FINAL REPORT

South Metro Water Supply Authority

Aquifer Storage and Recovery Feasibility Study

September 2018

CDM Smith

Table of Contents

List of Figures

List of Tables

List of Appendices

Page intentionally left blank.

Acronyms

2D	two-dimensional
3D	three-dimensional
ACWWA	Arapahoe County Water and Wastewater Authority
ac-ft	acre-feet
AFY	acre-feet per year
amsl	above mean sea level
ASR	aquifer storage and recovery
C	well loss coefficients
CBL	cement bond log
CCR	Colorado Code of Regulations
CDPHE	Colorado Department of Public Health and Environment
CDWR	Colorado Division of Water Resources
CFR	Code of Federal Regulations
CSU	Colorado State University
CWCB	Colorado Water Conservation Board
CWSD	Centennial Water and Sanitation District
DOE	U.S. Department of Energy
ECCV	East Cherry Creek Valley Water and Sanitation District
EPA	U.S. Environmental Protection Agency
FCV™	Baski InFlex™ Flow Control Valve
ft/d	feet per day
ft^2/day	square feet per day
FRP	fiberglass reinforced plastics
gpm	gallons per minute
gpm/ft	gallons per minute per foot
HP	horsepower
IGA	Intergovernmental Agreement
kWh	kilowatt hour
m^2/d	square meters per day
m^3/d	cubic meters per day
MD	metropolitan district
µg/L	micrograms per liter
MG	million gallons
MGD	million gallons per day
mg/L	milligrams per liter
NCPA	Northern California Power Agency
PLC	programmable logic controller
psi	pounds per square inch
PW	Prairie Waters
Rangeview	Rangeview Metropolitan District
REDOX	reduced anoxic condition
ROI	radius of influence
SC	specific capacity
SCADA	supervisory control and data acquisition
SI	specific injectivity
SMCL	secondary maximum contaminant level
SMWSA	South Metro Water Supply Authority
SWL	static water level

SWSI	Statewide Water Supply Initiative
T	transmissivity
TDH	total dynamic head
TDS	total dissolved solids
TSV	target storage volume
UHMW	ultra-high molecular weight
UIC	underground injection control
USDW	underground source of drinking water
USGS	U.S. Geological Survey
VoSmart	variable orifice selective monitored artificial recharge throttle valve
VoV	variable orifice valve
WDA	Water Delivery Agreement
W&SD	water and sanitation district
W&WD	water and wastewater district
WISE	Water, Infrastructure, and Supply Efficiency Partnership
WISE Authority	South Metro WISE Authority

Executive Summary

This report documents the feasibility assessment of aquifer storage and recovery (ASR) at a local and regional scale of implementation in the Denver Basin as a water management strategy to meet the South Metro Water Supply Authority (SMWSA) member's future demands. This report was prepared through a Water Supply Reserve Account grant from the Colorado Water Conservation Board (CWCB) via the Metro Basin Roundtable.

Background

In 2004, CWCB completed the first phase of the Statewide Water Supply Initiative. That study included estimates of unmet water demands in the South Platte Basin, including over 40,000 acre-feet per year (AFY) in the South Metro Denver area, based on an assumption that existing levels of groundwater pumping could continue indefinitely. The southern metro area relies on groundwater supplies from the Denver Basin bedrock aquifers, the majority of which lie below a nearly impermeable geological formation and have very low rates of annual recharge, and are thus considered nonrenewable groundwater supplies.

A dramatic increase in groundwater withdrawals over the past two decades within the South Metro area has led to potentiometric surface declines. As a result, water providers in the South Metro area joined together as SMWSA to coordinate on a variety of activities leading to more sustainable water supplies. A 2007 study conducted for the CWCB under Colorado Senate Bill 06-193 evaluated potential locations for underground water storage in the South Platte and Arkansas River Basins. The study identified several areas within the Denver Basin bedrock aquifers, which included most of the SMWSA area, as good candidate underground water storage locations.

Within the SMWSA region, the Centennial Water and Sanitation District (CWSD) has a long and successful ASR program. Given this, and the area's groundwater background, it was appropriate and opportune for a pilot-scale ASR testing program to be undertaken to evaluate the feasibility of implementing ASR in additional areas within the SMWSA region using water sources that are variable in quality and quantity but more likely to be available in the future for ASR programs.

One original objective of the 2007 study was to perform a pilot-scale ASR testing program using Water, Infrastructure, and Supply Efficiency (WISE) project supplies to test and confirm the viability of ASR using identified renewable supplies. Unfortunately, this objective was not realized due to unforeseen circumstances with the proposed well and limited ability to supply WISE water to other wells at the time, therefore this option was abandoned. The information gained through the initial portions of this study was documented in an interim report and the study was put on hold until a WISE interconnect with Aurora Water could be completed.

The study restarted in 2016, maintaining the overall objective to gain additional understanding of ASR in the Denver Basin as a method of meeting future water supply needs in the South Metro region. The focus shifted to identifying additional information and developing tools to support entities in evaluating the feasibility of implementing ASR.

The following revised objectives were developed for Phase II of the SMWSA ASR feasibility study:

1. Provide a summary of ongoing ASR programs in the Denver Basin/South Metro area, including their status, historical operations, and lessons learned.
2. Develop tools and resources for water providers to assess ASR for their respective communities. This would include an economic costing tool to assess costs, and permitting guidance and geochemical analysis to test compatibility of supplies within the aquifer.
3. Provide recommendations for full-scale implementation of ASR in the South Metro area, including water pre-treatment needs, well preparation and retrofitting, and operations and maintenance.
4. Perform an analysis of groundwater levels in the South Metro area.
5. Provide recommendations for ongoing data collection programs to assist in developing a groundwater model.

This report documents the assessment of ASR feasibility in the South Metro area. It presents a summary of ongoing and planned ASR programs, tools developed to assess ASR, and recommendations for implementing ASR and ongoing data collection programs.

ASR Considerations

When evaluating ASR as a potential water supply management strategy, several components need to be considered at the onset to confirm the viability of implementation. These are:

- Recharge objectives
- Hydrogeology
- Geochemical compatibility
- Existing and proposed infrastructure
- Permitting
- Economics/costing

Recharge Objectives

ASR projects throughout the United States have been developed with multiple recharge objectives. Primary recharge objectives may be grouped into three broad categories: water storage, water utility operational or infrastructure needs, and environmental benefits. Storage is a primary objective of most ASR operations, but all three objectives should be considered in ASR planning.

Storage

Storage objectives can include seasonal storage, long-term storage (banking), emergency storage/supply, and storage of reclaimed water. The 2007 study of the South Platte and Arkansas River Basins concluded that significant portions of these basins' alluvial regions are acceptable for underground storage, including portions of the Dawson and Arapahoe aquifers. The study also identified several viable locations where ASR can be implemented.

