copper and brass.

Meanwhile, in January, the California Department of Fish and Game confirmed that zebra mussels had been identified in the San Justo Reservoir south of the San Francisco Bay area. Resource managers have been dreading the arrival of zebra mussels in the West; Reclamation scientists estimated those that were found were around one to three years old, reported the *Hollister Freelance*.

According to the 100th Meridian Initiative, the Lake Mead quagga population is in an explosive growth stage now. Of note, this is the first North American instance of quaggas invading a large water body that was not already invaded by zebra mussels. Quaggas may grow slightly larger and live in deeper waters than zebra mussels.

Visit www.lvrj.com, www.hollisterfreelance.com, and 100thmeridian.org.

Ag, Urban Activities Impact Shallow Groundwater Quality

A new U.S. Geological Survey report links the quality of shallow groundwater in alluvial basins of California, Arizona, Nevada, Utah, and New Mexico to present and past land use and chemicals used in agricultural and urban areas. Chemicals most heavily applied include fertilizers, herbicides, and insecticides. Volatile organic compounds (VOCs) are used in large volumes and associated with products such as plastics, adhesives, paints, gasoline, fumigants, refrigerants, and dry-cleaning fluids. Although shallow

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groundwater is not typically used as a drinking-water supply in these basins, in some areas it could be hydrologically linked to deeper basin-fill aquifer systems that are used for water supply.

The study showed that nitrate concentrations were highest beneath agricultural lands, and exceeded the U.S. Environmental Protection Agency drinking water standard of 10 milligrams per liter in 74 of 272 wells (27 percent) in those areas. Nitrate concentrations generally were lower in urban areas, exceeding the standard in 13 of 179 urban wells (7 percent). Shallow groundwater samples (median well depth of 35 feet) were collected mostly from monitoring wells, but some domestic wells were sampled.

Through geostatistical modeling techniques, the study estimated the probability of exceeding the nitrate standard in shallow groundwater underlying agricultural areas throughout the region. The information can help water quality managers anticipate conditions in unmonitored areas and implement nitrogen reduction strategies in priority areas.

The study also found that concentrations of organic compounds rarely exceeded drinking-water standards, and generally were detected at concentrations less than 1 microgram per liter. The most frequently detected pesticides in shallow groundwater beneath agricultural areas were simazine (28 percent of the wells), atrazine (17 percent), and diuron (13 percent). In urban areas, atrazine (24 percent of the wells), prometon (25 percent), and simazine (17 percent) were most commonly detected.

VOCs were typically detected underlying urban areas. Those most frequently detected were chloroform (in 29 percent of the wells) and PCE (10 percent); they were often found in well-oxygenated groundwater.

Because the quality of shallow groundwater can change relatively quickly, it can be an indicator of land-use stresses that may eventually affect deeper aquifer systems.

The 70-page report, "Effects of Agriculture and Urbanization on Quality of Shallow Groundwater in the Arid to Semiarid Western United States, 1993–2004," is available at pubs.usgs.gov/sir/2007/5179. Also visit water.usgs.gov/nawqa/studies/praq/swpa.

Humans Affect Western Water Flow

The Rocky Mountains have warmed by 2ºF in the last 50 years. Snowpack in the Sierras fell 20 percent and the temperatures there have increased by 1.7ºF. Why? Humans, according to scientists from Lawrence Livermore National Laboratory's (LLNL) Program for Climate Model Diagnosis and Intercomparison, and Scripps Institution of Oceanography. Their research appeared in the Jan. 31 online edition of *Science Express*.

"We looked at whether there is a human-caused climate change where we live, and in aspects of our climate that we really care about," said Benjamin Santer of LLNL and co-author of the paper. "No matter what we did, we couldn't shake this robust conclusion that human-caused warming is affecting water resources here in the Western United States."

By looking at air temperatures, river flow, and snowpack over the last 50 years, the scientists determined that a human-induced increase in greenhouse gases has seriously affected the water supply in the West. The researchers scaled global climate models down to the regional scale and compared the results to observations over the last 50 years. The results were consistent, giving confidence that the same models could be used to predict the future effects of the global scale increase in greenhouse gases on the western United States.

The projected consequences are bleak. By 2040, most of the snowpack in the Sierras and Colorado Rockies would melt by April 1 each year because of rising air temperatures. Earlier snowmelt would lead to a shift in river flows, potentially leading to flooding in California's Central Valley.

