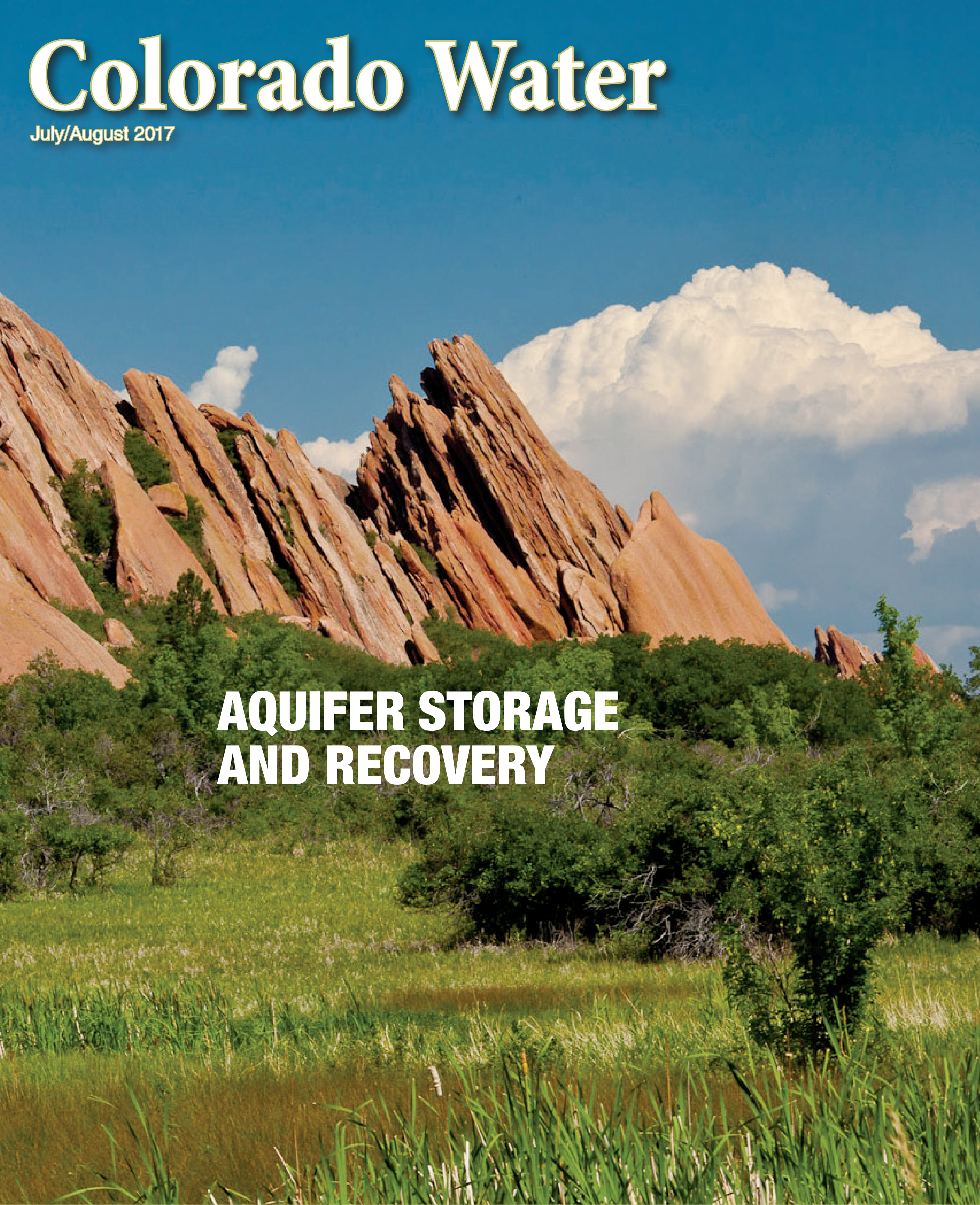
Colorado Water

July/August 2017



AQUIFER STORAGE AND RECOVERY

Colorado State University

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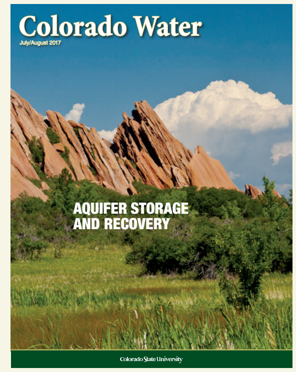

On the cover: Roxborough State Park. Photo by Greg Willis

From our Water Experts

From our Cooperators

In Every Issue

COLORADO **WATER**

Volume 34, Issue 4

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Director's LETTER

Settlers who came west quickly learned the rivers swell for only a few, brief summer months and that drought is an unpredictable but not uncommon occurrence. Building a modern civilization and the agriculture to sustain it would require the ability to store water to finish crops and provision cities after the annual runoff subsided. The drought period of 1887-1897 placed would-be civilization builders on notice – water in the arid lands was uncertain and precious, and contrary to popular belief, rain did not follow the plow. Most of the dams that private investors and local agencies could afford to build were completed by 1900, and westerners turned to Congress for help. Their demands and lobbying resulted in the Reclamation Act of 1902, and the period of big dam building began in earnest. Eastern taxpayers subsidized the building of dams on large rivers across the West to settle and "reclaim" the land. World War I, the Great Depression, and World War II solidified the success of these projects. Colorado benefitted from the Uncompahgre, Colorado-Big Thompson Project, Fry-Ark, Aspinall Unit, Dolores, and other federal projects. The West entered a period of sustained population growth following WWII that continues to this day.

The environmental movement of the 1960s led to sweeping environmental legislation in the early 1970s during the Nixon administration, and the public's appetite for large dam projects began to wane. Budget deficits led to President Jimmy Carter's "hit list" of water projects in the late 1970s, profoundly changing the direction of the United States Bureau of Reclamation. The eventual veto of Denver Water's planned Two Forks dam on the South Platte River above Denver by the Environmental Protection Agency's Administrator William Reilly in 1990 completely altered the reservoir building landscape. Since that time, only a few major reservoir projects have been built in Colorado – Reuter Hess, Aurora, and Nighthorse Reservoirs. Obtaining needed permits for large reservoir projects have become increasingly expensive, uncertain, and difficult. Northern Water completed their feasibility study of Glade Reservoir in 2001, filed for a federal permit for the Northern Integrated Supply Project in 2004, and still they await their final permit today.

Meanwhile, as Colorado and the West continue to grow, water demand only increases, while our reservoirs age and accumulate silt. The expense and uncertainty of new reservoir projects leads engineers to seek new solutions. Certainly, rehabilitation and enlargement of existing reservoirs is one pathway. But, can we take advantage of naturally occurring porosity underground to store excess water in times of plenty and withdraw it during drier times? Is aquifer storage cost effective and does our water law accommodate this approach? Does Colorado have promising geologic formations in feasible locations? How do we know the water stored underground will be there to recover when we need it? What about water quality aspects? What are the energy requirements and the carbon footprint of aquifer storage and recovery?

The focus of this issue of the *Colorado Water* newsletter is subsurface water storage, building on CSU's November 2016 Subsurface Water Storage Symposium. Speakers at the symposium noted that subsurface water storage has been widely embraced in Texas, Arizona, Utah, California, and internationally. In Colorado, there are just four active well-based subsurface water storage projects currently underway, but university scientists are actively evaluating subsurface water storage alternatives. The question is where and when does subsurface water storage fit into Colorado's needs? No one expects that subsurface water storage will replace surface reservoirs in Colorado but could they be a significant part of the larger system? Special thanks to Dr. Tom Sale and his colleagues for advancing the engineering, economics, geophysics, and policy aspects of subsurface water storage in Colorado and setting the stage for future work on the topic.

Director, Colorado Water Institute

Tom Sale

OVERVIEW

Subsurface Water Storage Symposium

Dr. Tom Sale, Associate Professor, Civil and Environmental Engineering, Colorado State University

A one-and-a-half-day symposium addressing subsurface water storage was held at Colorado State University (CSU) on November 15 and 16, 2016. The symposium was sponsored by the CSU Water Center with support from the Walter Scott Jr. College of Engineering and the Warner College of Natural Resources. The focus of the meeting was to share emerging knowledge, collaboratively debate critical issues, and prioritize future work to address key water management challenges. Approximately 100 people participated, including individuals from local government, state government, industry, academia, and students. The following document summarizes the meeting's focus, scope, and outcomes.

Tom Sale

Focus

Per the 2016 White House Water Summit, "*…there is a need to shine a spotlight on the importance of cross-cutting, creative solutions to solving the water problems.*" Similar themes can be found in the State of Colorado's 2016 Water Plan, including "storage as we conserve" and in the commitments, being made by water districts across Colorado and the western U.S.

An emerging "*cross-cutting, creative solution*" is the use of subsurface water storage in conjunction with existing surface water systems. Subsurface water storage projects can simplify permitting for new storage, provide an economical alternative to surface storage, minimize environmental impacts of new water storage, enhance the resiliency of water systems, and conserve water by reducing seepage and evaporative losses.

> "…there is a need to shine a spotlight on the importance of cross-cutting, creative solutions to solving the water problems."

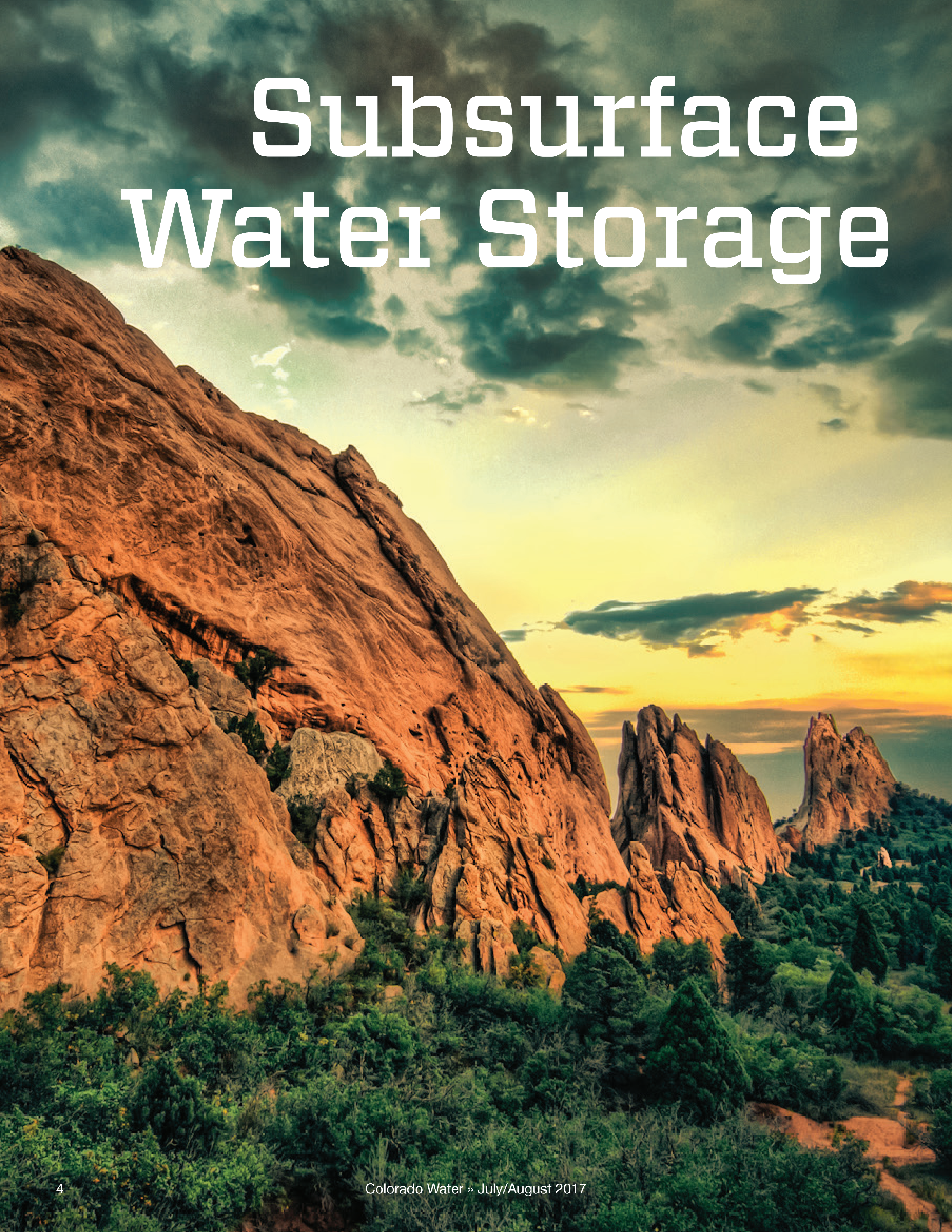
Scope

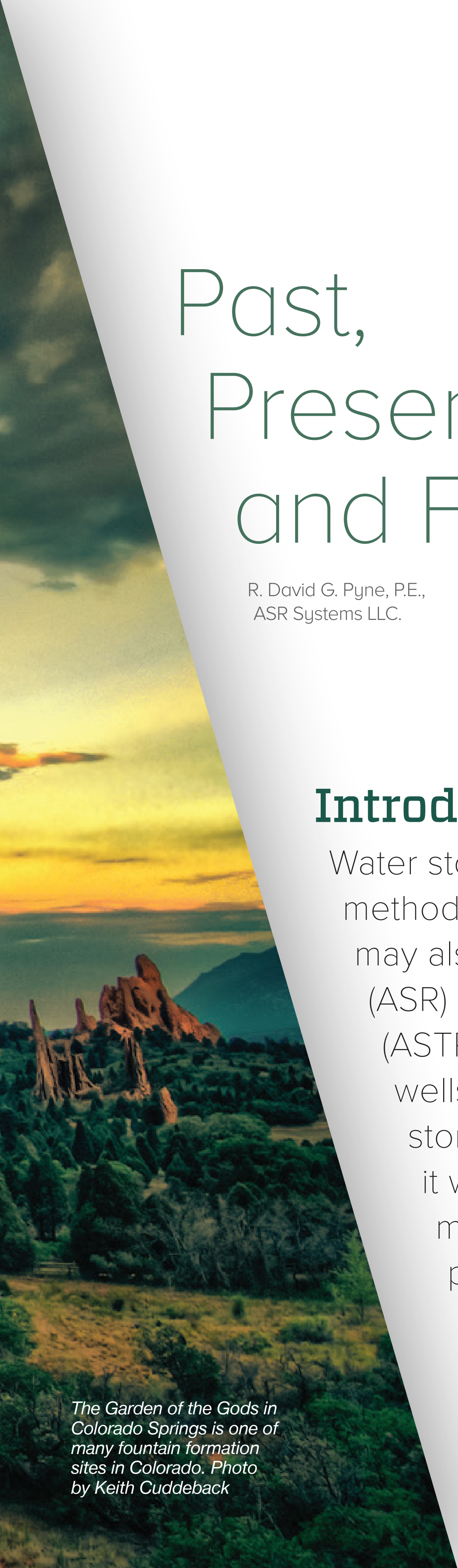
David Pyne was the keynote speaker and guiding participant in the symposium. Pyne is an internationally recognized leader in the field of subsurface water storage and is the widely acclaimed author of *Groundwater Recharge and Wells: A Guide to Aquifer Storage Recovery* (1995) and *Aquifer Storage Recovery: A Guide to Groundwater Recharge* (2005). Critical elements of the agenda for the first day included: 1) current best practices for subsurface water storage, 2) exploring water rights and permitting issues, 3) introducing new enabling technologies including research tools developed at CSU, and 4) sharing insights from active subsurface water storage projects. The first day concluded with a group dinner in Fort Collins. On the second day, participants convened in the morning for a lively review of findings, evaluations of constraints, and debate of areas for future investment.

Outcomes

The symposium was a great success. New collaborations were built, critical knowledge was shared, and vision for the future of subsurface water storage in Colorado was advanced. Meeting notes including meeting presentations are available at: http://www.engr.colostate.edu/CCH/2016_SWS_Symposium_Notes.docx. For the organizers, the greatest outcome was participants repeated departing comment," When will we do this again?"

Subsurface Water Storage





The Garden of the Gods in Colorado Springs is one of many fountain formation sites in Colorado. Photo by Keith Cuddeback

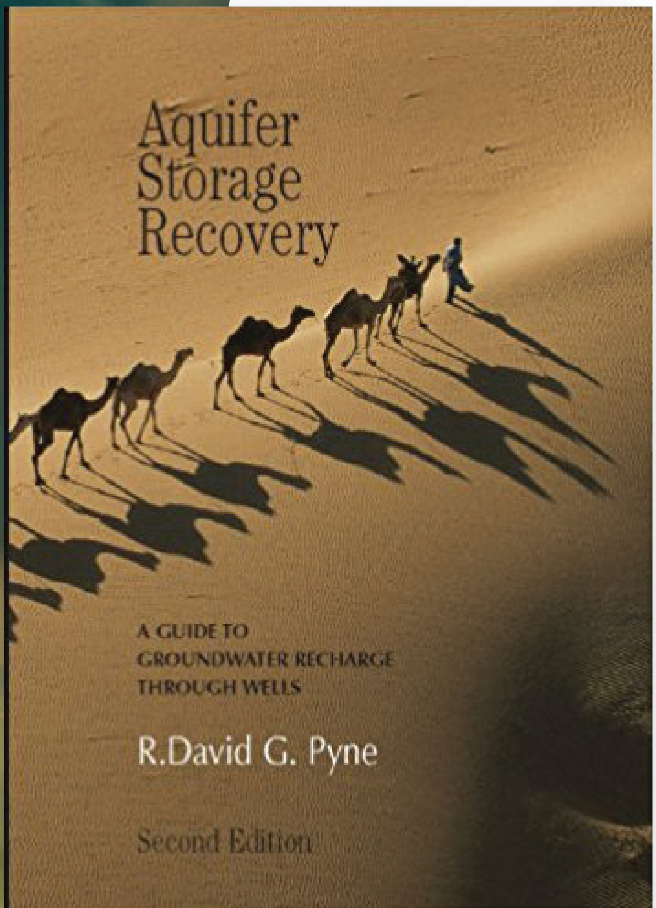
Past, Present, and Future

R. David G. Pyne, P.E.,
ASR Systems LLC.

Introduction

Water storage may be through surface recharge methods such as ponds and river channels. It may also be through Aquifer Storage Recovery (ASR) wells, Aquifer Storage Transport Recovery (ASTR) wells, Vadose Zone wells or Recharge wells. The objective is to get the water into storage during wet months and years so that it will be available for recovery during dry months and extended droughts. This paper primarily addresses ASR wells.

Jean Arthus Bertrand France



Cover Art for Aquifer Storage Recovery: A Guide to Groundwater Recharge through Wells.