Operation/Infrastructure

Improving water resource system operations is also a primary objective of many ASR operations. CWSD has experienced increased well performance from its groundwater wells because of its ASR program. This is a common occurrence for ASR systems with dual purpose wells due to the increased flushing of the well and its appurtenances by cycling water during injection and recovery phases.

Environmental Benefits

In addition to operational improvements, many environmental benefits can be realized due to implementing and operating a successful ASR program. For stressed aquifers, one primary benefit is often to slow or stop depletion by rebalancing the natural recharge and current pumping with increased, replenishing inflows. Also, if properly engineered and operated, the water stored in an ASR system is not subject to the evaporative losses encountered in surface storage reservoirs and remains available for future use.

Hydrogeology

Hydrogeology is assessed by identifying the target recharge zones and understanding the hydrogeologic properties of the aquifer or aquifer system and the geochemical compatibility of the source water and the rock-water in the receiving aquifer. A wide range of aquifer conditions are possible for successful implementation of ASR. Every location is unique, but to be successful, the hydrogeology must align with the ASR recharge objectives. Overall, the Denver Basin Bedrock Aquifer units (**Figure ES-1**) are favorable for ASR but need to be assessed along with the other considerations for specific situations.

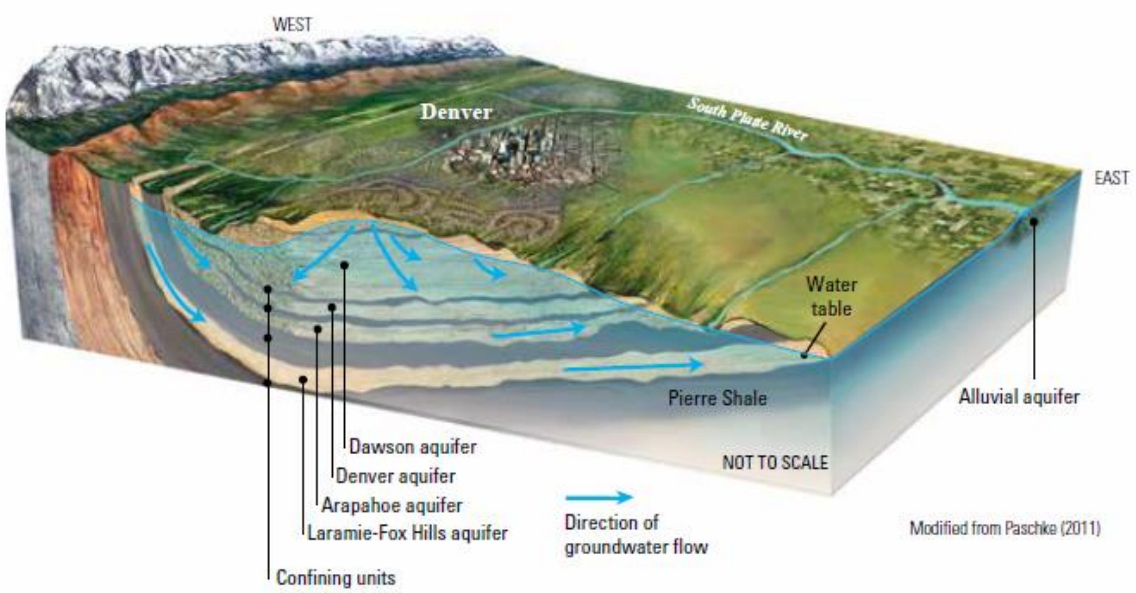


Figure ES-1 Conceptual Block Diagram Illustrating the Hydrogeologic Features of the Denver Basin Aquifer System

Geochemical Compatibility

One of the major considerations of implementing ASR is confirming the geochemical compatibility of the recharge water with the aquifer rock and groundwater in the receiving aquifer. This includes assessing the potential for plugging the recharge interval due to excess turbidity, assessing the entrained air for adverse geochemical reactions, and ensuring the water quality of the source water being recharged meets regulatory requirements.

Part of determining the likely success of ASR is initially gained by understanding the potential for geochemical reactions and the degree of mixing with the native groundwater. During the period when water is recharged into the aquifer, stored, and then recovered, the water quality of the source water may change as it equilibrates with the groundwater and minerals in the aquifer.

Based on the conditions at the Rangeview Metropolitan District (Rangeview) A-20 well and source water quality anticipated from Aurora, modeling of the treated water and Arapahoe groundwater was performed using the U.S. Geological Survey's PHREEQC model (Parkhurst and Appelo 1999). PHREEQC is an equilibrium speciation model that considers ionic complexing, activity effects, and the temperature and pressure conditions of the water being modeled to predict the saturation state of various minerals. The mixing evaluation looked at potential precipitation and dissolution reactions that could affect the quality of the water or the permeability of the aquifer. The processes of potential concern, the results of the evaluation, and the possible mitigation measures are presented in **Table ES-1**.

Table ES-1 Summary of Concerns, Results, and Possible Mitigation Measures Obtained During the Evaluation of Treated Aurora Water and Arapahoe Aquifer Groundwater Water Quality

Concern	Results	Possible Mitigation Measure
Precipitation of iron minerals	Predicted to occur but not likely to be a problem due to low iron concentrations (0.05 mg/L or less)	na
Precipitation of manganese oxide minerals	Not predicted to occur based on modeling	na
Precipitation of carbonate minerals	Not predicted to occur unless degassing of carbon dioxide (CO_2) occurs	Could be mitigated by pH adjustment using an acid
Dissolution of arsenic-bearing pyrite	Based on previous ASR projects within the Arapahoe Formation (i.e., Willows Well A-6A), no increase in arsenic is observed as a result of pumping oxygenated treated water into the formation	na
Dissolution of uraninite (a uranium-rich mineral)	Not predicted to occur based on modeling results	na

mg/L – milligrams per liter; na – not applicable

Note, although not fully considered in this evaluation, the potential for bio-fouling should also be considered. Bio-fouling is not common with the injection of treated water with a residual chlorine level, but issues were observed during recent ASR cycle testing of a Laramie-Fox Hills aquifer well.

Existing and Proposed Infrastructure

The most successful ASR wells are those that have been specifically designed for both recharge and recovery. There are some subtle and some not-so-subtle differences in the way a well behaves when in recharge mode compared to conventional withdrawal. For example, there are differences in hydraulic behavior, particularly in wells that intersect unconsolidated sediments and/or require well screens with gravel packs. Gravel packs are prone to plugging during recharge, therefore, the screen and gravel pack design must be sized to allow adequate backflushing or well development to remove any accumulated fines that would otherwise reduce the well performance.

Fortunately, potential exists for the retrofit of existing wells in the Denver Basin, primarily because the wells intersect competent bedrock aquifers with groundwater quality similar to the recharge water quality being contemplated. One of the primary reasons for considering the retrofit of wells is because the cost of a drilled ASR well, constructed to the depths and diameters required, can be significant. Nevertheless, it should be recognized that if retrofitted wells are used and the casing material is conventional carbon steel, then the asset life of the well will potentially be much shorter than if the well were used only for conventional supply.