Santer said the increase in predicted river flow should be a wake-up call to officials that the water supply infrastructure needs to be updated now, as opposed to waiting until the situation is urgent. As for the warming, existing greenhouse gases in the atmosphere will cause the Earth to continue to warm for the next 80 to 100 years.

Visit www.llnl.gov and www.sciencemag.org/sciencexpress/recent.dtl.

Coachella Valley is Sinking

A new study by the U.S. Geological Survey and Coachella Valley Water District (CVWD) confirms that land subsidence is occurring in areas of substantial groundwater use throughout Coachella Valley, located in the Palm

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Springs area of Riverside County, California. The two agencies initiated the study in 1996 when it was first believed subsidence was occurring there. USGS scientists used Global Positioning System (GPS) surveying and a satellite mapping process known as interferometric synthetic aperture radar (InSAR) to document drops in elevation between 1996 and 2005.

At all of the GPS benchmarks, some subsidence occurred between 1996 and 2005. At three benchmarks, the drop was less than an inch, while at three others subsidence was about one foot. At one benchmark, a one-foot drop in land-surface elevation happened from 2000 to 2005.

"The subsidence rates in many areas have more than doubled since 2000," said Michelle Sneed, USGS scientist and lead author of the study. "All the subsiding areas are near sites where groundwater levels declined between 1996 and 2005, and some water levels in 2005 were at the lowest levels in their recorded histories."

The research, which has cost about $790,000 since 1995, has been funded primarily by USGS and CVWD, with the City of Palm Desert contributing $17,000.

Since the 1920s, groundwater has been a major source of agricultural, municipal, and domestic supply in the Coachella Valley, resulting in significant groundwater pumping that has contributed to water-level declines of as much as 100 feet. The heavy groundwater use, in turn, has led to subsidence.

In 2001, CVWD adopted a comprehensive Water Management Plan (WMP) to address the groundwater overdraft problem. The plan takes a three-tiered approach to groundwater management: increasing the imported water supply, promoting and assisting conservation efforts, and providing existing groundwater users an alternative source of water.

CVWD planned and prioritized nearly 50 programs and projects for the

WMP. Current efforts aimed at keeping groundwater levels stable include construction of the $70 million Mid-Valley Pipeline to enable as many as 50 golf courses to use a blend of recycled water and Colorado River water in lieu of groundwater, and a $40 million groundwater recharge facility.

The 41-page report, "Detection and Measurement of Land Subsidence Using Global Positioning System Surveying and Interferometric Synthetic Aperture Radar, Coachella Valley, California, 1996-2005," is available at pubs.usgs.gov/sir/2007/5251/pdf/sir_2007-5251.pdf.

Global Warming Linked to Extreme Precipitation

A recent report published by Environment America found that global warming is likely to cause an increase in the intensity of precipitation events regardless of whether the total annual rainfall increases or decreases.

Researchers evaluated trends in the frequency of storms with extreme levels of rainfall or snowfall across the contiguous United States over the last 60 years. They analyzed daily precipitation records from 1948 through 2006 at more than 3,000 weather stations, and examined patterns in the timing of heavy precipitation relative to the local climate at each. They found that storms with extreme amounts of rain or snowfall are happening more often.

According to the report, global warming increases the intensity of precipitation in two key ways. First, by increasing the temperature of the land and the oceans, global warming causes water to evaporate faster. Second, by increasing air temperature, global warming enables the atmosphere to hold more water vapor. These factors combine to make clouds richer with moisture, making heavy downpours or snowstorms more likely.

The researchers found that storms with extreme precipitation have increased in frequency by 24 percent across the continental United States since 1948. New England experienced the largest increase in extreme precipitation frequency, at 61 percent. "Extreme" precipitation was defined relative to the local climate at each weather station as any storm with a 24-hour precipitation total equal or larger than the least of the 59 largest one-day precipitation totals over the 59-year period of analysis.

In the Southwest, where total annual precipitation is projected to decline, extreme downpours may punctuate longer periods of relative dryness, increasing the risk of drought. The increase since 1948 in frequency of storms with extreme precipitation ranges from 26 to 32 percent for Arizona, California,

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Colorado, Nevada, Texas, and Utah, up to 44 percent for New Mexico.

The researchers note that their findings are consistent with previous studies of extreme precipitation patterns. In 1999, studies at the Illinois State Water Survey and the National Climatic Data Center (NCDC) found that storms with extreme precipitation became more frequent by about 3 percent per decade from 1931 to 1996. In 2004, scientists at NCDC concluded that most of the observed increase in storms with heavy and very heavy precipitation levels since the early 1900s had occurred in the last three decades. In other words, the change is relatively recent. Furthermore, NCDC found that extremely heavy storms are increasing in frequency more rapidly than very heavy storms—which in turn are increasing in frequency more rapidly than heavy storms.