To date, 29 different ASR objectives have been identified, meeting different needs at different sites. The most common of these are seasonal storage, long-term storage, or "water banking" for droughts and emergency storage. Others objectives include, but are not limited to, diurnal storage, disinfection byproduct reduction, restoring groundwater levels, controlling subsidence, maintaining distribution system pressures and flows, aquifer thermal energy storage (ATES), reducing environmental effects of streamflow and/or reservoir diversions, agricultural water supply, nutrient reduction in agricultural runoff, enhanced wellfield production, delaying expansion of water treatment facilities, storing reclaimed water for indirect potable reuse, stabilizing aggressive water, hydraulic control of contaminant plumes, maintenance or restoration of aquatic ecosystems, and achieving water supply reliability. An initial step in any ASR program is to conduct a feasibility study, and an early task in any feasibility study is to identify and prioritize the project goals. This then guides the location of the project and the appropriate selection of the storage aquifer.

Water sources for ASR recharge are primarily drinking water, however increasingly they are for highly-treated reclaimed water, groundwater from overlying, underlying or adjacent aquifers, or partially-treated surface water. Storage aquifers are fresh, brackish, and saline. About one-third of all ASR wells store water in brackish aquifers, while almost all stored fresh water in aquifers have at least one water quality constituent that is unwanted in the recovered water. ASR storage aquifers are confined, semi-confined, or unconfined. Storage aquifer lithologies can consist of sand, clayey sand, gravel, sandstone, limestone, dolomite, basalt, and glacial deposits. It is not uncommon to "stack" ASR storage intervals vertically, utilizing different aquifers or producing intervals at the same location.

ASR well depths range from about 150 ft to 3,000 ft. Thickness of storage intervals range from 20 ft to 400 ft. Individual ASR well yields range from a few hundred gallons per minute (GPM) to eight million gallons per day (MGD). Wellfield production capacities to date are up to 157 MGD (Las Vegas), with several larger wellfields in the early design stage with capacities up to 400 MGD.

The principal drivers for ASR have been the following: cost-effectiveness relative to other water management options, proven success, ability to develop in small phases, adaptability to meet a wide variety of water management needs, and environmental and water quality benefits. Wells have a small storage footprint compared to surface reservoirs and they can be utilized to maintain minimum flows and levels. They do not have significant losses to evapotranspiration, however they do have to address lateral movement of the water stored underground. Most ASR wells store water in deep aquifers where lateral movement is typically very slow. For most ASR wells, the storage bubble radius is less than 1,000 ft.

Integrated Operation of Reservoirs and Wells

A great opportunity exists to integrate design and operation of surface reservoirs and wells. Often the storage volume available underground is greater than that which can be achieved in surface reservoirs, while requiring very little land for wellfield construction. Surface reservoirs are relatively expensive compared to wells but they can capture water rapidly, transferring it slowly to storage underground through wells. Treatment of the surface water is typically needed, not only to meet regulatory criteria but also to avoid excessive well clogging due to particulates, microbial, or geochemical reactions. Most ASR wells store water meeting all drinking water standards, while some have water quality criteria exemptions for one or more secondary (aesthetic) criteria, particularly for aquifers where ambient groundwater quality exceeds these criteria. During droughts when reservoir levels are low, the stored water is recovered for use. The integrated operation of surface reservoirs and ASR wells can achieve levels of overall reliability more efficiently than either technology can achieve by itself.

Control of the Water Stored Underground

Legal, institutional, and political issues are usually the greatest factors affecting whether an ASR program progresses. Each state has its own evolving slate of these issues and constraints. Progress is often stalled pending confirmation that stored water can be recovered by the entity storing the water, not by some other entity. This may be achieved by owning or controlling land use on property surrounding the ASR well to a sufficient distance that the storage bubble underground is effectively controlled. This could be through land acquisition, lease or easement, municipal or county ordinance, or state legislation. There are many Wellhead or Wellfield Protection Areas (WPA) nationwide, most of which are efforts to protect wells and wellfields from contamination by inappropriate surrounding land use. For many ASR wellfields, the same WPA approach may be adapted to reserve specific aquifers, within certain defined areas, for ASR storage. Compensation to the surrounding landowners may be needed to achieve the intended result.

Economics

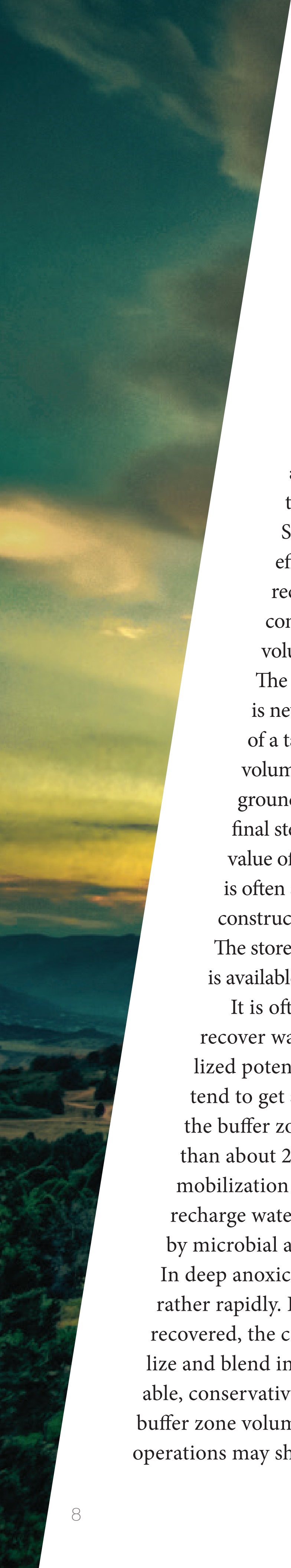
Storing treated drinking water in ASR wells to meet water supply and reliability needs can usually be achieved at less than half the capital cost of other water supply alternatives. In many cases the capital cost savings are as much as 90%. If pre-treatment or post-treatment of the stored water is needed, then ASR costs increase but are usually still cost-effective. Comparison of alternative water supply measures should be made in two different units: $/gallon per day of ASR capacity, and $/1,000 gallons of recovered water. Alternative units might be $/acre ft/ day ($/AFD) and $/acre foot ($/AF). Both types of units are valid measures, however seasonal storage and recovery of a relatively small annual volume can be highly cost-effective if it eliminates the need for water treatment plant expansion to meet short duration peak demands, yet may tend to have a very high unit cost in terms of $/1,000 gallons or $/AF. A suggested basis for comparison with other water supply alternatives would be $/AF for achieving 100% reliability during a design drought event, or a repeat of the Drought of Record, which typically extends for several years and requires large storage volumes that often exceed the reliable capacity of surface reservoirs.

Target Storage Volume

Almost all ASR wells store water in an

Principal Drivers for ASR

- Cost-effectiveness relative to other water management options
- Proven success
- Ability to develop in small phases
- Adaptability to meet a wide variety of water management needs
- Environmental and water quality benefits



aquifer that has one or more water quality constituents that are not wanted in the recovered water. At some sites, unwanted constituents in the recharge water attenuate naturally underground. Examples include iron, manganese, hydrogen sulfide, arsenic, selenium, chromium, fluoride, chloride, total dissolved solids, nutrients, disinfection byproducts, bacteria and viruses. Experience has shown that initial formation of a Target Storage Volume (TSV) is usually effective at ensuring acceptable recovered water quality. The TSV is comprised of two parts: a buffer zone volume and a stored water volume. The buffer zone is formed first and is never recovered. It is like the walls of a tank, separating the stored water volume from the surrounding ambient groundwater. It may be considered the final step in ASR well construction. The value of the water forming the buffer zone is often amortized along with the cost of constructing and equipping the ASR well. The stored water volume is then added and is available for recovery when needed.

It is often tempting, but inadvisable, to recover water from the buffer zone. Mobilized potential contaminants such as arsenic tend to get adsorbed and concentrated in the buffer zone, usually not extending more than about 200 ft from an ASR well. Arsenic mobilization ceases when the oxygen in the recharge water has been consumed, whether by microbial activity or geochemical reactions. In deep anoxic aquifers this usually occurs rather rapidly. If the buffer zone is inadvertently recovered, the contaminants will tend to remobilize and blend into the recovered water. A reasonable, conservative starting assumption is that the buffer zone volume is 50% of the TSV. Subsequent operations may show that a lower percentage is sufficient, particularly in unconsolidated, fresh aquifers. The TSV is often formed over a few annual cycles, during each of which up to half of the cumulative volume stored is recovered.

Challenges to ASR Implementation

While each ASR project has its own set of engineering, hydrogeologic, geochemical, and other technical and scientific issues, most projects that follow a proven, phased pathway to ASR implementation overcome these challenges and progress toward implementation. The principal challenges are the legal, regulatory, and policy framework that, in some areas, are not well-matched to the technical realities. Great progress has been made in the last few years, particularly in California, Texas, and Florida, and at the federal (EPA) level, regarding the legal and regulatory framework for ASR, reducing or removing obstacles to storing water underground. Political issues are often significant since "water is power". The control of water is therefore the currency of personal, regional, and national ambitions.

> "Storing treated drinking water in ASR wells to meet water supply and reliability needs can usually be achieved at less than half the capital cost of other water supply alternatives. In many cases the capital cost savings are as much as 90%."

For some people and interests, ASR is too cost-effective. More capital-intensive projects may be viewed more favorably and achieve widespread support. For such situations, a suggested approach is to increase the cost further, combining ASR with the favored water management option, perhaps doubling the water supply yield while increasing the cost by only 10%.

A common constraint is the general lack of awareness of the broad range of ASR applications that have been found beneficial at different sites. A recommended initial task in any ASR feasibility study is to review the possible applications, identify those that are pertinent to the selected project, and then prioritize the short list. The resulting selection provides a good framework for ASR planning and design.

Public opposition to ASR has arisen in a few areas. Specifically, opposition to the potential contamination of public drinking water supplies from public and private wells due to storing water underground has come up because of a lack of understanding that stored water must meet drinking water standards. Misinformation has been disseminated, confusing some people. This is unfortunate but is not unique to ASR. It is a reality for the world in which we live.

Suggestions for Subsurface Water Storage in Colorado

1. Start with conducting an ASR Feasibility Investigation. Then proceed with design, permitting, and construction, expanding in phases and learning as you go.
2. For storage aquifers with poor water quality, or for which there are concerns regarding potential geochemical reactions, manage ASR wellfields so that cumulative volume recovered does not exceed cumulative volume stored.
3. Operate ASR wellfields by initially forming and then maintaining the Target Storage Volume (TSV), including a buffer zone.
4. Develop ASR Wellfield Protection Area (WPA) provisions that work for Colorado, particularly for shallow, alluvial subsurface storage systems.
5. Clearly establish that storage of water through ASR wells, and recovery of the stored water for beneficial uses when needed, is a beneficial use of water, along with municipal, industrial and agricultural uses of water.
6. Establish that stored water recovered from ASR wells is not subject to any production limits applicable to native groundwater.
7. Provide time and distance for natural processes underground that enhance water quality.
8. Establish a single regulatory framework that is consistent statewide, or coordinated ASR regulation by multiple agencies.
9. Avoid use of the term "injection" as applied to ASR wells. Instead use the term "recharge." Semantics is everything.

R. David G. Pyne, P.E.

About the Author

David Pyne is the President of ASR Systems LLC., providing ASR and related consultant services nationwide and in several other countries. He pioneered the development of ASR technology, beginning in Florida during 1979. He is the author of "Aquifer Storage Recovery: A Guide to Groundwater Recharge Through Wells," now in its second edition (2005). He is a civil engineer with a P.E. license in several states. He has a BSCE degree from Duke University and an MSE degree from the University of Florida. He can be contacted at **dpyne@asrsystems.ws**.

Opportunities and Hurdles for Aquifer Storage in Colorado

Ralf Topper, Certified Professional Geologist, State of Colorado: Colorado Division of Water Resources (Retired)

Introduction

A recent subsurface water storage symposium held at Colorado State University (CSU) highlighted a renewed interest in this alternative water management strategy. Increasing storage is an integral theme of Colorado's 2016 Water Plan, and has been a focus of Front Range water managers since the rejection of the Two Forks project by the Environmental Protection Agency (EPA) in 1990. Expanded surface-water storage remains the preferred infrastructure option of Colorado's water managers in part because of an entrenched institutional mindset, but also in response to restrictions in Colorado water law. The greatest opportunity, however, to increase water storage in the state is to store excess water below ground utilizing the unsaturated storage capacity in aquifers. Aquifers exist as natural capital infrastructure with storage, transmission, and treatment capacities. Subsurface water storage in aquifers significantly reduces the financial, permitting, environmental, security, and socio-economic hurdles associated with construction of new surface water reservoirs. Storing water underground avoids the massive losses to evaporation experienced by surface-water reservoirs in the semi-arid west, and greatly reduces the environmental impacts of changes in the natural flow of rivers and streams. State sponsored studies have identified numerous subsurface storage opportunities with large storage volumes.

Terminology

Aquifer recharge (AR), formerly known as "artificial" recharge, is defined as any engineered system designed to introduce water to, and store water in, underlying aquifers whether the water is recharged at the surface or underground. Aquifer storage and recovery (ASR) adds the extraction component to the water being stored and is typically implemented through wells, though for tributary aquifers it might be possible to recover stored water through accretions to a surface stream. The American Society of Civil Engineers has been promoting the term managed aquifer recharge (MAR) as an umbrella term for a range of technologies. MAR is the intentional recharge of water to suitable aquifers for subsequent recovery or to achieve environmental benefits; the managed process assures adequate protection of human health and the environment. MAR has also been adopted by the National Groundwater Association as the preferred terminology.

Studies Quantifying Aquifer Storage Capacities

It is easy to recognize and grasp storage volumes in a big surface-water reservoir full of water, versus visualizing the vast potential groundwater reservoir beneath the ground. In 2004, the Colorado Geological Survey (CGS) published a reconnaissance level, statewide assessment of available storage capacities in the state's alluvial and bedrock

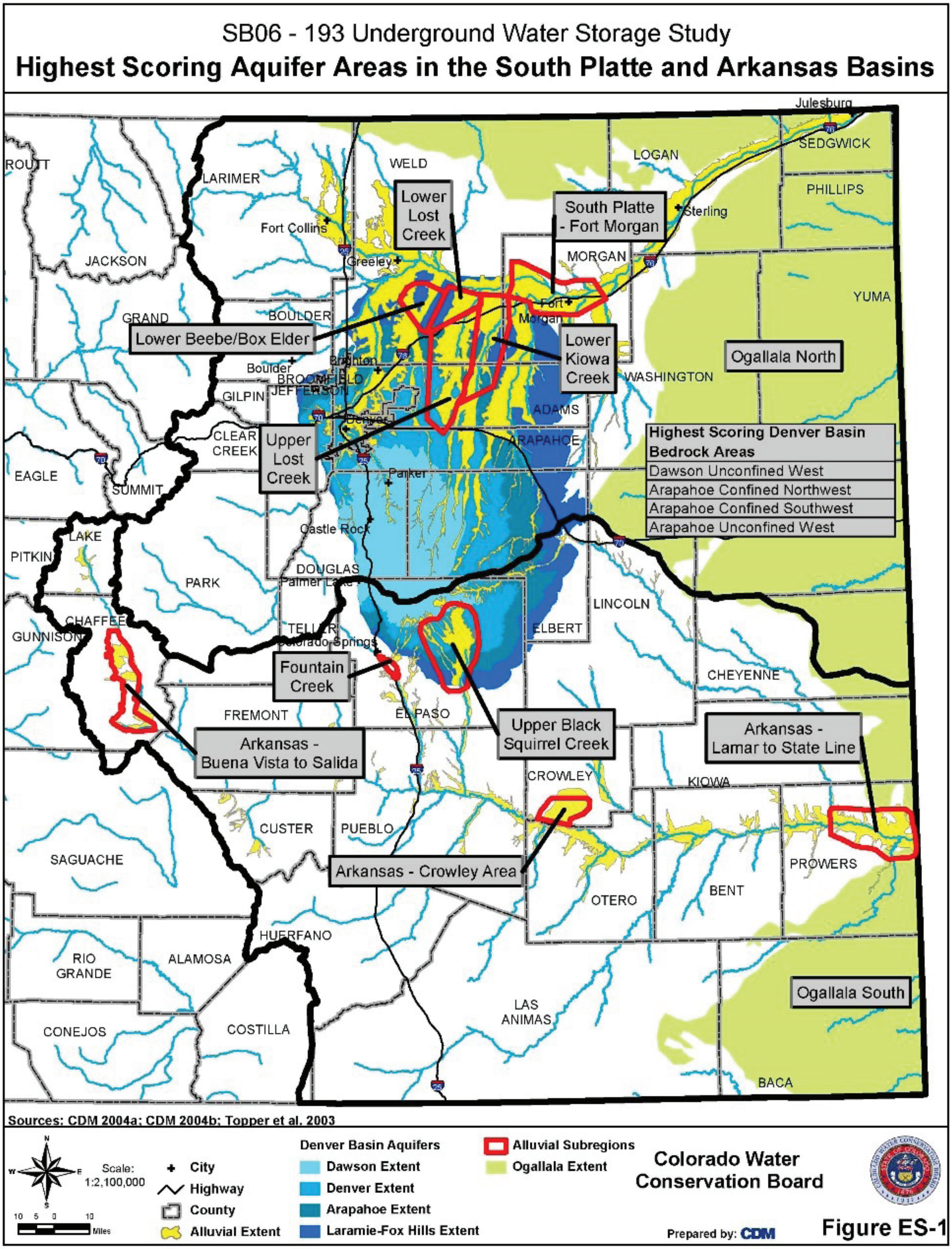


Figure 1. Alluvial and bedrock aquifers with highest ranking score from the SB06-193 study.