Water Utility Infrastructure

The ideal hydrogeological location for siting ASR wells may not necessarily occur where existing water utility infrastructure is located, including the location of any diversion and surface water storage system (in-channel or off-channel) used so that recharge water may be temporarily stored prior to recharge. The cost of moving water can be expensive, therefore well siting needs to consider this factor. Although the cost of drilling ASR wells can also be expensive, the overall project cost may still be less with an additional ASR well to make up for any loss in well yield, rather than installing additional pipelines to convey the recharged and recovered water.

Permitting

There are unique regulations and permits that must be obtained to construct or retrofit an existing well for ASR. These permits may vary based on location and the purpose of injection. For ASR in the Denver area, permits must be obtained from the Colorado Division of Water Resources, the Colorado Department of Public Health and Environment, and the U.S. Environmental Protection Agency.

ASR Programs and Plans in Denver Basin

One of the objectives of the feasibility study was to summarize the ongoing and planned ASR projects in the Denver Basin/South Metro area. Since completing Phase I, several entities have embarked on their own ASR studies and programs. To gain a better understanding of each entity's ASR program, CDM Smith, on behalf of SMWSA, reached out to each member entity through a series of phone calls, surveys, and meetings. A summary of the survey results are shown in **Table ES-2**. The information obtained through this process is important in assessing the viability of ASR as part of the water supply solution for each water provider in the South Metro area.

Table ES-2 Overview of Existing and Planned ASR Systems in SMWSA

Member	Status	Source Water	Number of ASR Wells
CWSD	existing system	South Platte River	33
East Cherry Creek Valley Water and Sanitation District (W&SD)	existing pilot system and planned expansion	Northern Water Supply Project	1 (pilot)
Rangeview	existing pilot system and planned expansion	WISE	1 (pilot)
Town of Castle Rock	existing pilot system and planned expansion	WISE, Plum Creek surface water and alluvial water, treated reuse water	2 (pilot)
Cottonwood W&SD	Permitting for ASR	Cherry Creek, WISE, and Denver Basin groundwater	3
Dominion W&SD	Planning for ASR and partnering with Castle Rock	WISE	Currently unknown
Inverness W&SD	Permitting for ASR	Denver Water, Denver Basin groundwater, WISE, and Cherry Creek (when developed)	4
Meridian Metropolitan District	Permitting for ASR	Denver Basin groundwater and WISE	1 to 2
Pinery Water and Wastewater District	Planning for ASR	WISE and Cherry Creek alluvial well water	Up to 9

Denver Water

Denver Water is undertaking a feasibility study of ASR within the bounds of the City and County of Denver. The focus of the data collection is to obtain additional hydrogeologic data, since hydrogeologic information within the city and county is not as prevalent as other areas of the Denver Basin. The project consists of drilling eight boreholes, collecting core samples, and evaluating the hydrogeologic properties of the core. Denver Water is looking at ASR as a viable alternative to future, increased surface storage; however, preliminary results of the study show an ASR program within the city and county may be limited due to the properties of the Denver Basin aquifers within the city's boundaries, and land access concerns as Denver continues to urbanize and experience infill.

Aurora Water

Aurora Water is considering ASR as a future storage option that would primarily serve as drought supply. Currently, the utility is not conducting any formal studies; however, they have added technical staff that will be exploring the potential for ASR in more depth in the near future. The City of Aurora, as part of their annexation process, also obtains rights to Denver Basin groundwater as their service area grows. In addition, Aurora Water's Peter D. Binney Purification Facility, located near Aurora Reservoir, serves as the primary treated water supply for WISE water and serves as a source of injection water for Aurora Water as well as WISE participants.

Tools to Support ASR Planning

Another ASR feasibility study objective was to develop tools and resources for water providers to assess ASR for their respective communities. The development of tools and resources is valuable for the assessment of ASR in the Denver Basin due to the potential program scale and interrelated technical issues that must be considered. The tools developed allow for user-specified inputs to assist in the performance and economic comparisons of ASR facilities in different sites and configurations, and for comparisons with other storage and management approaches.

Hydrogeologic Conceptual Model

Fundamental to a successful ASR program is having favorable hydrogeological conditions underlying the wellfield. The conceptual understanding of the Denver Basin aquifers has recently undergone modification as new and unpublished data have been evaluated. In coordination with Colorado State University (CSU), the results from two hydrogeologic case studies illustrate this and have contributed to a better understanding of basin hydrogeology and how it might integrate with a potential ASR system.

Water Level Prediction Tool

In the context of ASR site screening, water level prediction tools are beneficial for simulating recharge mounding and localized aquifer-level responses to recharge and recovery. Fundamental to applying predictive tools is having reasonable initial estimates of aquifer parameters (e.g., transmissivity, storage coefficients, and water levels) that match historical data and achieve the desired degree of correspondence between the model simulations and observations of the groundwater flow system.

Historical (observed) groundwater head data provided by CWSD at each of the district's Arapahoe aquifer wells were evaluated using an analytical model based on the Theis superposition approach. The model accounts for well interference effects and the influence of recharge and recovery influences on local water levels, and provides an option to incorporate two well loss coefficients at each well to account for different recharge and recovery rates (**Figure ES-2**).

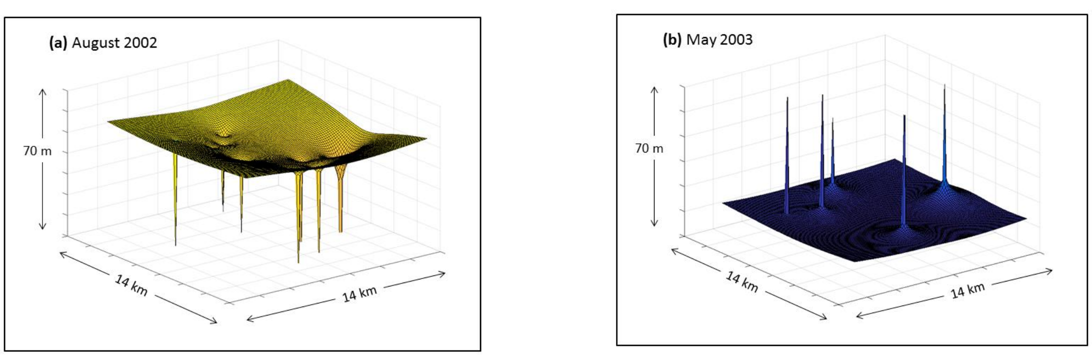


Figure ES-2 Spatially Distributed Drawdowns During Recharge and Recovery – Graphic Representation from Theis Wellfield Superposition Analytical Model (Sale et al. 2017)

Economic/Costing Tool

Cost estimating is one of the most important steps in the site screening process. A cost estimate was developed that allows for economic comparison of competing approaches selected to address a specific design objective, for comparing different configurations of design alternatives, and establishing the baseline of the project cost at different stages of development (Hendrickson 1998). However, due to relatively low levels of project definition at the concept screening level, the accuracy of the estimate can range from -50 percent to +100 percent of the bid/tender estimate (American Association of Cost Engineering 2005).