Environment America is a federation of state-based, citizen-funded environmental advocacy organizations with staff in 23 states and Washington, D.C. The 48-page report is available at environmentamerica.org.

Sandia Developing Integrated Energy-Water Model

Researchers at Sandia National Laboratories are developing an interactive computer model that integrates water and energy demands for planning and management purposes. The objective of the model is to "allow energy and water producers, resource managers, regulators, and decision makers to look at the different tradeoffs of water use and energy production caused by uncertainties in population, energy demand, climate, and the economy," said Vince Tidwell, principal investigator.

Concurrent with the energy-water modeling, the research team will put together a set of optimization tools that could be used to assist in the siting of power plants, balancing the energy portfolio (including fossil, nuclear, and renewable fuels) to keep pace with growing power demands, and in making decisions about when to build the next power plant. Cost, availability of water and fuels, access to transmission lines, and greenhouse gas emissions all need to be considered.

The research is in its second year of three-year funding. The team is now compiling data to go into the program. The model will allow users to tailor their investigations to meet specific needs. For example, they can get results on energy and water scenarios at the national, state, or local levels and will be able to look at specific watersheds. This would be particularly helpful in determining water-energy trends in states like New Mexico where most of the power is generated at in-state plants but used by people outside the state.

"Energy data is provided by DOE, and water information is coming from different agencies," says Peter Kobos, who is also doing energy modeling at Sandia. "The challenge will be to have enough data to tell a story. We think we do. If not, we'll identify gaps and address them as the project progresses."

Visit www.sandia.gov.

Business Directory

Damming Grand Canyon: The 1923 USGS Colorado River Expedition

by Diane E. Boyer and Robert H. Webb, Utah State University Press, 2007, $35

*Reviewed by **Betsy Woodhouse** – Southwest Hydrology, University of Arizona*

In 1922, the Colorado River Compact allocated the river's water among the seven basin states. However, no means to control that water existed. The U.S. Geological Survey and the much younger U.S. Reclamation Service were struggling to figure out their respective roles, and both wanted a say in control of the Colorado. The notes and maps of John Wesley Powell's earlier Grand Canyon explorations were not reliable enough for their engineering needs: a detailed map was needed.

For nearly three months in the summer and fall of 1923, 12 men in four aged, wooden boats traveled through and mapped 29 potential dam sites in Grand Canyon. *Damming Grand Canyon: The 1923 USGS Colorado River Expedition* sets the stage for this wild adventure and then provides a day-by-day account as recorded in the participants' journals.

Prelude to the Expedition

The book begins with the history of development of the Colorado River, including early attempts to control it. It delves into politics as well, discussing the formation and early leadership of USGS and Reclamation and their disagreements over where dams should be built and how the decision should be made. Finally, it describes how the 1923 expedition was organized and the dynamics of the group.

Journal Entries

The expedition included engineers, geologists, topographers, boatmen, and cooks. Eight of the men kept journals; their entries, supplemented with narrative, make up the middle part of the book.

The journal entries are daily; often several men's accounts of the same day are included. Personal notes, such as what they ate or heard on the radio in the evening, add interest. The entries also offer insight about the pre-dam Grand Canyon. They wrote of abundant flying insects and the scarcity of sandbars in Upper Granite Gorge, conditions typically—and incorrectly—attributed today to the presence of dams, according to the authors.

Virtually no mention was made of environmental or aesthetic impacts should a dam be built in the canyon, except in one brief entry where the trip leader noted that a proposed damsite might have engineering drawbacks, but "at least it wouldn't inundate Bright Angel Creek and Phantom Ranch."

Aftermath

The book ends with a description of the subsequent careers of the expedition members, the outcome of their work, and the paths the agencies followed.

For readers lacking familiarity with the agencies' histories and the individuals involved, it can take some time to keep it all straight. The book is heavily footnoted, which is variously distracting, helpful, and interesting. Some footnotes explain the significance of a particular entry, describe how the reports conflict, or elaborate on a relationship. Without the footnotes, the journal entries alone would not convey the same level of conflict among the group.

Damming Grand Canyon also contains abundant photos from the expedition that provide interesting insight on the men, their equipment, and how the canyon looked at that time.

This book has appeal for a diverse audience ranging from those interested in USGS/Reclamation history to those familiar with the canyon and its geology, river rafters, environmentalists interested in fate the canyon escaped, and those who dream of big dams.