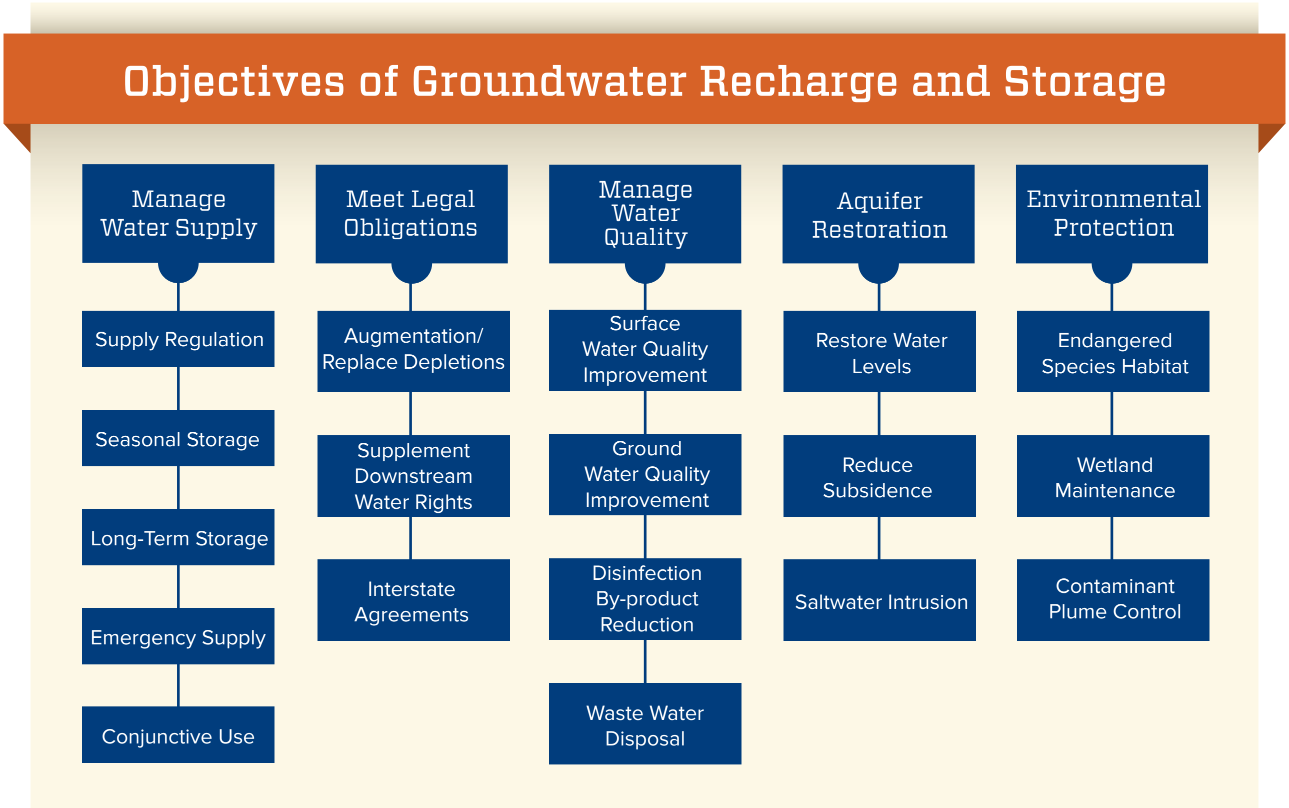


Figure 2. Managed aquifer recharge projects can meet a variety of water management objectives.

aquifers (Topper et al., 2004). The CGS study assessed the opportunities for implementing MAR to meet water storage needs statewide, focusing primarily on the aquifer's hydrogeologic properties. While numerous small scale subsurface storage opportunities exist throughout the state, the CGS focused on aquifers with potential large storage volumes by establishing a minimum area criterion. For consolidated aquifers, this equated to 100 square miles while 80 square miles were used for unconsolidated alluvial aquifers. Their report identifies and ranks 13 unconsolidated alluvial aquifer systems and 24 consolidated bedrock aquifer systems throughout the state with potential storage capacities in excess of 100,000 acre-feet each.

In 2006, the Colorado General Assembly authorized an underground water storage study that focused on the alluvial and bedrock aquifer systems on the eastern plains (CWCB, 2006). The aquifers within the South Platte and Arkansas River basins were divided into four regions for evaluation: South Platte River basin alluvial aquifers, Arkansas River basin alluvial aquifers, Denver Basin bedrock aquifers, and the Ogallala and Dakota-Cheyenne bedrock aquifers. The SB-193 study considered 10 evaluation criteria for hydrogeologic, environmental, and implementation considerations. The regional aquifers identified in the CGS study were evaluated on a subregional basis in this study and smaller area alluvial aquifers were also included. The SB-193 study concluded that numerous areas for potential underground water storage exist in both alluvial and bedrock aquifers in the South Platte and Arkansas River basins, and that available underground storage capacities are on the order of tens to hundreds of thousands of acre-feet. The highest scoring subregions in both the alluvial and bedrock aquifer systems are shown in Figure 1.

Aquifer Recharge Objectives

Aquifer recharge projects can meet numerous water management objectives including: water supply management, satisfying legal obligations, managing water quality, aquifer restoration, and environmental protection (Figure 2). Storing water underground is also less expensive than building new dams. Colorado water users have been very effective in operating AR projects, predominantly in the South Platte and Arkansas River basins, to meet their legal obligations of replacing stream depletions resulting from out-of-priority groundwater pumping through implementation of augmentation plans. Recharge facilities in the lower South Platte River basin have developed over 230,000 acre-feet of augmentation supplies (Waskom, 2013). Recharge facilities have also been constructed to protect or enhance wetland habitat, largely for waterfowl, and to help meet downstream endangered species obligations. These projects that deliver water in timed fashion to mitigate impacts at the river, however, do not have a typical storage objective. Water storage is a beneficial use, but the nuances of Colorado water law restrict that use to specific classifications of water.

Implications of Colorado Water Law

A brief discussion of the basic legal classifications of water is necessary to understand these restrictions. Of the four primary classifications of groundwater: tributary, nontributary, Denver Basin, and designated, it is helpful to first consider tributary and nontributary. Tributary groundwater is hydrologically connected to a surface stream. Nontributary groundwater is groundwater whose connection to any surface stream is so insignificant that it is considered isolated from the surface water for water rights administration purposes. Nontributary groundwater is quantitatively defined in section 37-90-103 (10.5), C.R.S.

Long-term (decades) storage in tributary aquifers may be impractical, as any water introduced into the aquifer will naturally migrate down gradient and discharge to surface water, quickly moving downstream. Recovery of water placed into a tributary aquifer may cause an impact to senior surface water rights. The Prior Appropriation Doctrine, established by Colorado's Constitution, gives the framework for regulating the use of surface water and tributary groundwater, and protects senior surface water rights holders from injury that may occur due to out-of-priority diversions. Thus, while studies have documented tremendous storage capacities in tributary alluvial aquifers, implementation of MAR projects are hampered by this system of water rights administration. In contrast, nontributary groundwater, designated groundwater, and groundwater within the Denver Basin aquifer system are not subject to the doctrine of prior appropriation (Hobbs, 2015).

That leaves but limited areas in the state where aquifer storage and recovery projects can be implemented without modifying Colorado water law. The Colorado Division of Water Resources administers and manages both the surface and groundwater resources of the state. Outside of their Produced Water Rules, the Division has not categorically defined aquifers, or areas thereof, that would be classified as non-tributary other than on an application by application basis. Given their hydrogeologic characteristics, nontributary aquifers lend themselves to long-term storage of water. Colorado water law, however, presumes that all groundwater is tributary. Regional or aquifer-specific determinations of nontributary groundwater have not been conducted by the state. Because nontributary groundwater is allocated to the overlying landowner, nontributary determinations are only made in association with a well permit application. No aquifer storage projects have been implemented in nontributary aquifers outside of the Denver Basin. That may be about to change with the passage of HB17-1076 which requires that the state engineer promulgate rules, on or before July 1, 2018, for the permitting and use of waters recharged into nontributary groundwater aquifers outside of the Denver Basin.

Designated Basins offer Opportunities for Alluvial Aquifer Storage

Designated basins offer the only other alternative for storage projects within unconsolidated alluvial deposits. In

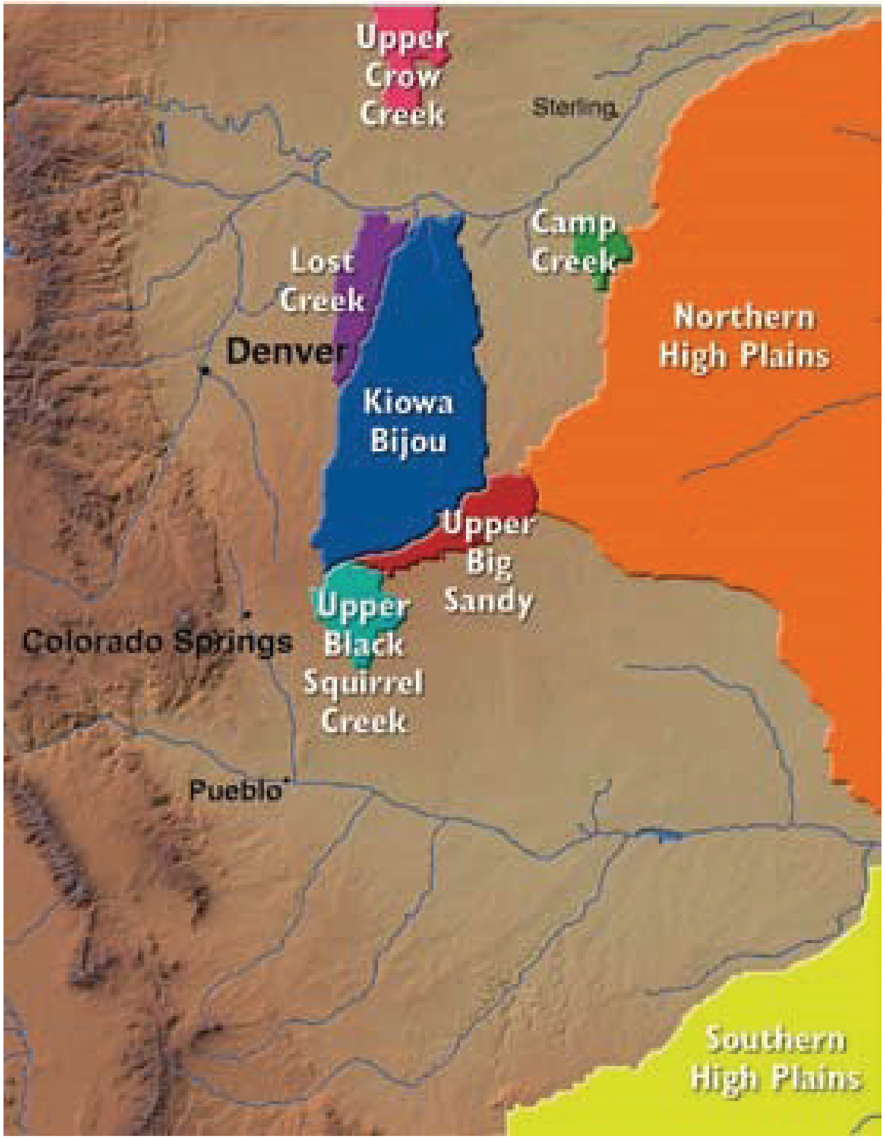


Figure 3. Location of Colorado's designated basins.

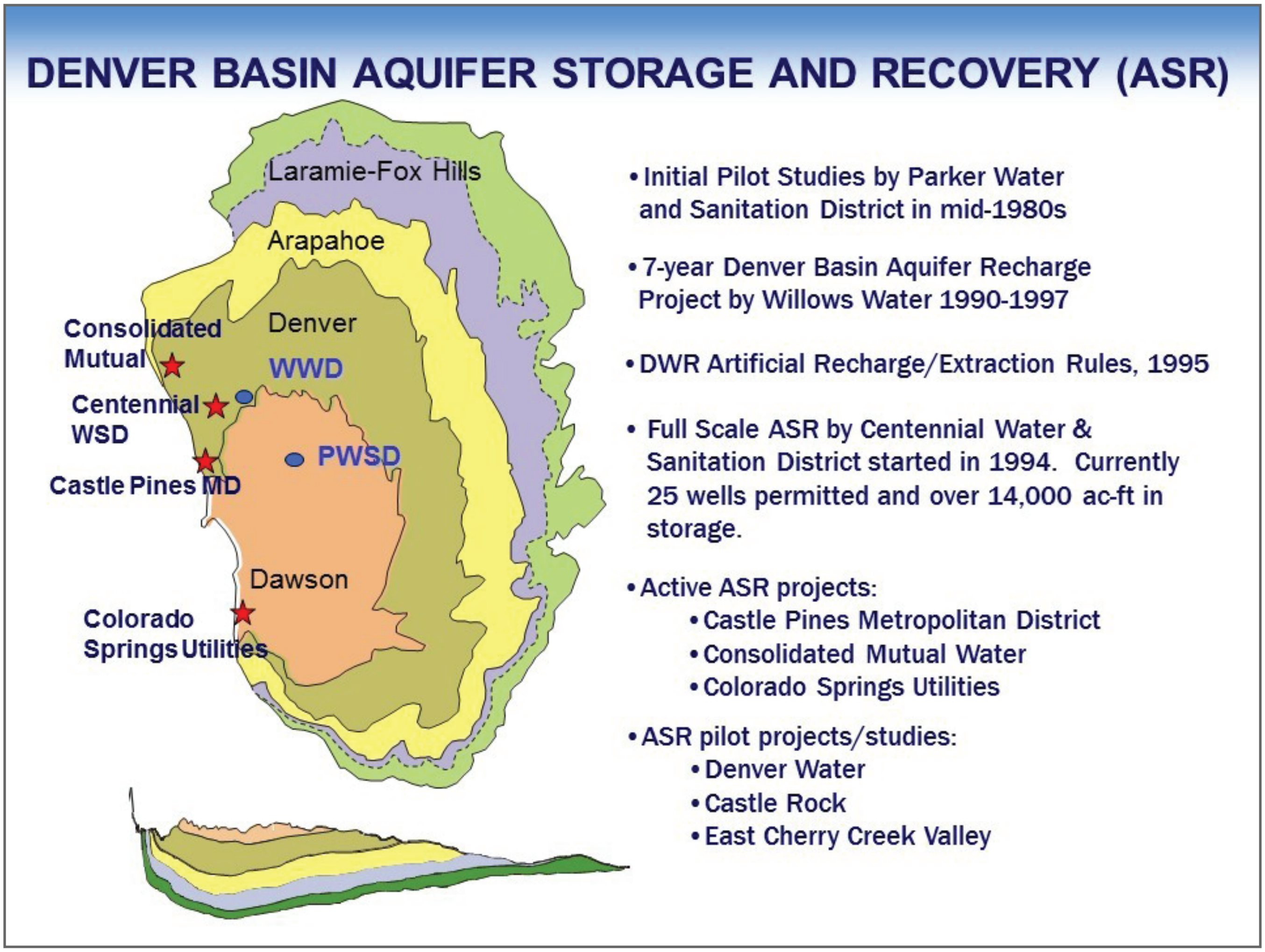


Figure 4. Active ASR projects in the Denver Basin.

1965, the Colorado General Assembly authorized the Colorado Groundwater Commission to create designated groundwater basins containing groundwater characterized as "that groundwater which in its natural course would not be available to and required for the fulfillment of decreed surface rights, or groundwater in areas not adjacent to a continuously flowing natural stream wherein groundwater withdrawals have constituted the principal water usage for at least fifteen years …", section 37-90-103 (6) (a), C.R.S. There are currently eight designated basins, all located on the eastern plains (Figure 3) in which the unconsolidated alluvium is the primary source of water.

Due to the hydrogeologic character of the unconsolidated aquifers in these basins and their legal distinction, designated basins offer good locations to implement ASR. Staff of the Colorado Groundwater Commission are currently in the process of proposing changes to Rules 5.6 & 5.8 which pertain to replacement plans and aquifer storage and recovery plans. If adopted by the Commission, these new rules will provide operators with rules and legal protection for emplacement and recovery of groundwater within designated basins.

Denver Basin Bedrock Aquifer Storage and Recovery Projects

In 1985, the General Assembly directed the State Engineer to promulgate rules and regulations governing the withdrawal of groundwater from the Denver Basin aquifers. Denver Basin groundwater is water within four successively overlying aquifers; the Dawson, Denver, Arapahoe, and Laramie-Fox Hills located within the 6,700-square mile structural Denver Basin between Greeley and Colorado Springs (Figure 4). Groundwater in these aquifers is allocated to the overlying landowners at a rate of one percent per year assuming a 100-year sustainable supply. In 1995, the State Engineer promulgated rules and regulations for the permitting and use of waters "artificially" recharged and extracted into the Denver Basin aquifers. The Denver Basin is currently the only aquifer system in Colorado with specific rules regulating the recharge and extraction of non-native water for storage purposes and as such, is an example of a hydrogeologic system where ASR can and has been pursued in a straightforward way.

The Denver Basin is currently the only area in Colorado with active MAR projects. It currently hosts six well fields with 45 individual ASR wells. ASR feasibility studies in the Denver Basin were initiated in the late 1980s and early 1990s by Parker Water & Sanitation District, Willows Water District, and Centennial Water & Sanitation District (CWSD). CWSD has the longest running history of ASR implementation starting storage and recovery in 1994. It currently has 25 wells permitted for ASR within the Denver, Arapahoe, and Laramie-Fox Hills aquifers. Through 2014, CWSD has stored 14,095 acre-feet of water or nearly a year's supply for its Highlands Ranch customers. Other districts that have implemented ASR operations include: Consolidated Mutual (6 wells), Colorado Springs Utilities (2 wells), and Castle Pines Metropolitan (1 well). East Cherry Creek is currently in the testing phase and implementation plans are moving forward in Castle Rock, Meridian, Rangeview, Inverness, and Cottonwood. Denver Water has initiated a significant evaluation program and South Metro Water Supply Authority considers ASR a critical component of utilizing water supplies from WISE.

Summary Comments

Subsurface water storage in aquifers significantly reduces the financial, permitting, environmental, security, and socio-economic hurdles associated with construction of new surface water reservoirs. The capital infrastructure already exists naturally, and avoids massive evaporation losses. State sponsored studies have quantified numerous aquifers, both bedrock and alluvial, throughout the state with tens to hundredths of thousands of acre-feet of storage capacity. Until the recent passage of HB17-1076, however, rules and regulations for aquifer recharge and extraction only existed in the administrative portion of the Denver Basin. While HB17-1076 opens the doors for project implementation in nontributary aquifers throughout the state, obtaining a nontributary determination is extremely difficult. The best storage opportunities are in alluvial aquifers both due to their hydrogeologic characteristics and ease of implementation. As previously stated, however, extraction operations in tributary aquifers have the potential to impact senior water rights, and the concept of transient storage has not been addressed in Colorado water law. Under the current legal framework, unconsolidated aquifers in designated basins offer the best opportunities to implement subsurface storage.