ASR Local and Regional Planning

For this planning exercise, a preliminary evaluation of the local hydrogeology has been completed using published data, SMWSA member borehole information previously provided during earlier studies, and a follow up questionnaire as part of this study. A summary of the hydrogeological evaluation is presented in Section 5.1.

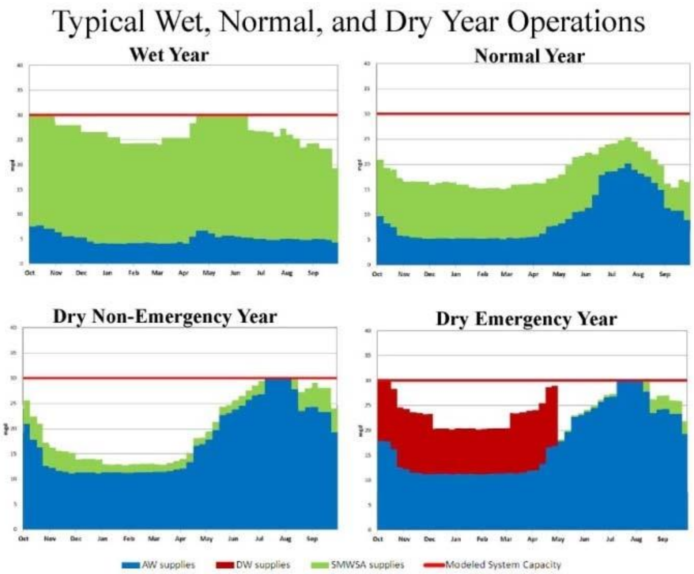
A primary recharge objective for SMWSA members is to store surplus WISE water, as described in Section 5.3, so that additional water may be available to offset the use of potentially nonrenewable groundwater. However, it has quickly become apparent that there may be additional recharge benefits beyond storing surface WISE water in different aquifers.

Aquifer water level declines are not uniform across the region, and there are aquifers with locations where water levels are greater than 100 feet below the top of well screens with pumping water levels that are even lower. These are not favorable aquifer conditions for multiple reasons. Therefore, a recommended secondary recharge objective is the restoration of aquifer levels. The technical difficulty is the cone of influence (i.e., the radius at which significant rises in aquifer water levels occur) around each well used for recharge is relatively limited. Therefore, to be more effective and provide greater environmental benefit, more closely spaced wells in a single aquifer creating recharge mounds that will locally replenish depleted aquifer heads and allow improved recovery characteristics is likely the preferred approach.

WISE Authority Program

In February 2008, Aurora Water and Denver Water entered into an Intergovernmental Agreement (IGA) with the WISE Authority to investigate cooperative water supply opportunities (i.e., the sharing of water and/or infrastructure that could be mutually beneficial). Sharing available excess infrastructure capacity and available excess water supplies provides significant benefits to all three partners. Aurora and Denver offered to make available 100,000 acre-feet (ac-ft) every 10 years. Of this, the WISE Authority subscribed to 72,250 ac-ft every 10 years with an average delivery of 7,225 AFY. Under an option agreement with Douglas County, the project can grow to the full 100,000 ac-ft per 10 years. Deliveries are based on the current Water Delivery Agreement ; if additional options are exercised, delivery volumes and flow rates will be adjusted accordingly. Long-term WISE delivery commitments are shared equally by Aurora Water and Denver Water, although daily deliveries from each entity may vary based upon availability.

WISE water deliveries can vary significantly from year to year and are interruptible. Annual deliveries can range from 0 up to a maximum of 18,063 ac-ft. the WISE Authority can manage the variability of WISE supplies because they have alterative supplies during years of minimal WISE availability. Some WISE Authority water providers may store WISE water in Parker Water's Rueter-Hess Reservoir or in ASR facilities, further firming the yield of the project.



The initial engineering studies for WISE showed that the components of the project, excess Prarie Waters capacity and available supplies from Aurora and Denver Water, fit together remarkably well. WISE water deliveries are possible due to the manner in which the partners' water supplies and infrastructure can be utilized both seasonally and under varying hydrologic conditions. The chart to the left shows examples of how WISE could operate in modeled wet, normal, and dry years, and in a year when Denver Water needs to use its supplies. The blue area represents Aurora's planned use, the red area represents Denver's use, and the green area represents water available to the WISE Authority. The chart shows Denver Water using its supplies during a dry year for illustration. The red line represents the capacity of Aurora's Prarie Waters (PW) system.

When evaluating each of the considerations identified above for assessing the feasibility of local (individual) and regional ASR planning, several viable options stand out at the local and regional level. These options will need to be considered in relation to each SMWSA member utilities' objectives and plans.

Individual ASR Approach

Individual ASR development has significant merit, primarily because it will offset the use of unsustainable, nontributary groundwater supplies. Although recharge that is more evenly distributed amongst member utilities is less likely to result in locally replenished aquifer levels, it will still offset the use of groundwater by replenishing some of the withdrawals. In addition, it is less complicated operationally, since operations are performed within a member's own system.

Regional ASR Approach

The hydrogeologic review has identified the Arapahoe aquifer as the primary target aquifer for ASR implementation at a regional-scale. It has the highest aquifer permeabilities/well performance as measured by specific capacities (**Figure ES-3**), and there are several locations with significantly declined aquifer levels that would benefit from replenishment. Although the Denver aquifer has a slightly lower specific capacity, it also may benefit from a regional ASR project, particularly in the Castle Rock area. The Laramie-Fox Hills aquifer has possible promise for the Highlands Ranch area, but currently there is insufficient data to demonstrate its regional viability, and the depleting aquifer heads in the overlying aquifers are likely a higher priority.