MAY 2008

May 6-8 Midwest Geosciences Group. **Assessing Ground Water Movement and Contaminant Migration Through Aquitards: From Field Investigation to Hydrogeologic Analysis**. Naperville, IL. *www.midwestgeo.com/fermi2008.htm*

May 6-9 Association of California Water Agencies. **ACWA Spring Conference and Exhibition**. Monterey, CA. *www.acwa.com/events/SC08/*

May 12-16 Environmental and Water Resources Institute of ASCE. **World Environmental and Water Resources Congress: Sustainability from the Mountains to the Sea**. Honolulu, HI. *content.asce.org/conferences/ewri2008/*

May 14-16 33rd Colorado Foundation for Water Education. **Colorado Water Workshop: Mining, Energy, and Water in the West**. Gunnison, CO. *www.western.edu/water/*

May 15 Arizona Hydrological Society. **Surface Water Seminar**. Phoenix, AZ. *www.azhydrosoc.org*

May 18-23 Association of State Floodplain Managers. **2008 Conference: A Living River Approach to Floodplain Management**. Reno, NV. *www.floods.org/Conferences%2C%20Calendar/Reno-Sparks.asp*

May 19-21 International Ground-Water Modeling Center. **MODFLOW and More: Ground Water and Public Policy**. Golden, CO. *www.mines.edu/igwmc/events/modflow2008/*

May 28-31 U.S. Society for Irrigation and Drainage Professionals. **Urbanization of Irrigated Land and Water Transers**. Scottsdale, AZ. *www.uscid.org/08conf.html*

JUNE 2008

June 3-6 National Ground Water Association. **The New MODFLOW Course**. Las Vegas, NV. *www.ngwa.org/development/shortcourses.aspx*

June 4-6 Water Education Foundation. **Bay-Delta Tour**. Sacramento-San Joaquin Bay, CA. *www.water-ed.org/tours.asp#tourdates*

June 8-12 American Water Works Association. **ACE08: Annual Conference and Exposition**. Atlanta, GA. *www.awwa.org/ace08/*

June 9-10 National Ground Water Association. **Environmental Forensics: Methods and Applications** (short course). Greenwood Village, CO. *www.ngwa.org/development/calendar.aspx*

June 9-11 Groundwater Resources Association of California. **Vadose Zone Hydrology, Contamination, and Modeling Short Course**. Los Angeles, CA. *www.grac.org/*

June 9-12 Utton Transboundary Resources Center, University of New Mexico School of Law. **The Winters Centennial: Will Its Commitment to Justice Endure?** Santa Ana Pueblo (near Albuquerque), NM. *uttoncenter.unm.edu/winters_conference.html*

June 24 Arizona Water Resources Research Center. **The Importance of the Colorado River for Arizona's Future**. Phoenix, AZ. *ag.arizona.edu/azwater/programs/conf2008/*

JULY 2008

July 6-10 Numerous agencies and organizations. **Computational Methods in Water Resources: XVII International Conference**. San Francisco, CA. *www-esd.lbl.gov/CMWR08/*

July 14-18 HCI Publications. **HydroVision 2008** (conference on hydropower). Sacramento, CA. *www.hcipub.com/hydrovision/*

July 26-30 Soil and Water Conservation Society. **2008 Annual Conference**. Tucson, AZ. *www.swcs.org/en/conferences/2008_annual_conference/*

AUGUST 2008

August 12-13 Groundwater Resources Association of California. **Climate Change: Implications for California Groundwater Management**. Sacramento, CA. *www.grac.org/climate.asp*

SEPTEMBER 2008

September 7-10 WateReuse Association. **23rd Annual WateReuse Symposium: Water Reuse and Desalination**. Dallas, TX. *www.watereuse.org/2008Symposium/Index.html*

September 15-18 National Ground Water Association. **Fundamentals** (Sept. 15-16) **and Applications** (Sept. 17-18) **of Ground Water Geochemistry** (short course). Denver, CO. *www.ngwa.org/development/shortcourses/FundamentalsGroundWaterGeochemistry235.aspx*

September 20-24 Arizona Hydrological Society and American Institute of Professional Geologists. **2008 Annual Symposium: Changing Waterscapes and Water Ethics for the 21st Century**. Flagstaff, AZ. *www.azhydrosoc.org*

September 24-26 Groundwater Resources Association of California. **17th GRA Annual Meeting and Conference - Groundwater: Challenges to Meeting Our Future Needs**. Costa Mesa, CA. *www.grac.org/am08.asp*