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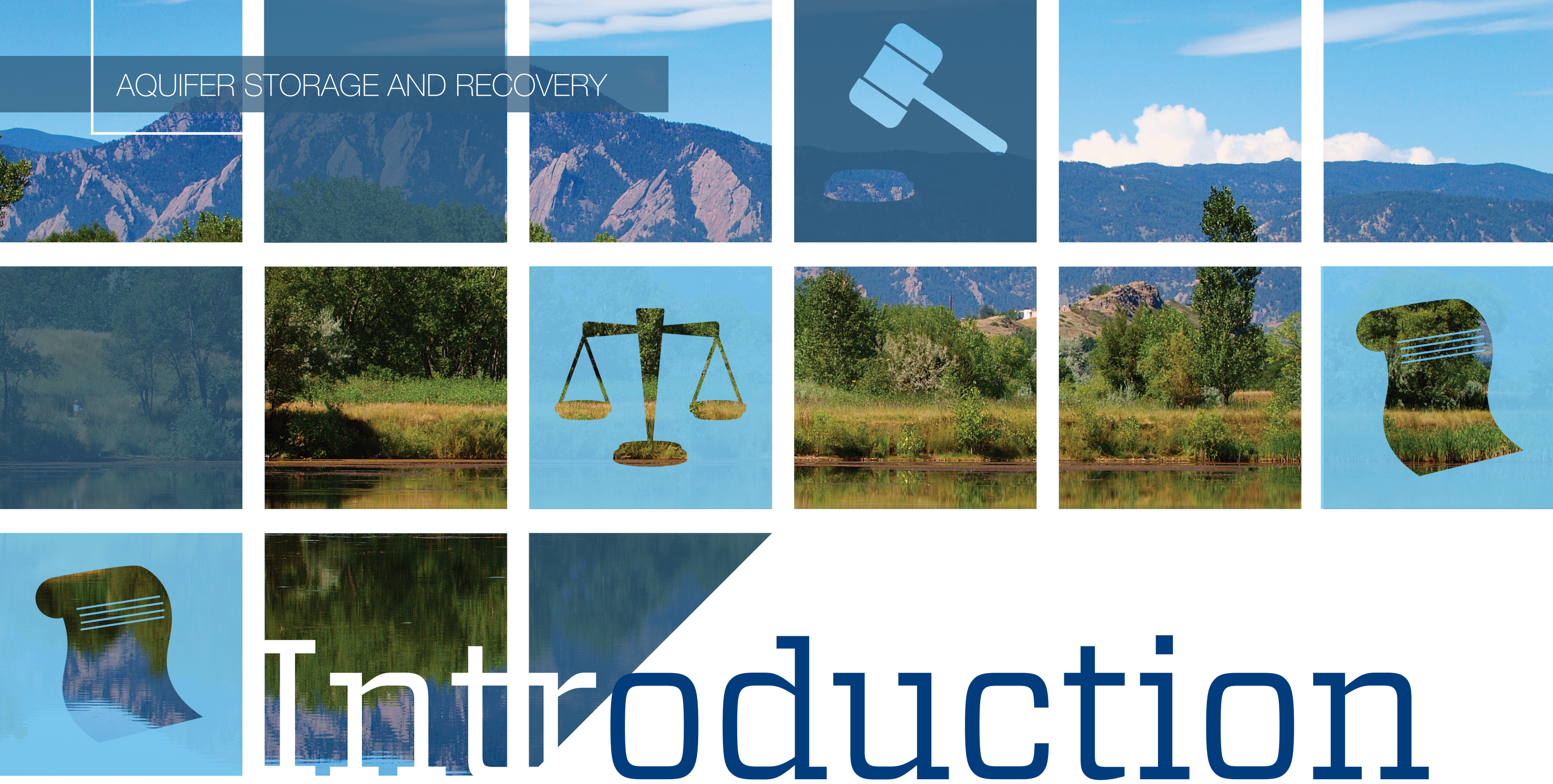
Ralf Topper

About the Author

Ralf Topper recently retired with 16 years of service as the senior hydrogeologist in both the Colorado Division of Water Resources and the Colorado Geological Survey. He has earned advanced degrees in Geology (BS, MS) and Hydrogeology (MS) from CU-Boulder and Colorado School of Mines, and has over 35 years of professional geoscience experience in both the private and public sectors. He is a Certified Professional Geologist, a Geological Society of America Fellow, and an active member of both national and state ground water societies. Ralf has authored numerous papers and publications on Colorado's groundwater resources including the award-winning Ground Water Atlas of Colorado. Ralf and his wife, Karen, are long-term residents of Conifer (30 years) where he enjoys snowboarding, riding motorcycles, boating, hunting, and fishing.



Introduction to Water Use Legal Issues for Subsurface Water Storage Projects in Colorado

Eric Potyondy, Fort Collins Assistant City Attorney

Introduction

There are numerous legal components to any subsurface water storage (SWS) project. These range from real property issues associated with the rights to construct, operate, and access wells and facilities, to federal and state permitting issues associated with water treatment and well construction, to a host of others. This article focuses on legal issues regarding water use in Colorado.

The water use legal issues for any SWS project will be unique, depending on any number of factors, from the legal and factual characteristics of the sources of water to be stored, to the legal and physical nature of the aquifers to be used, to the hurdles and opposition that may be faced in any legal proceedings. Nevertheless, most SWS projects will face various legal issues regarding the water to be stored in the aquifer, the storage of the water in the aquifer, and withdrawal of that water from the aquifer.

The Legal Context for SWS Projects

Water (including groundwater) use in Colorado is governed by several legal regimes, generally depending on geographical location. These various legal regimes have different venues, as well as different statutes, rules and regulations, and controlling and persuasive case law.

Most matters regarding groundwater are generally heard by the District Court for the Water Division where the groundwater is located (commonly known as "Water Court") and the Colorado Division of Water Resources (also known as the Office of the State Engineer). However, there are several unique legal regimes applicable to certain waters, including the groundwater in the San Luis Valley Water Division 3, on the eastern plains, in the Denver Basin Aquifers (Dawson, Denver, Arapahoe, and Laramie-Fox Hills), and other waters that are the subject of specific Water Court decrees. Identifying the specific water use legal context of an SWS project is a fundamental first step in any planning and analysis for a project in order to ascertain what specific approvals are needed for a project.

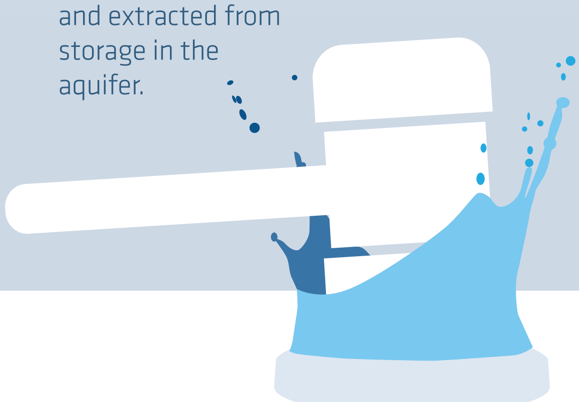
(Above) Boulder, Colorado by Bryce Bradford

Underground Water Storage in Colorado, Generally

Despite these various legal regimes, it can nevertheless be generally stated that the use of aquifers to store water is contemplated in Colorado law. *E.g.,* C.R.S. §§ 37-87-101(2), 37-92-103(10.8). The Colorado Supreme Court ("Supreme Court") addressed the use of aquifers to store water in its opinion in *Board of County Commissioners of County of Park v. Park County Sportsmen's Ranch, LLP*, 45 P.3d 693 (Colo. 2002) ("*Park County*").

The Supreme Court's opinion in *Park County* includes an exposition in footnote 19 regarding the conditions an applicant in Water Court would have to meet to utilize an aquifer for storage of artificially recharged water. The Supreme Court stated that an applicant "at least":

1. must capture, possess, and control the water it intends to put into the aquifer;
2. must not injure other water use rights, either surface or underground, by appropriating the water for recharge;
3. must not injure water use rights, either surface or underground, as a result of recharging the aquifer and storing water in it;
4. must show that the aquifer is capable of accommodating the stored water without injuring other water use rights;
5. must show that the storage will not tortiously interfere with overlying landowners' use and enjoyment of their property;
6. must not physically invade the property of another by activities such as directional drilling, or occupancy by recharge structures or extraction wells, without proceeding under the procedures for eminent domain;
7. must have the intent and ability to recapture and use the stored water; and
8. must have an accurate means for measuring and accounting for the water stored, and extracted from storage in the aquifer.



There may be some question as to whether the identification of these elements was before the Supreme Court in *Park County*. There have also been no subsequent Supreme Court opinions on this issue, and limited Water Court litigation. This opinion nevertheless provides some guidance.

Legal Issue Area: Water to Be Stored Underground

Most SWS projects will need to address the question of what water will be stored in the aquifer. In this analysis, the legal "color" of the water is significant.

Colorado's system of laws regarding water use is premised on rights to use water. In this system, water is physically diverted and stored and is attributed to specific rights. For instance, water may be attributed to a water right under one decree, to a water right under a different decree, to a contractual right to use water, or to some other right. These attributions are colloquially known as "colors" of water.

This system likewise treats water as generally fungible and does not track specific molecules of water. For instance, a water user with a reservoir with two colors of water in it may want to deliver only one color of water out of the reservoir. Here, the water user would deliver the amount of water out of the reservoir and label it as the desired color. There would be no need to only remove water originally attributed to that color (if it were indeed physically possible).

The question of what color of water to store in an aquifer turns on what the legal characteristics and limitations of the right are, and whether they are compatible with the SWS project. For instance, some general questions may include: whether the right includes the right to store water in the aquifer; whether the approved uses are what is needed for the ultimate uses under the project; and whether changes to the right can (or should) be sought and at what risk. This analysis is inherently specific to the SWS project and the subject rights.

Legal Issue Area: Storage of Water in the Aquifer

Most SWS projects will need to address questions related to the storage of the water in the aquifer. As is often the case on water projects, these legal issues are informed greatly by the geological and hydrological physical setting of the project.

The inquiry on storage turns to the physical characteristics of the aquifer to be used. Though there is little case law or litigation in this area, it can be anticipated that underground storage will raise questions regarding whether the water user will be able to maintain dominion and control over the water in storage in the aquifer. For instance, some general questions may include: whether the water will remain in the aquifer or whether it will leave the aquifer and at what rate; and whether there is an adequate methodology to distinguish the water being stored in the aquifer from other waters that may be in the aquifer. This analysis is inherently specific to the SWS project and the subject aquifer.

Legal Issue Area: Withdrawal of Water from the Aquifer

Most SWS projects will also need to address questions related to the withdrawal of the stored water from the aquifer. Again, these legal issues are informed by the geological and hydrological physical setting of the project.

The inquiry here turns to the physical characteristics of the aquifer and the impacts on natural stream resulting from withdrawing water from the aquifer. In Colorado, all groundwater is legally presumed to be tributary to a natural stream, and its diversion (i.e., pumping) and use is thus subject to water rights on the impacted surface streams. This presumption can be overcome with clear and convincing evidence that the groundwater is nontributary, as defined by C.R.S. §37-90-103(10.5) (which provides, among other things, that the withdrawal of nontributary groundwater must not, within one hundred years of continuous withdrawal, deplete the flow of a natural stream at an annual rate greater than one-tenth of one percent of the annual rate of withdrawal).

Whether the water withdrawn from the aquifer is deemed nontributary is thus significant. If the water is deemed nontributary, withdrawals can occur generally without regard to water rights on surface streams. With nontributary groundwater, the aquifer could thus likely be used in a manner analogous to a surface reservoir. However, if the water is deemed tributary, any impacts on water rights on the impacted surface streams will need to be addressed. With tributary groundwater, the aquifer may thus need to be used in a manner less analogous to a surface reservoir. There are numerous examples of such projects throughout the state, many of which separately track and balance recharge accretions and withdrawal depletions to ensure that no injury to other water rights results. This analysis is inherently specific to the SWS project and the subject aquifer.

Conclusions

The basic legal infrastructure for SWS projects in Colorado is in place, though many of the legal issues have not been particularly well developed through previous litigation and court rulings. As interest in SWS projects increases, the Colorado Legislature may step in to provide additional clarity and to facilitate these projects.

As with any water project, acquiring the necessary approvals through the appropriate venues requires thoughtful analysis, adequate resources, and reserves of stick-to-itiveness. Though perhaps not mandatory, a willingness to work with fellow water users to address disputed issues on this common resource may facilitate reaching the goal. For any SWS project, what is thus needed is the will to develop the facts and to find and plow the path forward.

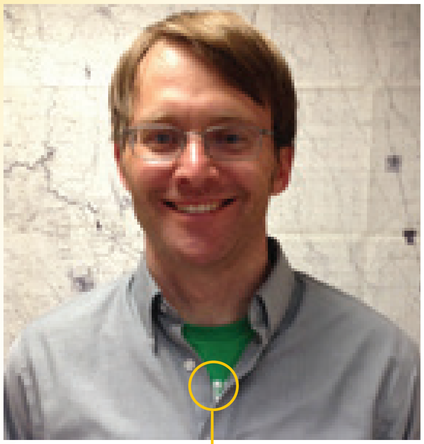


Photo from http://cle.cobar.org/

About the Author

Eric Potyondy attended the University of Colorado School of Law, focusing on water issues, and graduated in 2006. He then clerked for Judge Roger A. Klein for two years at the Water Court for Water Division 1. Following six years in private practice at a small Colorado water rights firm, he became the in-house water attorney for his hometown of the City of Fort Collins. He lives in Fort Collins with his wife, two sons, two cats, and several bicycles.

Estimation of Costs for Subsurface Water Storage

Abdulaziz Alqahtani, PhD Student, Civil and Environmental Engineering, Colorado State University;
Courtney Hemenway, Hemenway Groundwater Engineering, Inc.;
Dr. Tom Sale, Associate Professor, Civil and Environmental Engineering, Colorado State University

Introduction

For nearly a decade, students and staff at Colorado State University (CSU) have been advancing tools for estimating the costs for subsurface water storage projects including ASR projects. Figure 1 presents a conceptual illustration of an ASR project. Cost is a primary factor used to screen, select, and design water storage alternatives. Unfortunately, estimating costs for subsurface water storage projects can be challenging. Little published information is available regarding historical cost for subsurface water storage and the number of experienced practitioners is limited. Typically, subsurface water storage infrastructure and operation evolve through time on an as-needed basis. While in time, delivery of infrastructure allows the system to be tailored to the actual needs, an economic advantage, it complicates anticipating costs. Lastly, subsurface water storage projects commonly build on existing water supply infrastructure. As such, planning of subsurface water storage projects often requires the integration of preexisting infrastructure into estimates of cost. The following article provides a brief introduction to key aspects associated with estimating costs for ASR projects and general subsurface water storage projects. More comprehensive developments are presented in recent CSU Master's theses, including Mauer (2012) and Alqahtani (2015).

Supply and Demand

The first step in estimating costs is to resolve when water is available for storage and recovery. In general, water

> In general, water is:
>
> 1 Stored during periods when demand is less than available water and sufficient aquifer space is available, and
>
> 2 Recovered when demand exceeds available water, and sufficient water has been stored

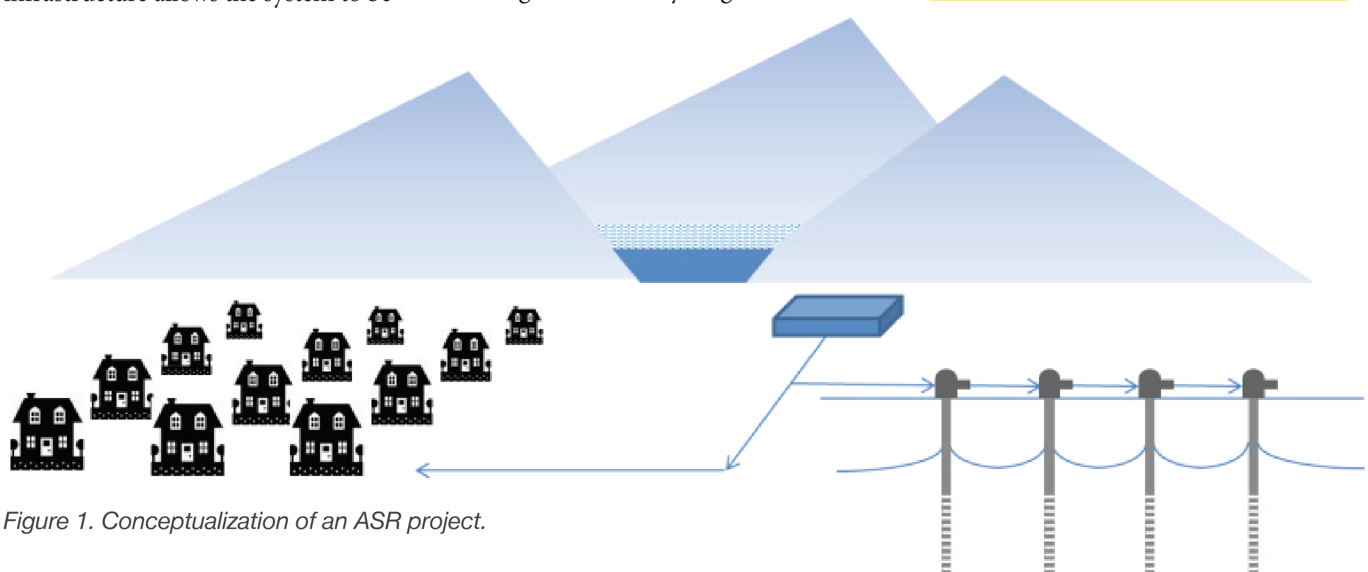


Figure 1. Conceptualization of an ASR project.

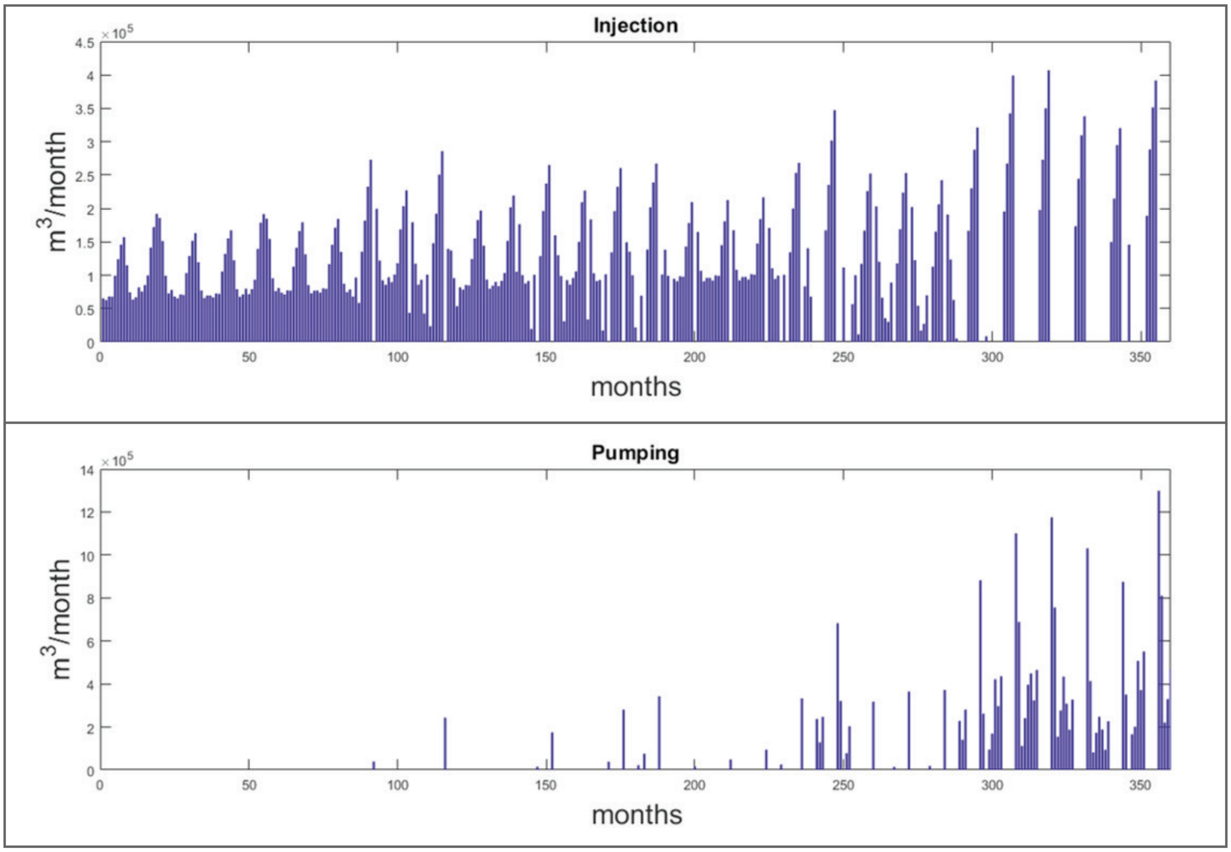


Figure 2. Planned water storage and recovery over a 360-month (30-year) period.

is: (1) stored during periods when demand is less than available water and sufficient aquifer space is available, and (2) recovered when demand exceeds available water, and sufficient water has been stored.