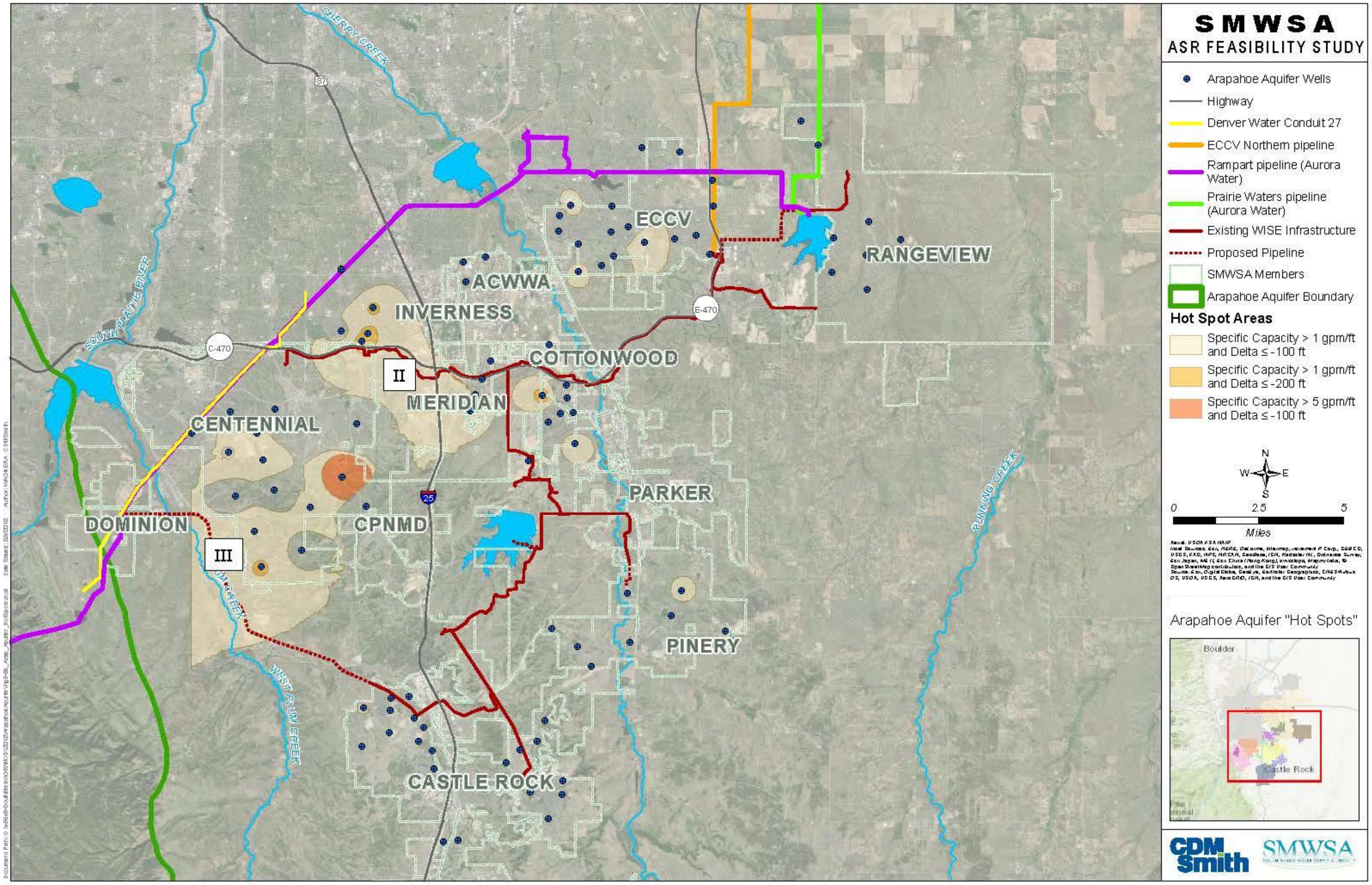


Figure ES-3 Favorable Locations in the Arapahoe Aquifer for ASR

There are generalized risks and benefits associated with all the local and regional options considered in this study. For comparison, specific benefits and challanges associated with each option are summarized in **Table ES-3**.

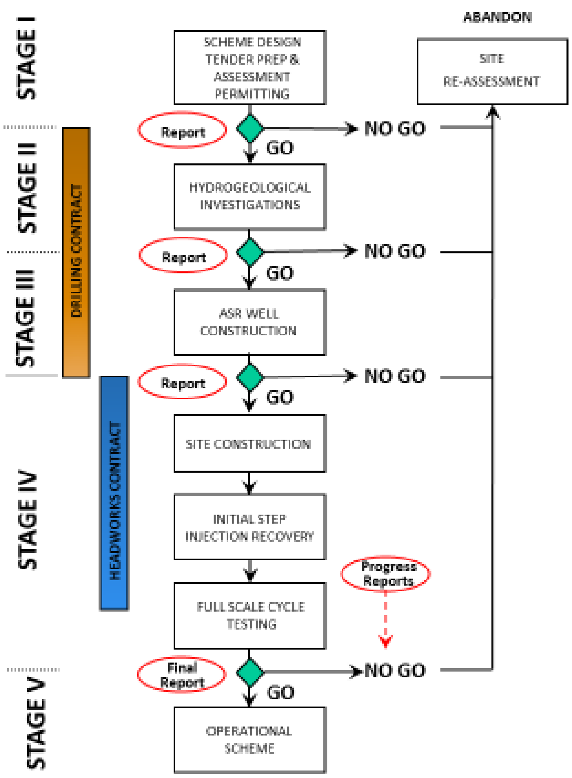
Table ES-3 ASR Option Benefits and Challanges

Option	Aquifer	Benefits	Challenges
Local Implementation			
IL	Dawson	Seasonal storage	Lower priority for recharge
IIL	Denver	Seasonal storage, drought banking, aquifer replenishment	Well spacing required for recharge mounding in areas of depleted groundwater not understood.– Care needed in areas of declining water levels.
			Lower aquifer permeabilities except south, where permeabilities need to be confirmed. Variable permeabilities and the potential local leaching of radionuclides may be a concern
IIIL	Arapahoe	Seasonal storage, drought banking, aquifer replenishment	Well spacing required for recharge mounding in areas of depleted groundwater not understood. Care needed in areas of declining water levels.
IVL	Laramie-Fox Hills	Seasonal storage	Low aquifer permeabilities, with the exception of one well in the Highlands Ranch area, therefore generally low priority for recharge
Option	**Aquifer/Member**	**Benefits**	**Challenges**
Regional Implementation			
IR	Denver, Castle Rock	Replenish locally depleted groundwater	Need to confirm aquifer permeabilities are suitable
			Additional conveyance infrastructure likely required unless focus is with just adjacent member utilities
IIR	Arapahoe, Meridian	Replenish locally depleted groundwater	Locating sufficient well sites
		Strategically located close to WISE water infrastructure	Well spacing required for recharge mounding not understood
IIIR	Arapahoe, Centennial	Replenish locally depleted groundwater	Additional ASR wells required, leading to increased costs
		ASR proven with ASR wellfield already in place	Well spacing required for recharge mounding not understood
		Treatment plants for iron and manganese removal already in place	Ability to convey recovered water to member utilities not understood, additional expensive infrastructure may be required

Implementation Steps

ASR projects are typically implemented in phases. A phased program reduces risks and costs by ensuring the next phase of work is only implemented if the previous phase is successful (**Figure ES-4).** Implementation typically includes the following broad phases:

- Preliminary desk-top based feasibility and planning studies
- Design and permitting for an ASR pilot/demonstration project
- Exploratory well program (or assessment of existing wells intended for retrofitting)
- ASR pilot/demonstration construction
- Operational testing
- ASR system expansion



For the SMWSA member utilities, the feasibility and planning studies that need to be completed depend on the recharge objectives. For local implementation focused on recharging Denver Basin aquifers with WISE water to offset use of unsustainable, nontributary groundwater, more traditional approaches may be followed as outlined above. Primary considerations include the selection and use of existing wells for retrofitting versus the drilling of purpose-built ASR wells. Using the pricing tools developed as part of this study, ASR solutions can be compared with other water resource alternatives to ensure appropriate implementation.