Available water can be constrained by either surface water constraints and/or capacities of water treatment systems. Demands, as an example, can be estimated using projections of population and per-capita water usage. In general, both available water and demands can be deterministic (fixed values) or stochastic (multiple realizations, based on statistical analyses). An advantage of stochastic analyses is an ability to explore resiliency, the frequency at which capacities might be less than demands. As an example, Figure 2 from Alqahtani (2015), illustrates planned water storage and recovery over a 360-month (30-year) period.

Timing of Infrastructure

Given timing of storage required, infrastructure including wells, pipelines, water treatment, and other infrastructure can be added as needed through time. Specific locations for wells need to be based on hydrogeologic and land-access considerations. Following Alqahtani (2015), Figure 3 depicts the timing of infrastructure additions and associated costs over a 30-year period. Also shown in Figure 3 are operations and maintenance costs through time. Future costs are based on a 3% discount rate. Interestingly, an ability to defer cost into the future can provide significant advantages over alternatives that are "front-end" loaded with respect to expenditure including dams.

Total Cost

Estimating cost requires site-specific unit costs for critical elements including wells, pipelines, and water treatment. In the instance where pipelines and wells are already present, cost needs only to include retrofitting wells to facilitate water storage. A common ASR retrofit for an existing well would be the addition of flow control values. Again, following Alqahtani (2015), Figure 4 depicts primary costs on a percent of total cost basis. Note that the distribution of cost is highly dependent on whether the project is a "green field," no-existing-infrastructure project, or an add-on to an existing wellfield.

Available Model

Cost models developed by Mauer (2012) and Alqahtani (2015) are largely only applicable to specific projects. More recently, the South Metro Water Supply Authority, Colorado, (through the Colorado Water Conservation Board) provided funds for CSU to develop simpler Microsoft® Excel-based spreadsheets for estimating cost for ASR projects. Costs from the Microsoft® Excel costing tools are currently being compared to actual cost for the Highlands Ranch ASR program. Parties interested in CSU's subsurface water storage costing tool should contact the authors of this article.

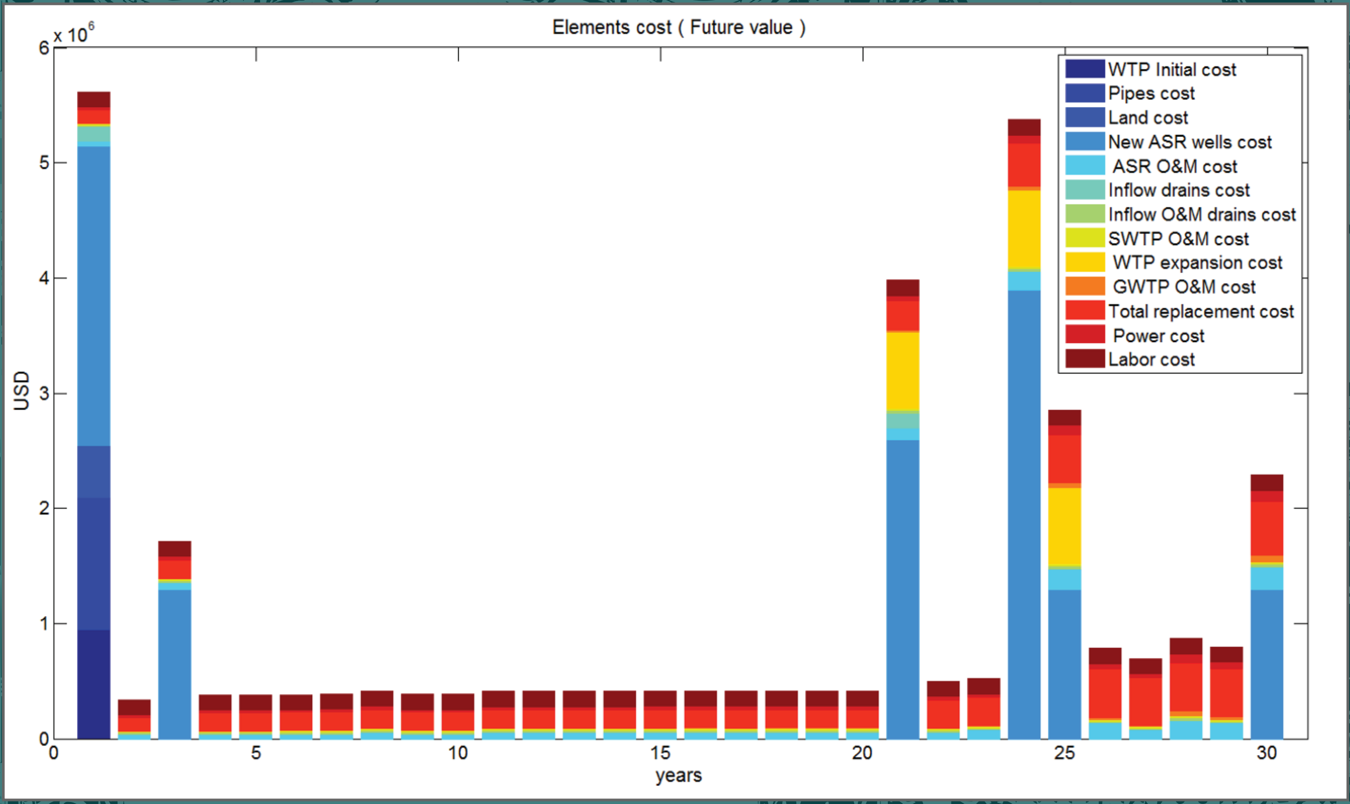


Figure 3. Timing of infrastructure and associated costs over a 30-year period.

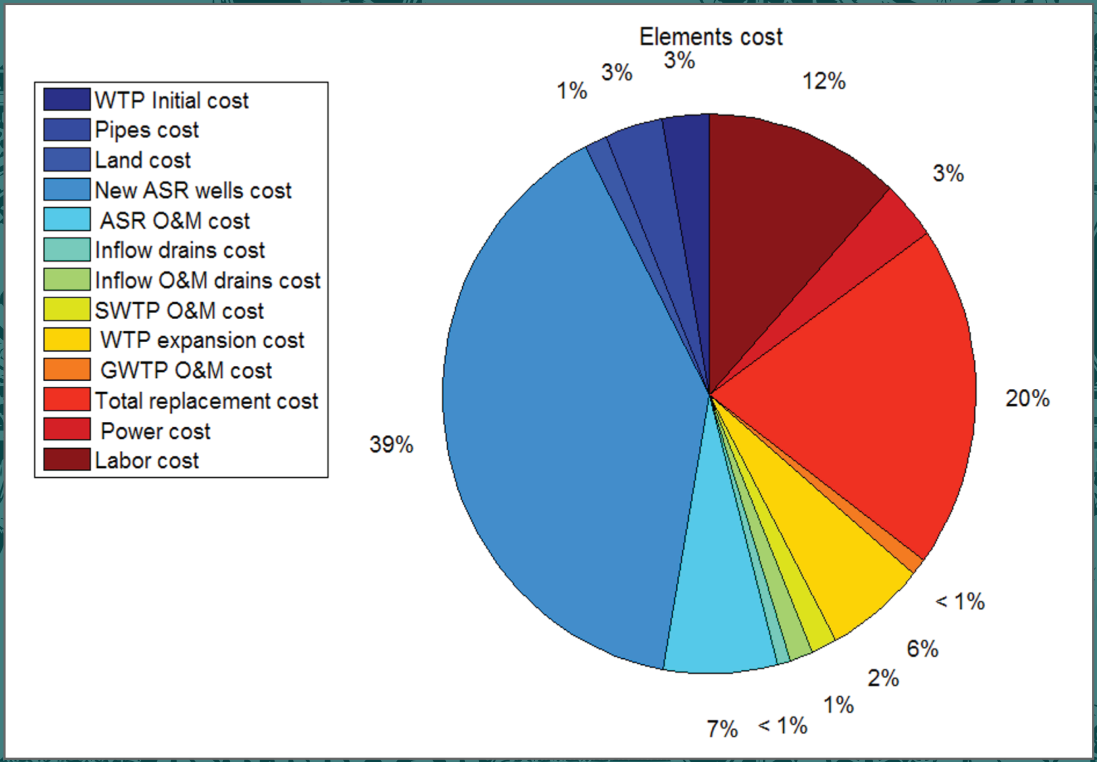
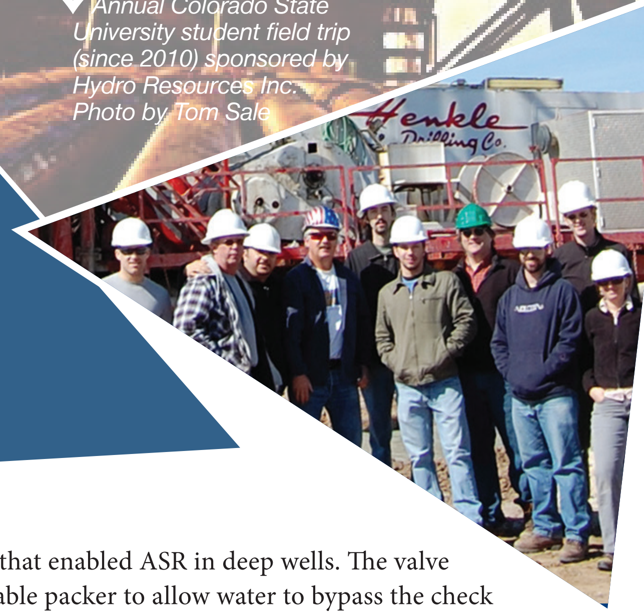


Figure 4. Primary costs on a percent of total cost basis.

Drilling and Completion of ASR Wells

Fred Rothauge, Hydro Resources

Deep water well drilling in Colorado



Annual Colorado State University student field trip (since 2010) sponsored by Hydro Resources Inc. Photo by Tom Sale

Few aspects of aquifer storage and recovery (ASR) are more important than design and completion of wells, pumps, and flow control systems. Over the past half century, Colorado firms including Hydro Resources Inc. (and parent firms), Baski, and Hemeneway Groundwater Engineering have made remarkable advancements that have enabled ASR in Colorado, throughout the U.S. and around the world. The following description provides a review of key aspects of drilling, design, and completion of ASR wells including historical developments.

Well Drilling and Completion

Key aspects of drilling ASR wells include minimizing formation damage, using well screens with large open areas, rigorous well development, and minimizing microbial fouling of wells.

Specifically:

1. **Formation damage** can be controlled by using reverse circulation drilling techniques, drilling fluids with limited additives, and polymers to control losses of drilling fluid to the formation.
2. **Large open areas** for water flow (storage and recovery) between the well and the formations are achieved using v-slot stainless steel wire wrap screens. Large open area well screens reduce near-well head losses, minimize the effects of scale formation, and facilitate well development.
3. **Effective well development** can be achieved using focused airlift in conjunction with chlorine and dispersants to breakdown filter cake and drilling mud. Development can last up to 72 hours.
4. **Microbial fouling** of wells is emerging as a key challenge to sustainable use of groundwater in Colorado including ASR programs. Steps 1-3 (above) are the starting point for controlling microbial fouling of wells. Also, critical to controlling microbial fouling are periodic back flushing of wells during ASR storage cycles and well rehabilitation.

Flow Control

ASR wells are completed using the Baski InFlex™ Flow Control Valve (FCV™). The Baski valve was a pioneering development that enabled ASR in deep wells. The valve uses an inflatable packer to allow water to bypass the check valve above the well pump. The valve facilitates using a single riser pipe for water recovery and storage. Furthermore, the value controls the rate of water flow into wells during storage cycles and prevents cavitation while dropping water hundreds of feet.

Prior to the Baski valve, separate pipes were required for water recovery and storage, forcing a need for large-diameter well completion that was cost prohibitive at large depths. Courtney Hemenway recognized the need for a flow control valve in Colorado's deep aquifer in the mid-1990s. Hank Baski subsequently designed prototype and optimized flow control values. Collaboratively, Hydro Resources has deployed hundreds of Baski valves. Over the years, the design and deployment of flow controls has evolved. Today, the Baski valve is a standard component of deep-well ASR programs around the world.

Summary

ASR is a promising choice for water storage in Colorado, through many parts of the U.S. and around the world. To name just a few benefits, evaporation losses can be minimized, favorable cost can be achieved, and permitting for water storage can be simplified. Over the past half century, well drilling and completion technology has made remarkable advancements enabling ASR in Colorado and around the world. Further developments are ongoing, including ongoing testing at Colorado State University's Hydraulics Laboratory of Hydro Resources' systems for generating electrical power, using downhole pumps, during ASR storage cycles.

Potential Bedrock Opportunities for Aquifer Storage and Recovery in Northern Colorado

Dr. Sally J. Sutton, Associate Professor, Geosciences, Colorado State University;
Daniel F. Collazo, Graduate Student, Geosciences, Colorado State University;
Adam S.O. Adam, Graduate Student, Department of Geosciences, Colorado State University

Bedrock aquifers in Northern Colorado present multiple potential opportunities for water storage utilizing aquifer storage and recovery (ASR). Hydrologic properties derived from water well records suggest particular stratigraphic units deserving further evaluation.

The Colorado Division of Water Resource AquaMap database contains a wealth of data on Colorado water wells drilled throughout the state. Data from AquaMap for northern Colorado, and particularly for eastern Larimer County, have been compiled and combined with reconnaissance geologic fieldwork and a review of pertinent geological maps and literature to characterize the hydrologic properties of sedimentary rock units utilized as aquifers in this area. These aquifer units are mainly sandstones that are exposed at the surface in a belt

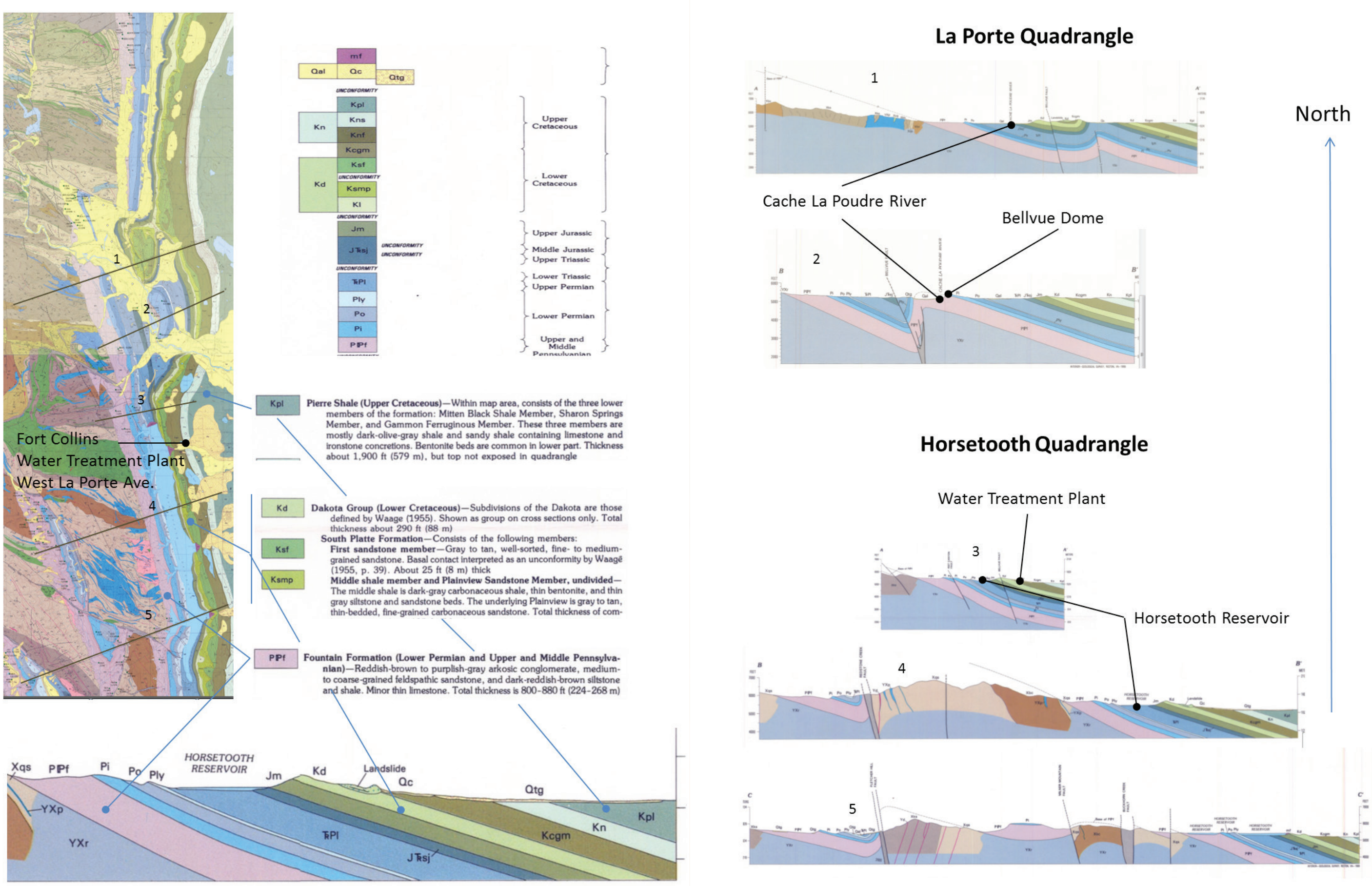


Figure 1. (Left) Plan and cross-section view of Fort Collins area aquifers with high potential for ASR (modified from Braddock et al., 1988 and Braddock et al., 1989). (Right) Geologic cross-sections modified from Braddock et al. (1988) and Braddock et al. (1989) keyed to section lines on the left side of this figure.

Dakota Sandstone. Horsetooth Reservoir, Fort Collins, Colorado. Photo by Flickr User Maitri that lies immediately to the west of Fort Collins and abuts against crystalline igneous and metamorphic rocks exposed further west. This belt of exposed sedimentary rocks marks the western edge of the Denver-Julesburg Basin; eastward into the basin these tilted layers disappear into the subsurface as they become more deeply buried. Within and just to the east of this belt several sedimentary units may have good potential for ASR.