For regional implementation with additional recharge objectives that consider restoring depleted groundwater levels in the most impacted aquifer locations, additional feasibility evaluations are required.

Recommendations

To offset the groundwater declines resulting from historic and ongoing withdrawals from the Denver Basin aquifers, supplementing the natural recharge with artificial recharge is potentially a key water management strategy and has already been successfully implemented in the past by CWSD. Several other SMWSA utility members including Castle Rock are actively engaged in implementing ASR programs. The potential for recharging WISE water into one or more Denver Basin aquifers is a significant opportunity, although the volumes of water proposed are still a smaller percentage of the total groundwater withdrawn by SMWSA member utilities. Therefore, careful consideration is required in order to maximize this opportunity.

To move these projects and opportunities forward, the following recommendations (which essentially fall into three categories) are made:

- Define recharge objectives
- Develop and improve planning tools
- Path forward

Define Recharge Objectives

Two broad recharge approaches have been identified: local ASR development and regional ASR development. Within these two broad approaches, there are specific recharge objectives that include offsetting seasonal groundwater use to meet peak water demands with WISE water, recharging and storing surplus WISE water during wet years for drought banking, and replenishing depleted groundwater levels. Clear resolution of the appropriate recharge objectives is required to be successful.

Develop and Improving Planning Tools

The tools, developed in collaboration with CSU during Phase II of this study, provide a significant step forward in understanding and making decisions for ASR. However, benefits can be gained from the following enhancements:

- The hydrogeologic model is a synthesis of hydrogeologic data using geophysical log plots, formation strata picks, and pump test data to identify the lateral extent and suitability for ASR storage zones, but wellfield-scale analysis can be improved with additional data released by member utilities.

- The water level prediction tool would benefit from user interfaces or a user manual to aid use of this tool. Ongoing data collection programs that include water level monitoring and analysis of aquifer test data is required to ensure the tool is applied using the best available data. The water level prediction tool is an analytical model designed for application at a wellfield scale and is calibrated by adjusting aquifer parameters to match observed water level changes. Therefore, to ensure accuracy, ongoing data collection programs that include water level monitoring and analysis of aquifer test data are needed.

- The economic costing tool is currently suitable for planning-level estimates but would benefit from several refinements, including adding functionality to account for increased lifting costs related to well performance degradation with time, and refining the head loss calculations and indexing of costs.

Path Forward

For local ASR development, the feasibility evaluation and planning steps outlined in this report are recommended, including use of the tools offered. For member utilities still deciding whether to proceed with ASR, the economic costing tool should be helpful for comparing ASR costs with other water supply alternatives.

For regional ASR development, increased member coordination will be required to consider key components, which include confirming hot spots, formulating share agreements, completing further groundwater modeling, and better understanding hydraulic constraints to identify infrastructure needs and opportunities. Given the coordination required for regional implementation, it is appropriate for SMWSA to assume a continued leadership role, using ASR specialists as needed and guidance from a technical steering committee to ensure the best interests of the member utilities are met. There are significant opportunities for ASR development with WISE water deliveries as potential source of recharge water, and existing infrastructure for groundwater withdrawals from the Denver Basin. Although the volumes are notable, they do not fully offset the current groundwater withdrawals. However, with careful planning and coordination, the benefits can be maximized, with the ultimate benefits of reducing SMWSA members' reliance on nonrenewable groundwater and providing a drought reserve when renewable supplies are unavailable.

Section 1

Introduction

1.1 Background

In 2004, the Colorado Water Conservation Board (CWCB) completed the first phase of the Statewide Water Supply Initiative (SWSI). The study included estimates of unmet water demands in the South Platte Basin including over 40,000 acre-feet per year (AFY) in the South Metro Denver area (CWCB 2004). This 40,000 AFY gap assumed that existing levels of groundwater pumping could continue indefinitely. The southern Metro area relies on groundwater supplies from the Denver Basin bedrock aquifers, the majority of which lie below a nearly impermeable geological formation and have very low rates of annual recharge and so are considered nonrenewable groundwater supplies.

There has been a dramatic increase in groundwater withdrawals over the past two decades within the South Metro area, which has led to potentiometric surface declines. As a result, one of the key findings from SWSI is that continued reliance on nonrenewable, nontributary groundwater supplies brings serious concerns over the reliability and sustainability of this supply along the Front Range.

Water providers in the South Metro area joined together as the South Metro Water Supply Authority (SMWSA) to coordinate on a variety of activities leading to more sustainable water supplies. In 2004, the South Metro Water Supply Study (Black & Veatch 2004) was completed on the effects of future pumping of the Denver Basin bedrock aquifers by SMWSA water providers through 2050. This study concluded that substantial investment in new wells will be required just to meet current demands. Alternative sources of supply, including conservation, reuse, and conjunctive (combined surface and groundwater) use, were recommended as methods to extend the life of the bedrock aquifer supplies. The Underground Water Storage Study (CDM Smith 2007) conducted for the CWCB under Colorado Senate Bill 06-193 evaluated potential locations for underground water storage. That study identified several areas within the Denver Basin bedrock aquifers and within SMWSA boundaries that would be suitable for underground water storage locations.

The Centennial Water and Sanitation District (CWSD) has a long and successful aquifer storage and recovery (ASR) program. Given this, and the area's groundwater background, it is appropriate and opportune for a pilot-scale ASR testing program to be undertaken to evaluate the feasibility of implementing ASR within the SMWSA region apart from CWSD's program, using water sources that are variable in quality and quantity but more likely to be available in the future for ASR programs.

The objective of this ASR feasibility study is to build upon and gain additional understanding of ASR in the Denver Basin as a method of meeting future water supply needs in the South Metro region. The SMWSA began Phase I of an ASR pilot project in 2011. The purpose of Phase I was to identify existing wells to retrofit for ASR and perform pilot testing using a water supply of similar water quality to the supplies SMWSA members may receive via the Water, Infrastructure, and Supply Efficiency (WISE) project. SMWSA began the ASR pilot project in 2011 to identify existing wells to retrofit for ASR and perform pilot testing using a renewable surface water supply and build upon the existing knowledge of ASR in the Denver Basin aquifers.

The ASR pilot study started by assessing available infrastructure to identify areas where a potential interconnect was feasible and candidate entities existed within range of these potential interconnects. During discussions with the South Metro Technical Advisory Team (selected by SMWSA members including Mark Palumbo, Courtney Hemenway, Bruce Lytle, Scott Mefford, Eric Hecox, and Rick Marseick), a consensus was reached recommending incorporating a monitoring well to help assess the fate of injected water and geochemical interactions in the aquifer. An Arapahoe aquifer well owned by the Rangeview Metropolitan District (Rangeview), Well A-20, was identified as a good candidate for ASR retrofitting due to its proximity to WISE water supplies, which would be delivered by Aurora Water. This option was investigated, agreements were developed, and a design for a temporary pipeline and appurtenant equipment was prepared. A draft field operation plan for conducting the injection and recovery testing and monitoring was prepared in May 2013. However, due to issues with permitting and logistics at the Well A-20 site, this option was eventually abandoned.

Before the decision was made to abandon the Well A-20 site, valuable information for implementing ASR in the Denver Basin in the South Metro area was obtained. When evaluating the first location (Well A-20), a geochemical compatibility analysis was performed to verify no adverse chemical reactions would occur due to the water quality of the source water and aquifer. Available information on mineralogy of the target aquifers was also compiled for this analysis. A limited water quality database was developed using information provided by SMWSA entities. SMWSA established a working relationship with Aurora Water to supply water for the ASR pilot testing. When working with Aurora Water, interconnection requirements and concerns were identified to provide renewable supplies. The U.S. Environmental Protection Agency (EPA) was contacted and the ASR permitting requirements were identified.

A second existing well was identified for retrofitting for ASR—East Cherry Creek Valley Water and Sanitation District's (ECCV’s) State Land Board wellfield Well A-6, operated by Rangeview. The feasibility of using this site for the pilot ASR test was investigated. It was determined that the costs to perform the pilot test at this location would exceed the funds available, and after an attempt to rehabilitate this well by Rangeview, it was determined that Well A-6 was not suitable for ASR.

The efforts untaken and lessons learned during Phase I were documented in the *SMWSA Aquifer Storage and Recovery Pilot Study Interim Report* (CDM Smith 2014), **Appendix A**.

The scope and priorities of Phase I changed as the project progressed; the current focus is to gain additional understanding of the use and cost effectiveness of ASR as a function of meeting future water supply needs in the South Metro region.

1.2 Study Objectives

After consultation with SMWSA staff and the Technical Advisory Team, the study objectives were updated for Phase II to meet the South Metro area's water supply planning needs. ASR has the potential to provide additional storage, maintain existing groundwater supplies, and provide additional supplies during dry years. This, combined with additional water supplies being identified such as WISE, will provide additional resources for the South Metro area to meet their future needs and address the gap identified in SWSI.

The Phase II SMWSA ASR study objectives are to:

1. Provide a summary of ongoing ASR programs in the Denver Basin/South Metro area, including their status, historical operations, and lessons learned.
2. Develop tools and resources for water providers to assess ASR for their respective communities. This would include an economic costing tool to assess costs and permitting guidance and geochemical analysis to test compatibility of supplies within the aquifer.
3. Provide recommendations for full-scale implementation of ASR in the South Metro area, including water pre-treatment needs, well preparation and retrofitting, and operations and maintenance (O&M).
4. Perform an analysis of groundwater levels in the South Metro area.
5. Provide recommendations for ongoing data collection programs to assist in the development of a groundwater model.

This report documents the assessment of ASR feasibility in the South Metro area, and presents a summary of ongoing and planned ASR programs, tools developed to assess ASR, and recommendations for implementing ASR and ongoing data collection programs.

Page intentionally left blank.

Section 2

ASR Considerations and Planning

This section summarizes the information, analysis, and permitting required to implement ASR in the SMWSA region of the Denver Basin. It is intended to provide guidance for entities investigating ASR as a potential alternate water supply option to address their water supply needs. ASR may play a critical role in meeting SMWSA member's needs in maintaining their groundwater resources to be used in conjunction with new supplies as they are identified and brought online.

Key components that should be considered when evaluating ASR include:

- Recharge objectives
- Hydrogeology
- Geochemical compatibility
- Existing and proposed infrastructure
- Permitting
- Economics/costing

Each of these components is outlined in more detail within the subsections that follow. Tools that may be used to assist with defining the hydrogeologic suitability for a proposed storage zone (e.g., a groundwater model to predict likely hydraulic responses), along with economic costing tools, are further outlined in Section 4, ASR Tools/Models.

Different methods of recharging and injecting of water into the ground have been practiced for well over 100 years, however the concept of ASR is more recent. The strictest definition of ASR is the storage of water in a suitable aquifer through a well during times when water is available, and recovery of the water from the same well during times when it is needed. This definition has been adopted by EPA and other organizations.

ASR has already been implemented in portions of the Denver Basin. CWSD has successfully operated an ASR system for more than 20 years. CWSD has observed increased well production and has been able to use groundwater to supplement surface water supplies, particularly in times of drought. Although ASR may not be a universal solution for water management for all agencies or all supplies, ASR can be an effective management tool for portions of supplies or for smaller entities without large demands. Existing projects, pilot projects, and planned ASR operations are described in more detail in Section 3, Summary of ASR in the Denver Basin.

2.1 Recharge Objectives

ASR projects throughout the United States have been developed with multiple recharge objectives. Primary recharge objectives may be grouped into three broad categories: water storage, water utility operational or infrastructure needs, and environmental benefits. A summary of these primary objectives and subobjectives are described below.

2.1.1 Storage

Storage is a primary objective of most ASR operations and would be one of SMWSA's primary objectives. Storage objectives can include seasonal storage, long-term storage (banking), emergency storage/supply, and storage of reclaimed water.

Colorado Senate Bill 06-193 commissioned a study of potential underground storage areas in the South Platte and Arkansas River basins. This study evaluated the potential for underground storage in the alluvial and bedrock aquifers in 44 areas in eastern Colorado. Each of these areas was evaluated using a series of 10 criteria that included hydrogeologic, environmental, and implementation considerations. The study concluded that there are significant portions of the South Platte and Arkansas River alluvial regions that are acceptable for underground water storage, including portions of the Dawson and Arapahoe aquifers. The study also identified several viable locations where ASR can be implemented in both the alluvial and bedrock aquifers.

The target storage volume (TSV) is the volume of water required to be in storage at all times to meet the recovery goals for the project. TSV includes the sum of the water that will be recovered and the volume of water held as a buffer between the native groundwater and the stored water. It is a simplistic approach for calculating the size of an ASR system or recharge "bubble."

2.1.2 Operation/Infrastructure

Improving water resource system operations is also a primary objective of many ASR operations. As noted above, CWSD has experienced increased well performance from its groundwater wells because of its ASR program. This is a common occurrence for ASR systems with dual-purpose wells due to the increased flushing of the well and its appurtenances by cycling water during injection and recovery phases.