Bedrock Geology

In the foothills to the west of Fort Collins, Precambrian crystalline igneous and metamorphic rocks uplifted by the formation of the Rocky Mountains are exposed at the surface (Figure 1). Moving to the east, the crystalline rock is overlain by eastward dipping late Paleozoic and Mesozoic sedimentary sandstone, shale, and limestone units (Figures 1 and 2). Lateral variability in the sedimentary processes that deposited these units has resulted in a degree of heterogeneity in aquifer characteristics within individual units and in the compartmentalization of some units. Nearly every sedimentary unit hosts some productive water wells, but some units host many more productive wells than other units. This variation in numbers of productive wells partly reflects local demand for water, but also likely reflects the ease with which a particular bedrock sedimentary unit yields water in a particular location.

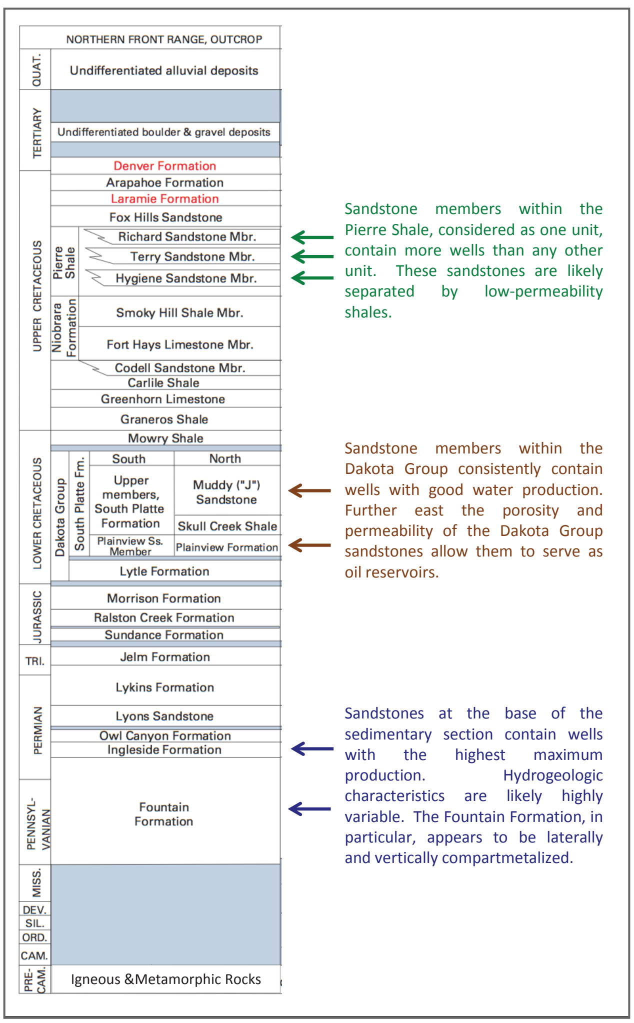


Figure 2. Stratigraphic column showing sedimentary units present along the Northern Front Range. Arrows denote units identified as meriting further investigation as ASR host aquifers. Modified from Higley and Cox (2007).

Surface exposures of some the sedimentary units have been investigated in this and other studies (e.g. Hogan and Sutton, 2014) and reveal evidence of variable permeability. The degree of variability is not uniform from unit to unit and is particularly large in the basal Fountain Formation, where variable water movement in the past has been recorded in the alterations that have affected the unit (Figure 3). Other units, for example the Muddy Sandstone (Figure 4) of the Dakota Group, display less evidence of variability likely to be related to hydrogeologic properties.

In addition to heterogeneity in sedimentary units that is attributable to sedimentary processes, tectonic deformation has affected the aquifer units of the area. The uplift associated with the mountains to the west created a complex set of faults and folds that have modified the arrangement of the sedimentary geologic units (Figure 1). In some instances:

- Geologic units are laterally offset.
- Rock outcrops of the same formation occur at multiple east-west locations. For example, moving east to west along cross-section 5 (Figure 1), the Fountain Formation outcrops at three locations.
- Moving to the east, individual geologic units generally get deeper. For example, the Fountain Formation outcrops in Lory State Park, whereas at the City of Fort Collins Water Treatment Plant, the same formation is encountered approximately 3,000 ft beneath the surface.

Well Data

Data obtained from the Colorado Division of Water Resources AquaMap database have been compiled for over 900 water wells hosted in sedimentary bedrock strata of eastern Larimer County. Data compiled include well location, host sedimentary unit, yield, static water level, and pumping water level. In addition, drawdown and specific capacity have been calculated. As a first-order approximation, water production from a well, Q (gal/min), can be estimated as:

$$Q = S_c s$$

where S_c is the specific capacity of the well (gal/min/ft of drawdown), and s is the depression of water levels at a production well (ft).

Sedimentary bedrock well locations have been mapped and keyed to the producing sedimentary units; Figures 5 and 6 show examples of maps produced for a subset of the wells

Figure 3. Fountain formation displaying effects of variation in ancient water movements. Water movements stripped iron oxides from the otherwise reddish rock (Hogan, 2013).

Figure 4. Muddy sandstone exposed east of Horsetooth Reservoir. Photo by A. Adam.

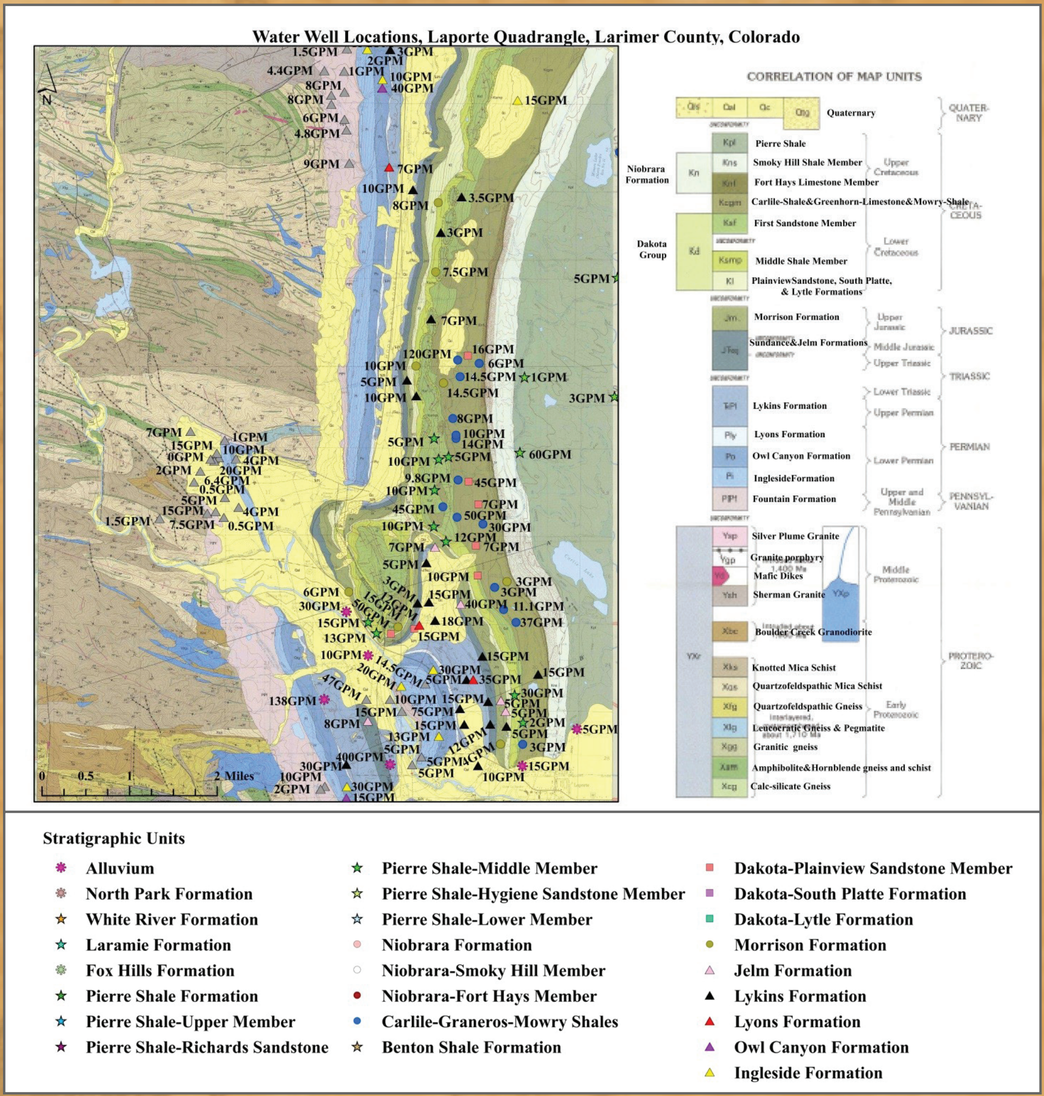


Figure 5. AquaMap wells shown on the Laporte Quadrangle geologic map of Braddock et al. (1988).

in the vicinity of Fort Collins. Bedrock groundwater use in the vicinity of Fort Collins is largely limited to domestic water supply in unincorporated areas, and hence well yields reported in AquaMap may reflect design of wells for the low-demand of domestic uses. These well yields may understate the production capacity of these wells and almost certainly are less than could be achieved with wells designed for large-scale production needs (municipal, industrial, or agricultural) or for ASR.

The available well data show that production profiles vary by formation (Figure 7) as well as by geographic location (Figures 5 and 6). Given larger-diameter well completions, full penetration of the targeted aquifers, and potential drawdowns of 1,000 feet, yields from high capacity wells could be significantly larger than the values reported in Figure 7. Figure 8 presents a ranking of the aquifers by use (number of wells), maximum production, and median production. Based on Figures 7 and 8, the most promising stratigraphic units for ASR in the vicinity of Fort Collins appear to be the Fountain, Ingleside, and Pierre Formations, as well as sandstones belonging to the Dakota Group. Other units of secondary interest include the Jelm, Lykins, and Morrison Formations.

Critically, the biggest factor affecting cost and overall ASR feasibility, is the capacity of the wells. Potential yields from wells designed for municipal applications in the noted formations remain a significant data gap. The existing well data harvested from AquaMap, however, can be viewed as minimum yields and support the view that multiple aquifers in Northern Colorado are good candidates for ASR development. At any single location, one or more of the underlying formations could potentially be used for ASR.

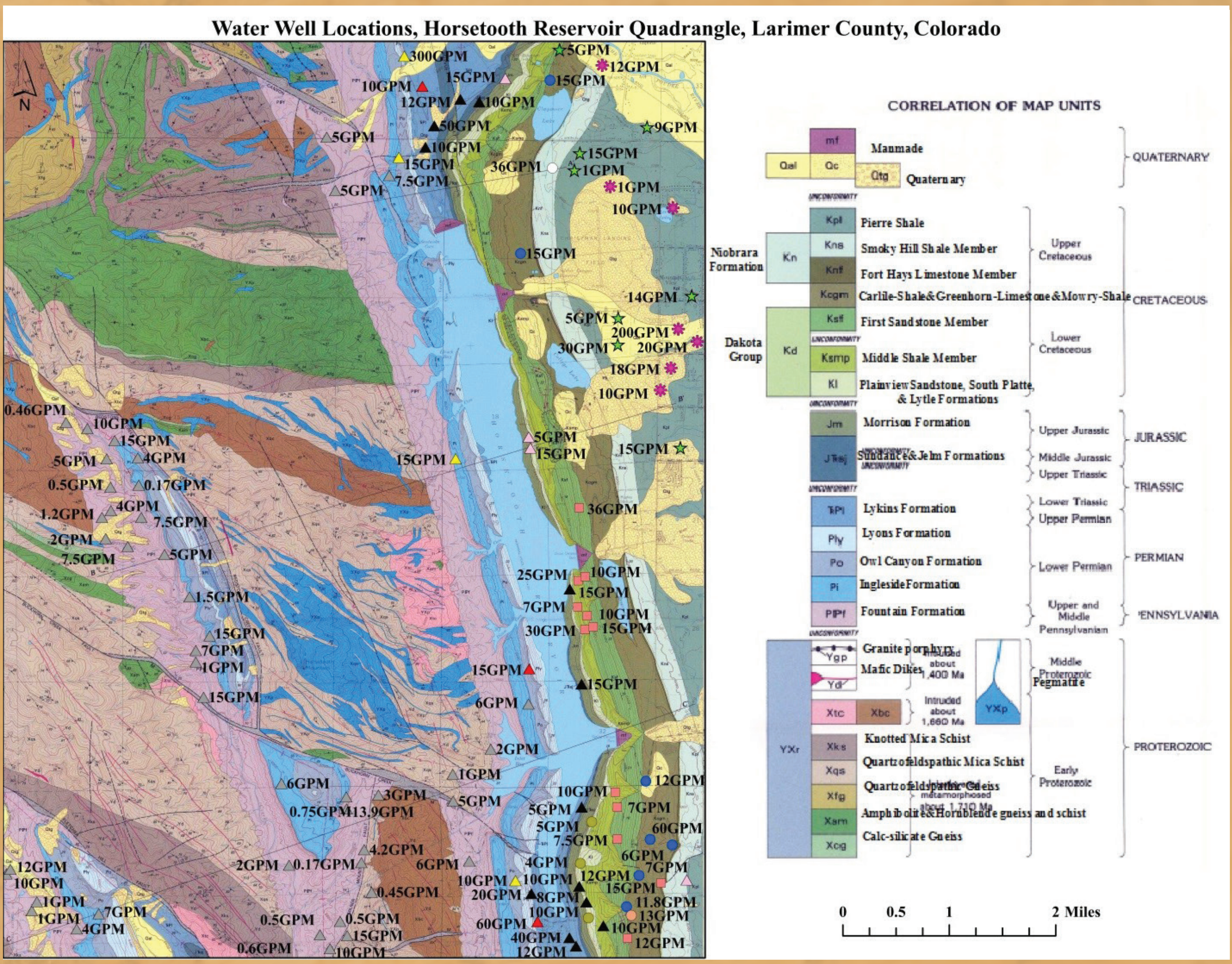


Figure 6. AquaMap wells shown on the Horsetooth Quadrangle geologic map of Braddock et al. (1989). Stratigraphic unit key as in Figure 5.

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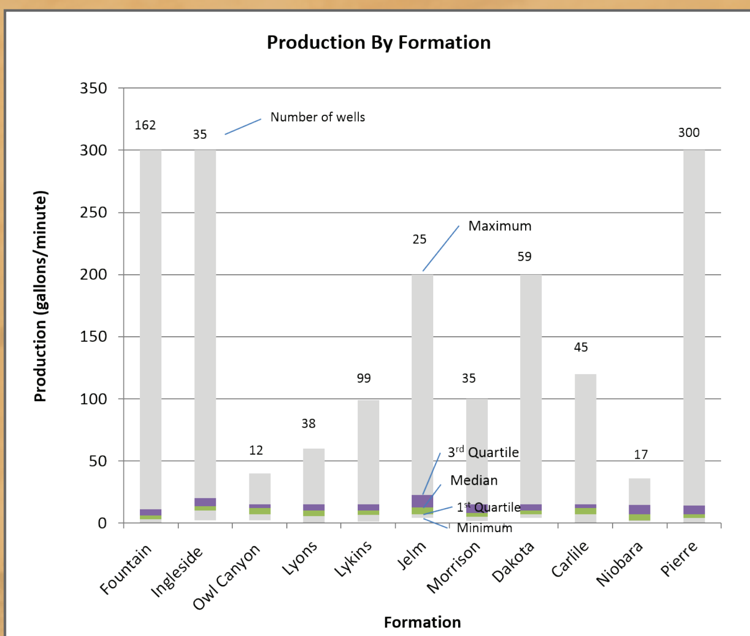
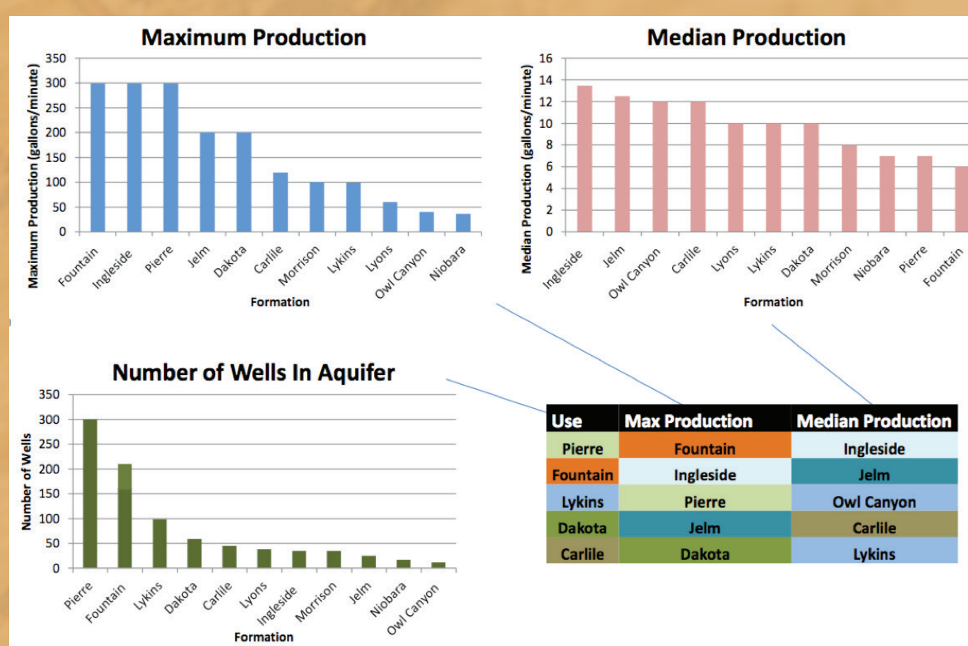


Figure 7. Production by formation.



Use	Max Production	Median Production
Pierre	Fountain	Ingleside
Fountain	Ingleside	Jelm
Lykins	Pierre	Owl Canyon
Dakota	Jelm	Carlile
Carlile	Dakota	Lykins

Figure 8. Ranking of aquifers by use, maximum production, and minimum production.

Analytical Modeling of ASR Wellfields

Dr. Michael Ronayne, Associate Professor, Geosciences, Colorado State University;
Dr. Tom Sale, Associate Professor, Civil and Environmental Engineering, Colorado State University;
Alan Lewis, MS Graduate, Geosciences, Colorado State University, Daniel B. Stephens & Associates Inc.

Introduction

Aquifer storage and recovery (ASR) is an emerging water management strategy that is particularly useful in regions with high temporal variability in available surface water resources. This study considered data from a municipal wellfield in Highlands Ranch, Colorado that has been used for ASR during the past two decades. A novel modeling framework was applied to analyze historical water levels at ASR wells, and to assess aquifer response to ASR stresses.

Study Area and Historical Data

Centennial Water & Sanitation District (Highlands Ranch, Colorado) has 19 ASR wells completed in sedimentary aquifers of the Denver Basin. The aquifers are comprised of heterogeneous channel sandstones and interbedded layers of siltstone and shale (Raynolds, 2002; Barkmann et al., 2011). More than 4.5 billion gallons of water has been placed in storage using Centennial wells in the Highlands Ranch area (Pyne, 2005). This project focused on Centennial's ASR wells in the Arapahoe aquifer. The wellfield in this aquifer consisted of 12 wells that were active during a historical observation period with high-quality data (2000-2015). Example time-series data for one ASR well is shown in Figure 1. Spacing between wells is approximately 1 mile.

Wellfield Modeling and Parameter Estimation

Historical water levels at each of the Arapahoe aquifer wells were analyzed using a model that considers drawdown in the aquifer, drawdown due to well-loss effects, and the background (or recoverable) water level at each well. Aquifer drawdown is calculated using a Theis superposition approach to account for multiple wells with complex pumping histories (i.e., wellfield conditions with interference effects). Drawdown may be positive or negative depending on the timing of groundwater extraction or recharge during ASR cycles. Historical pumping rates, required to drive the forward model to calculate water levels through time, were consolidated into discrete blocks using the method described by Lewis et al. (2016). A parameter estimation run was performed to identify aquifer and well properties that adequately reproduce the water level data at each ASR well.

Relevant parameters estimated from the historical time-series data include the aquifer transmissivity (T) and storativity (S) and, for each well, the recoverable water level and well-loss coefficients. The following sequential parameter estimation approach developed by Lewis et al. (2016) was used to estimate these parameters for the Highlands Ranch wellfield:

- Aquifer properties (T and S) are estimated using temporal water level derivatives. This approach attempts to reproduce the observed derivative behavior, rather than the absolute hydraulic head or drawdown value, minimizes the influence of the static (pre-pumping) water level, which is unknown.
- Recoverable water levels are estimated for each well by fitting data collected during nonpumping time periods.
- Well-loss coefficients are estimated for each well by fitting data collected during pumping time periods (extraction or storage and recovery).

Example Results

A comparison of the observed and modeled water levels is provided in Figure 2. During nonpumping periods, discrepancies between modeled and observed levels are generally less than 5 m. Larger discrepancies (5 – 25 m, on average) are apparent during active pumping periods; this is a consequence of the model's flow rate averaging scheme (detailed daily variations in the pumping rate

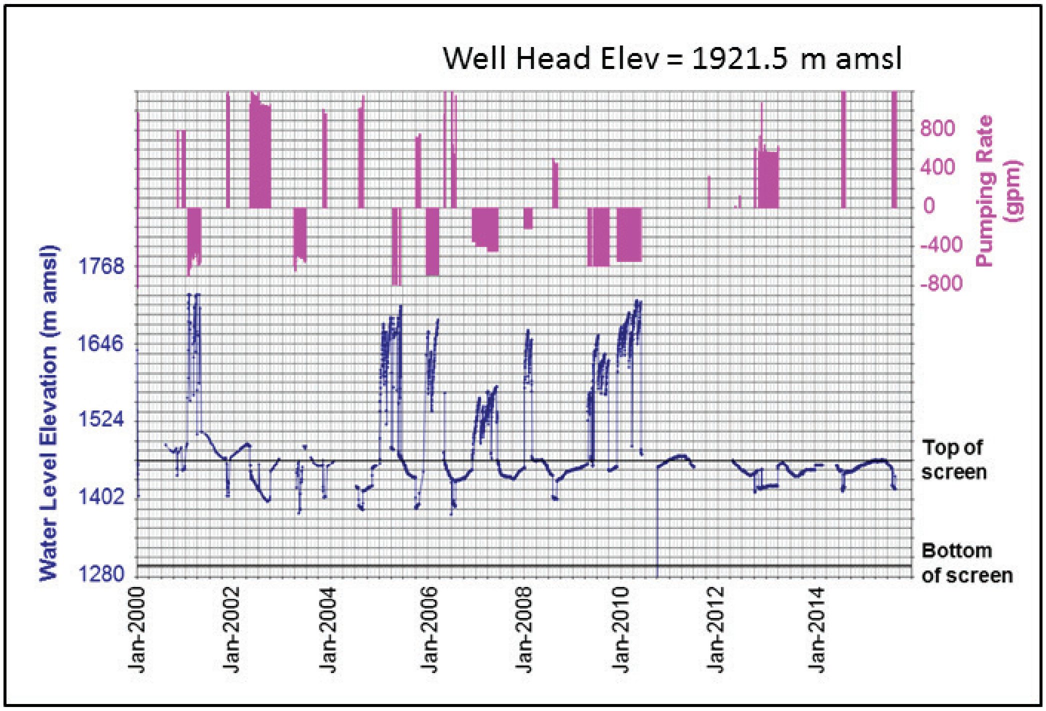


Figure 1. Example of a historical dataset for an ASR well in the Arapahoe aquifer. Positive pumping rates indicate extraction and negative rates indicate injection.

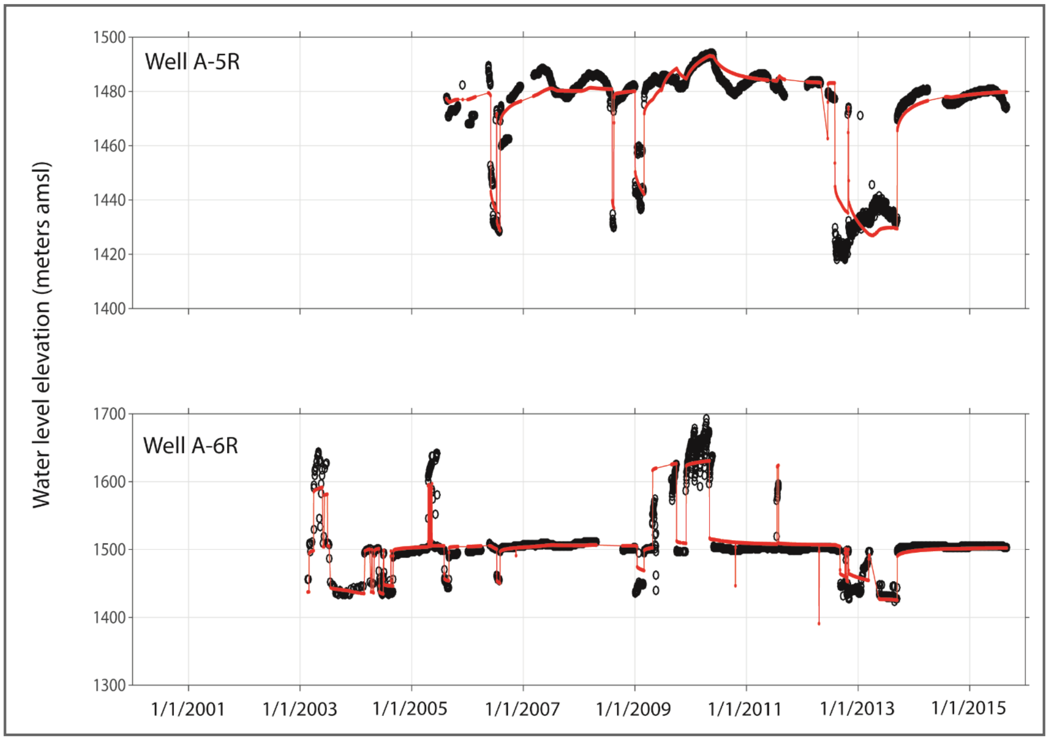


Figure 2. Comparison of modeled (red line) and observed (open circles) water levels at individual ASR wells. Well A-6R had multiple periods of extraction and injection during 2000-2015, whereas Well A-5R was used for extraction only.

Highlands Ranch, Colorado. Photo by Angela Pace are not explicitly modeled), along with the simplified approach used to calculate well-loss effects.

In addition to the water level behavior at individual wells, the analytical model can be used to assess the effects of ASR throughout the aquifer. Figure 3 shows the spatially distributed drawdown surface during periods of extraction (Aug 2002) or recharge (May, 2003). While some well interference effects are observed, particularly during extended periods with extraction, hydraulic head changes tend to be localized around individual wells.

Concluding remarks

The analytical model developed in this study represents a useful tool for evaluating ASR projects. Water level behavior at individual ASR wells is reasonably approximated by considering recoverable water levels, aquifer drawdown influenced by well interference, and well-loss coefficients. The magnitude of the well-loss effect is strongly dependent on the direction of flow (extraction versus recharge pumping), an issue that warrants further investigation. Additional research should focus on the influence of aquifer heterogeneity, as well as the fate and residence time of stored water.

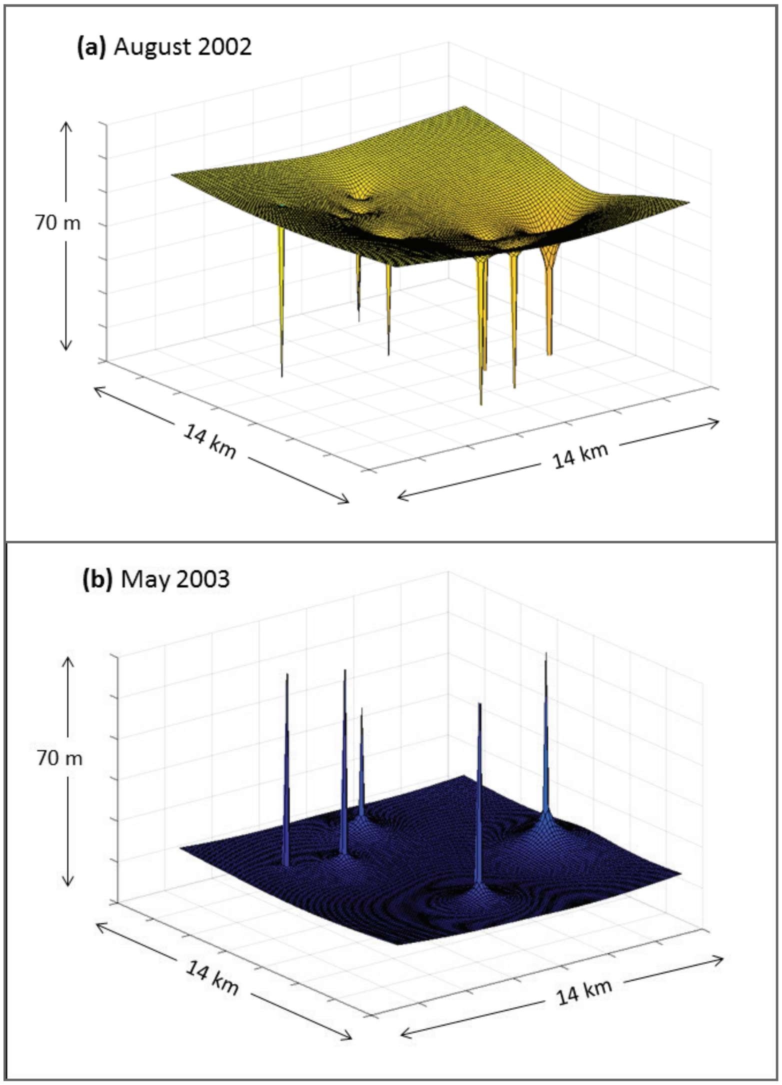


Figure 3. Modeled drawdown surface during (a) extraction and (b) injection. Surfaces are constructed using the sum of aquifer drawdown and drawdown due to well-loss effects and represent change since the beginning of the historical simulation period (July 1, 2000).

Acknowledgments

This research was funded by South Metro Water Supply Authority. Data were provided by Centennial Water & Sanitation District. We thank Courtney Hemenway for assistance with data compilation and interpretation.

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Aquifer Storage and Recovery Program

Centennial Water & Sanitation District Highlands Ranch, Colorado

Courtney Hemenway, Hemenway Groundwater Engineering, Inc.

Highlands Ranch, CO. Photo by Dominic Sagar

Introduction

Centennial Water and Sanitation District (CWSD) provides potable drinking water to Highlands Ranch with a service population of approximately 95,000. CWSD has a conjunctive use water supply system using surface water from the South Platte River through alluvial wells and groundwater from three principal aquifers of the Denver Basin (Denver, Arapahoe, and Laramie-Fox Hills). During periods of low water demand when there is excess capacity in the CWSD water treatment plant (WTP), surface water is treated and stored in the bedrock aquifers. During the high-peak summer months or during extended drought periods when surface water supplies are limited, CWSD pumps navigate groundwater and artificially stored ASR water back to meet demands in conjunction with surface water supplies.

Why ASR?

ASR provides a very cost-effective, flexible method of storing surface water when excess water treatment capacity is available. Typically, peak demands for water during the summer are two to three times higher than the demand in off-peak periods, allowing for the excess treatment capacity in off-peak times to be used to treat and store the available water. This also provides better utilization of the existing capital investments in water treatment facilities. In addition, by recovering ASR water, which typically only requires disinfection (no additional treatment), peak demands can be met by the conjunctive use supplies, and in some cases, delaying water treatment plant expansion, saving a significant amount of capital. Using ASR also capitalizes on the existing CWSD wellfield, helps reduce water level declines, and sustains the groundwater supplies, while minimizing the risk of contamination to the stored water.

ASR also provides cost-effective storage compared to surface water alternatives. The cost and time required to permit and construct a surface water storage unit today can cost tens to hundreds of millions of dollars and may require decades to complete. The permitting of ASR is simple and requires minimal surface area. In addition, 100 percent of the injected water is recoverable with no evaporative losses, as is the case with surface water storage where losses can reach thousands of acre-feet per year. Public acceptance of ASR has been very favorable compared to surface water storage alternatives that cause significant impacts to rivers and require large surface areas.

Feasibility Study and Permitting

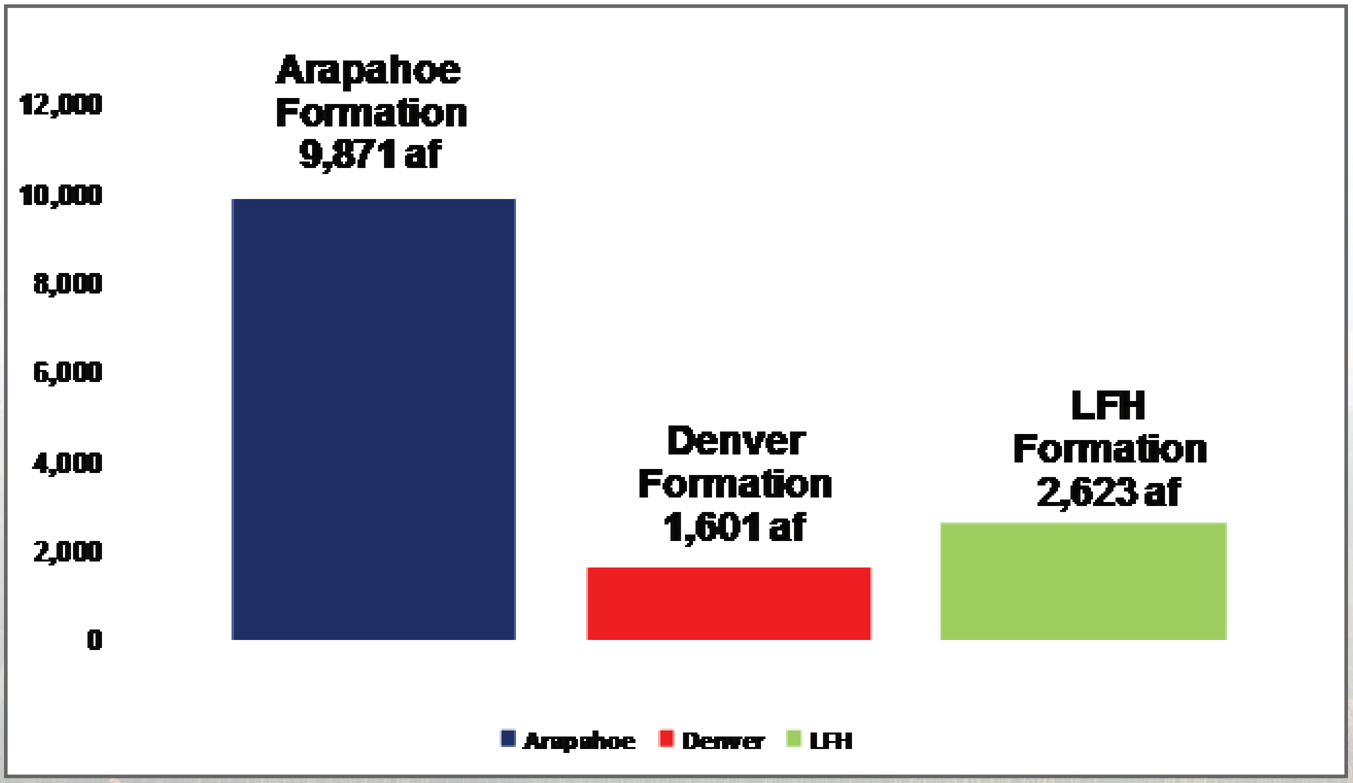
In 1990, CWSD initiated a Phase 1 Feasibility Study of ASR and its applicability as a water management tool for the CWSD. The Phase 1 study concluded in 1991 with the recommendation that ASR was a viable management tool to meet CWSD's water supply demands. Subsequently, CWSD conducted a Phase 2 testing program in one Arapahoe aquifer well in 1992 that verified the conclusions of the feasibility study. At the conclusion of the Phase 2 testing in 1992, no efficient framework was in place for the Colorado State Engineer's Office (SEO) to permit the recovery of injected water. Subsequently, legislation was passed to require the SEO to promulgate rules and regulations for the recovery of injected water. In 1995, the SEO set forth rules and regulations for ASR that are very straight forward and simple to accomplish. For the storage and recovery side of ASR operations, the United States Environmental Protection Agency (EPA) provided a Class V Underground Injection Control (UIC) Rule Authorization that was processed over a few months. Once the Rule Authorization was in place, addition of supplemental wells only required EPA notification with minimal data requirements.

> **100%** of the injected water is recoverable with no evaporative losses, as is the case with surface water storage where losses can reach thousands of acre-feet per year

ASR at Highlands Ranch

CWSD has 54 wells completed in the Denver Basin aquifers beneath Highlands Ranch with 25 wells equipped for ASR operations. ASR has been conducted in the Denver, Arapahoe, and Laramie-Fox Hills aquifers with a total 14,095 acre-feet of water currently stored in the three aquifers, representing nearly a year's supply for all of CWSD customers in Highlands Ranch. The storage and recovery capacity in the 25 wells is approximately five million gallons per day.

CWSD has successfully developed and operated ASR wells for over 22 years and has proved that ASR can be implement-



Total injection volumes per Denver Basin Aquifer and the Centennial Water and Sanitation District.

ed on a large-scale basis within the Denver Basin aquifers. CWSD has demonstrated that the Denver Basin aquifers offer a cost-effective and viable water supply and storage resource.

Discussion/Comments on 2016 Subsurface Water Storage Symposium

The information presented in this paper was part of the information provided at the Subsurface Water Storage Symposium conducted at Colorado State University on November 15 – 16, 2016. The symposium included several presentations that provided insights on the regulatory framework and support for ASR from the SEO, identified water rights aspects of storing water underground, highlighted innovative new technologies for constructing subsurface storage facilities, presented new computer models identifying well/aquifer responses to ASR operations, and documented several case histories related to successful subsurface storage of water. The second day of the symposium allowed for active and open discussions regarding the role of subsurface water storage in Colorado's State Water Plan, the factors constraining development of subsurface water storage projects, and the opportunities ahead for ASR operations within Colorado and surrounding states.

A typical ASR well site. (Centennial Water and Sanitation District).

About the Author

Ingrid Hemenway

Courtney Hemenway is the President of Hemenway Groundwater Engineering, Inc. and is a registered Professional Engineer in Colorado, having Bachelor and Master of Science degrees from Colorado State University. He is a civil engineer with expertise in groundwater hydrology and modeling, well design and construction, ASR, and hydraulic fracturing of deep bedrock aquifer wells, with over 36 years of experience in these areas. In his groundwater hydrology consulting, Mr. Hemenway has conducted numerous municipal groundwater development programs and has participated in many water resource management projects involving the conjunctive use and interaction of groundwater and surface water. Over his career, Mr. Hemenway has been involved in the design, drilling, and testing of more than 125 deep Denver Basin wells, numerous shallow alluvial wells, and over 1,500 shallow alluvial soil borings and monitoring wells. He has also been the project engineer on ASR projects since 1991 and has managed the installation and operation of 36 ASR wells in the Denver Basin.

Wave-overtopping of a grassed, soil slope placed in the wave-overtopping facility.

The Laboratory

for Water Engineering and Science at Colorado State University

Dr. Robert Ettema, Professor Harold H. Short Chair in Infrastructure, Civil and Environmental Engineering, Colorado State University;
Dr. Chris Thornton, Associate Professor, Civil and Environmental Engineering, Director of the Hydraulics Laboratory, Colorado State University;
Dr. Steven R. Abt, Emeritus Professor and Past Director of Hydraulics Laboratory, Colorado State University

Introduction

An illustrious history along with the availability of extensive facilities, a capacity to deliver remarkably large water discharges, and an array of instrumentation, make Colorado State University's (CSU) Hydraulics Laboratory a national and international resource for tackling fundamental and applied aspects of water engineering. The lab's earliest activities date back to the 1880s work of the pioneering hydraulics engineer of the American West, Elwood Mead (for whom Lake Mead on the Colorado River is named). Its current activities address a wide range of contemporary as well as enduring research topics and link closely to the university's extensive programs of graduate education in water engineering, science, and management. As with all vibrant laboratories, the hydraulics laboratory at CSU continuously develops its facilities and instrumentation in response to evolving research needs and opportunities associated with becoming a laboratory for water engineering and science.

Background

The history and potential of CSU's hydraulics lab quickly drew the attention of noted hydraulician Hunter Rouse, who in 1940 began a lengthy connection with the lab. Though his name is primarily associated with the University of Iowa's Hydraulic Lab, Rouse spent considerable time at CSU and produced a handy book (Rouse, 1980) describing the historic influences and people that led to the lab's prominence. In his customary concise, matter-of-fact manner, Rouse documents some of Mead's contributions, along with those by many other well-known engineers who contributed to the labs growth in productivity and stature (e.g., Ralph Parshall, Emory lane, Maurice Albertson, Daryl Simons, Ev Richardson, and Jim Ruff). Subsequent articles, including those by Bhowmik et al. (2008), Simons (2004), and Julien and Meroney (2003), recount the work of other notable engineers whose principle contributions to hydraulic engineering were made while at the lab. The lab's facilities also drew the interest of talented scientists, such as the acclaimed geomorphologist Stanley Schumm.

Setting

The physical and educational aspects of the lab's setting give it strategic advantages shared by few other hydraulics laboratories. Since 1962 the lab has occupied a major part of CSU's Engineering Research Center (ERC), located below Soldier Canyon Dam of Horsetooth Reservoir in Fort Collins, Colorado. Figure 1, an aerial view of the ERC, indicates the lab's physical setting. This setting is ideal for a hydraulics laboratory as it provides a large water discharge capacity (up to $5m^3/s$) at a very large head (107 m). Moreover, the reasonable centrality of Fort Collins within the United States, and its closeness to Denver International Airport, make the lab readily accessible.

The lab serves faculty and students involved in CSU's broad water-related graduate programs (see, for example, http://www.engr.colostate.edu/ce/degreeinfo.shtml). The programs connect contemporary technologies in water-related areas of civil and mechanical engineering, agriculture, and the geosciences. They include hydraulic and hydrologic systems and infrastructure, fluvial engineering, irrigation engineering, groundwater, environmental and ecological hydraulics, and are well-known for interdisciplinary studies involving water-resources planning and management. The programs emphasize the application of advanced laboratory and field instrumentation and methods, computer technologies and numerical modeling to practical water engineering, as well as to the enlightened management of environmental and ecological systems. Today, these programs have nearly 200 graduate students. Over the years, the programs have led innumerable graduates to careers in water engineering.

Facilities

The large space and water discharge available to the lab enable it to operate substantial permanent physical facilities and have the flexibility to construct large-scale, near-prototype size, project-specific facilities. Additionally, the lab has a well-equipped machine and instrument shop to support the facilities and build experiment set-ups and instrumentation. These attributes enhance the lab's ongoing capacity to undertake a wide range of fundamental as well as applied research projects.

The lab's permanent features include a comprehensive system of fourteen pumps connected to a network of sumps (volume of 1,223 m^3). Individual pumps range in capacity from about 1.5 m^3/s at a head of 6 m, to about 0.017 m^3/s at a head of 15 m. Portable pumps of various capacities are used for experiments involving flow recirculation. The pumps connect to a fleet of flumes, although some flumes are fitted with their own pumps for flow and sediment recirculation. The fleet includes a very versatile large flume, which Figure 2 shows in use for a study on sediment control in braided channels (Ettema et al., 2015). A large recirculating flume is capable of recirculating water at a discharge of 2.8 m^3/s and gravel-size sediment. This latter flume is fitted with a wave-maker to conduct various studies on the combined effects of wave and current action. The main lab building houses four other tilting flumes and has ample room for temporary experimental installations and hydraulic models.

A 40.7-hectare outdoor area adjoins the main lab, facilitating large-scale model and full-scale prototype experiments. Additionally, a further lab building exists for testing hydro-machinery equipment (its 1 m-thick concrete floor averts flexural vibration) and is at times used to house hydraulic models and large-scale experiments. A large flume and a wave-overtopping basin are presently in frequent use. This flume includes a deep recessed section for studies involving erosion of channel beds. Since 2010, CSU has operated the largest wave overtopping test facility in the world (featured image). This facility, its need prompted by the damage wrought on New Orleans by Hurricane Katrina, is operated using a computer system that simulates waves larger than 2 m in height. The waves spill water down over "trays" that simulate levees made of soils specific to any region (Thornton et al., 2014). Various types of grass are grown in soil trays placed in

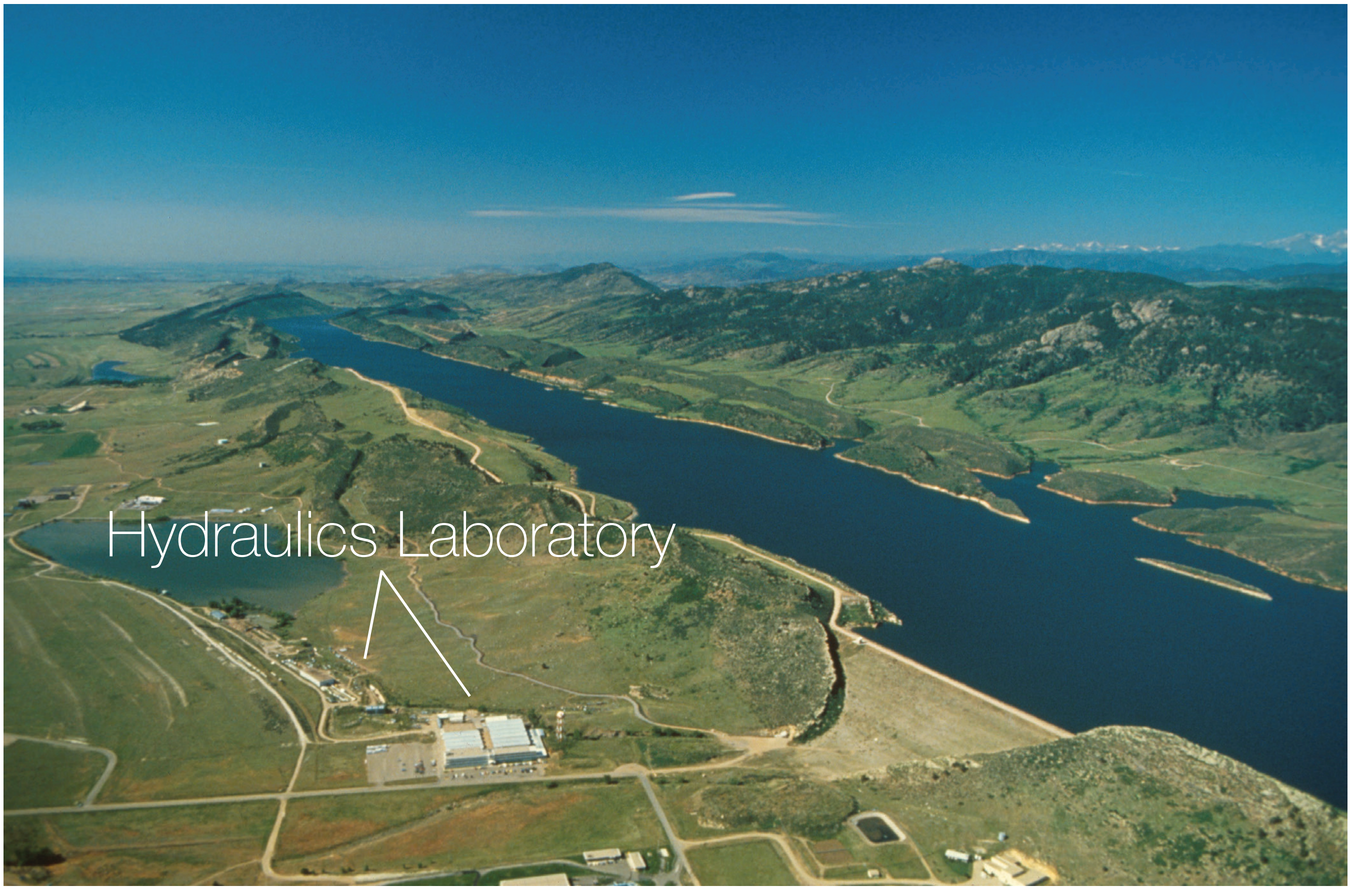


Figure 1. An aerial view of CSU's Hydraulics Laboratory at Horsetooth Reservoir.

a large greenhouse for the over-topping facility. A companion over-topping facility consisting of a concrete head box, chute, and tailbox is used for studying the erosion of soils and erosion countermeasures located on steep slopes.

Concluding Remark

By its physical and educational settings and the talents of the many people associated with it, CSU's Hydraulics Laboratory is well-positioned to continue as a national and international resource for water engineering and related sciences. Presently, CSU is seeking to position the laboratory to be part of an integrated set of research facilities for use in addressing water engineering and science issues associated with the western U.S.

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Figure 2. The 8 m by 33 m flume used to model a system of sediment-trapping structures placed in a braided-channel reach of a river that adjoins Mount Saint Helens, Washington.

Building for Research

A Photographic Essay

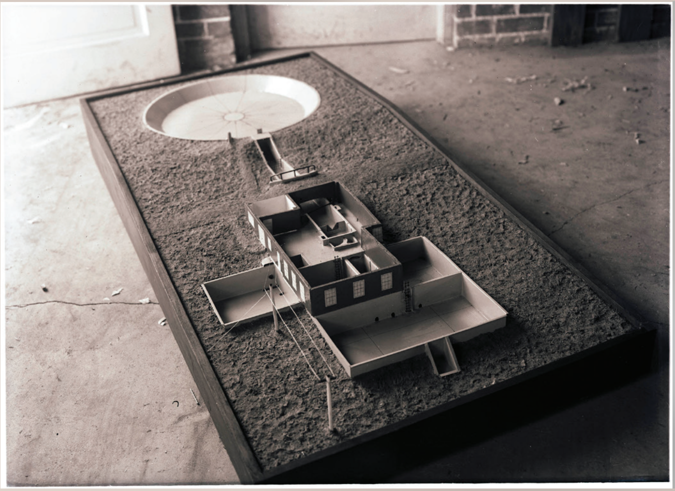
Patricia J. Rettig, Head Archivist, Water Resources Archive, Colorado State University Libraries

Back in 1912

when "west of campus" equated to where the Lory Student Center now stands at Colorado State University (CSU), planning for a new building dedicated to irrigation research began. The collaborative project involved the United States Department of Agriculture's (USDA) Fort Collins-based Irrigation Investigations Unit and Colorado Agricultural College (now, CSU).

The USDA's Victor Cone and CAC professor and alumnus Ralph Parshall led the design of the new facility. Parshall would be employed by the USDA the following year and eventually head the irrigation group until his retirement in 1948. This laboratory, and the outdoor one constructed at the Cache la Poudre River near Bellvue, served as the spaces that enabled him and his team to test equipment and ideas, including those that developed into the "improved Venturi flume," renamed for Parshall in 1930.

All photos courtesy of CSU Libraries



Innovative for its time, the lab served as an example for other institutions. The scale model, with roof removed, gave a good overview of the layout. End to end, the full-size facility measured about 240 feet.

Construction started after site selection in the spring of 1912. Lab operations began at the end of May 1913 and lasted here for five decades.

The availability of a dedicated research space attracted engineers and students alike to the modest building on the west edge of campus. This built on, and greatly expanded, the eventual university's solid foundation of and reputation for civil engineering expertise.

Work at the lab included studies on flumes, weirs, orifices, seepage, sedimentation, evaporation, and various types of meters. The team tested the Dethridge meter, an Australian invention, in the lab's rating tank in 1915.

Parshall and colleagues continually made improvements to the facility over the years. In 1925, they lined the laboratory's reservoir, 85 ft in diameter and 7 ft deep, with copper for evaporation experiments, some of the first conducted in the West.

By 1936, a significant expansion of the hydraulic lab occurred, partially funded by the Works Progress Administration. Two years after this, the Bureau of Reclamation, which had been doing testing in the lab since 1930, relocated its work to Denver. During its time in Fort Collins, the Bureau conducted tests related to the Hoover, Grand Coulee, and Imperial dams, among others.

The enlarged space was much appreciated, and collaborative experiments continued. In the early 1940s, Agricultural Experiment Station irrigation engineer Bill Code conducted numerous research projects, including measuring pipe discharge with a Hoff meter.

While these photos, which come from Parshall's USDA team—which evolved into what is now known as the Agricultural Research Service—end in the early 1950s, the lab's history continued for another decade. Lory Student Center construction began in 1962, and by 1965 it edged out the hydraulics lab. The lab's equipment was relocated to the new Engineering Research Center, which opened in 1963 on the Foothills Campus, about 3 miles west of main campus. Now, a plaque on the east side of the north end of Lory Student Center memorializes Ralph Parshall and his work at the lab site.

Though the physical building is lost to history, the lab and the work done there live on. Not only did the Parshall flume and other devices, formulas, and ideas tested there reach around the world, but CSU's continued reputation as a worldwide leader in water-related research and innovation continues to grow from these roots.

Thousands more photographs of the lab and the USDA's teamwork there and elsewhere reside in the Irrigation Research Papers at the CSU Water Resources Archive. Beyond visual formats, the collection also documents the extensive collaborative work between the USDA and CSU, especially that of Ralph Parshall, Victor Cone, Carl Rohwer, and Bill Code, on paper. Digitized portions can be viewed online, and the entire collection is available by visiting Archives and Special Collections in Morgan Library (see http://lib.colostate.edu/archives/findingaids/water/wirp.html).

For more information about the Water Resources Archive, see the website (https://lib2.colostate.edu/archives/water/) or contact the author (970-491-1939; Patricia.Rettig@ColoState.edu) at any time.

Tom Sale

Dr. Tom Sale, Associate Professor, Civil and Environmental Engineering, Colorado State University

As an undergraduate, 38 years ago, I took a groundwater course taught by Dr. Dwight Baldwin at Miami University in Oxford, Ohio. Ever since then, I have been passionately thinking about groundwater. Groundwater is an amazing interdisciplinary space that has provided a seemingly unbounded opportunity to solve problems relating to water, energy, and the environment. My educational background includes B.A. degrees in Chemistry and Geology, an M.S. in Watershed Hydrology, and a Ph.D. in Agricultural Engineering. My professional background spans over 22 years in engineering practice and 16 years in academic research and teaching.

Photo by Janice Sale

Engineering Practice

My experience in engineering practice includes extensive fieldwork, design, project management, department management, senior technical support, and independent consulting on high-level projects at state, national, and international levels. Technical highlights include construction and operation of an oil recovery system at an active refinery that achieved an oil production rate of 2,200 barrels per day and development and implementation of creosote recovery technology that produced 1.8 million gallons of high-viscosity dense non-aqueous phase liquids (DNAPL). To my knowledge, both the oil recovery rate and volume of recovered DNAPL are world records. In addition, a large part of my career has centered on developing groundwater for water supply.

Research

Since the early 2000s, I have been the director of the Center for Contaminant Hydrology (CCH) in Civil and Environmental Engineering and a lead investigator in industry funded University Consortium for Field Focused Groundwater Research. Reflecting the relevance of our work, gift funding from major industry has exceeded $7 million; similar support has come through grants. The Center has advanced ten patents and our work has been documented in over 100 journal articles, reports, and patents.

In the past years, I have been a session chair at three national conferences, a lead organizer for two meetings, and a keynote speaker at one conference. Active participation in key meetings and continuous conversations with our sponsors has kept our work and students at the cutting edge of current issues.

Most, importantly the center has supported over 90 students including 30 undergraduate, 40 M.S. students, and 20 Ph.D. students. Our biggest success has been the people we have prepared to meet the world's emerging challenges. Impressively, our students are highly sought after by industry, government, and academia.

Teaching

My teaching has included short courses and upper-level courses. Upper-level courses have covered Introduction to Groundwater, Contaminant Transport, Wells and Pumps, and Modern Oil & Gas. In these courses, it has been my goal to advance fundamental knowledge and skills that can serve as foundation for lifelong learning and remarkable careers.

Beginning this summer, we will teach a new CIVE580B2 Applied Groundwater Field Experience class. This course is intended to provide students with direct hands-on experience with practical concepts, techniques, and methods used by practicing professionals in the water supply, agricultural, and environmental professions. When I am not occupied with research and teaching, I enjoy outdoor activities with my family and friends.

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(Above Photo) Horsetooth Reservoir. Photo by Cassandra Turner

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Heron Lake at Pella Crossing. Hygiene, Colorado

Bryce Bradford