Aquifer storage and recovery can also provide cost benefits related to deferring capital investment. Water treatment and distribution systems need to meet peak demands. Water stored in an ASR system commonly requires only disinfection when recovered because it is treated to meet drinking water standards prior to storage. This recovered water can then be used to meet peak demands, thereby eliminating the need to expand a water treatment plant and resulting in capital cost savings, with the assumption that a sufficient number of ASR wells are installed. Furthermore, if the recovery well is sited near a utility's demand centers and is used to meet peak demands, smaller capacity pipelines can be used, resulting in potential cost savings. The benefits need to be assessed by each system due to the timing and costs of their specific source water supplies.

Objectives related to recovery rates and recovery durations determine the number of ASR wells required and the size of the recharge bubble. For planning purposes, an initial conservative recovery efficiency of 70 percent is assumed, meaning that 70 percent of the water injected and stored should be usable. For the Denver Basin aquifers, with native groundwater qualities close to drinking water standards , the actual recovery percentage will likely be higher, with a "loss factor" less than evaporative losses from surface reservoirs and typically should improve with successive injection and recovery "cycles." However,until a well is tested, the true recovery efficiency is unknown.

Other operational objectives for ASR systems may include diurnal storage for peak demand management, distribution system pressure management, and disinfection by-product removal.

2.1.3 Environmental Benefits

Many environmental benefits can be realized from implementing and operating a successful ASR program. For stressed aquifers, one primary benefit is often to slow or stop depletion by rebalancing the natural recharge and current pumping with increased, replenishing inflows. Also, if properly engineered and operated, the water stored in an ASR system is not subject to the evaporative losses encountered in surface storage reservoirs and remains available for future use. While water injected to establish the buffer zone is not recoverable and some water may drift from storage due to hydraulic gradients, over the life of a project, most of the stored water is available for recovery. Reducing evaporation increases the overall efficiency of a water supply system. Lastly, ASR systems can also be used to control subsidence by refilling the voids left by prior withdrawals.

2.2 Hydrogeology

2.2.1 Target Recharge Zones

A wide range of aquifer conditions are possible for successful implementation of ASR. Every location is unique, but to be successful, the hydrogeology must match the ASR recharge objectives. For example, for a single ASR well application with limited recovery requirements (volume and recovery rate), aquifers with lower permeability and limited aquifer thickness may work. However, aquifers with high permeabilities and steep hydraulic gradients, which means groundwater is flowing quickly as is observed in many limestone karst and shallow gravel aquifers, will likely not work. This is because the small volume injected will quickly move away from the recharge well and cannot be recovered later.

Multiple recharge zones are possible in the Denver Basin aquifer system, as already demonstrated by the CWSD ASR system. This system has multiple ASR wells that intersect the Arapahoe, Denver, and Laramie-Fox Hills aquifers. The total volume that has been successfully recharged since the first ASR well was completed in the early 1990s now exceeds 14,000 acre-feet (ac-ft) of treated water.

For reference, the following is a brief description of the regional Denver Basin bedrock aquifer units, with text extracted from the U.S. Geological Survey (USGS) Professional Paper 1770, *Groundwater Availability of the Denver Basin Aquifer System* (Paschke 2011). It should be noted that in Colorado, these bedrock aquifers are all termed "nontributary groundwater," meaning the groundwater will not impact surface water courses. More specifically, the withdrawal of nontributary groundwater will not, within 100 years, deplete the flow of a natural stream or its alluvial aquifer at an annual rate greater than one-tenth of one percent of the annual rate of withdrawal (2 Colorado Code of Regulations [CCR] 410-1).

2.2.1.1 Denver Basin Bedrock Aquifer Units

The Denver Basin aquifer system comprises Late Cretaceous to Tertiary-age sandstone bedrock aquifers with intervening claystone confining units that occur in the uppermost layers of the structural Denver Basin. From oldest to youngest, the four primary aquifers are the Laramie-Fox Hills, Arapahoe, Denver, and Dawson (**Figure 2-1**). In parts of the basin, the Arapahoe and Dawson aquifers are further differentiated into upper and lower units. The synclinal structure of the Denver Basin causes the bedrock aquifer units to crop out in a ring pattern where the oldest rocks of the Laramie-Fox Hills aquifer crop out around the outer margins of the basin and the youngest rocks of the Dawson aquifer crop out in the center of the basin (**Figure 2-2**). Confined groundwater conditions generally are found in the bedrock aquifers where they are overlain by younger units, and unconfined groundwater conditions are generally found in outcrop areas.

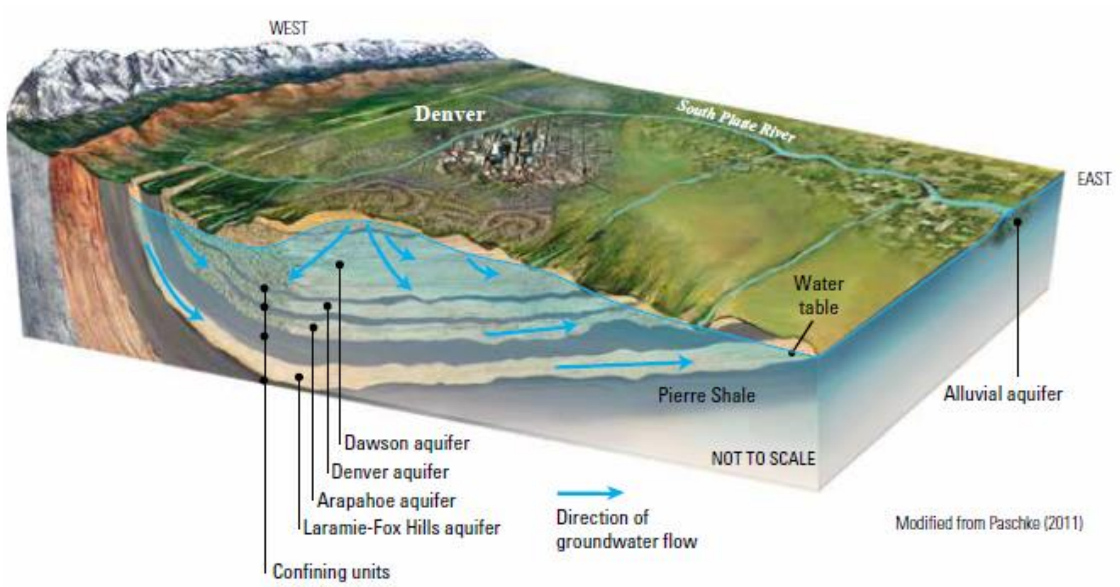


Figure 2-1 Conceptual Block Diagram Illustrating the Hydrogeologic Features of the Denver Basin Aquifer System

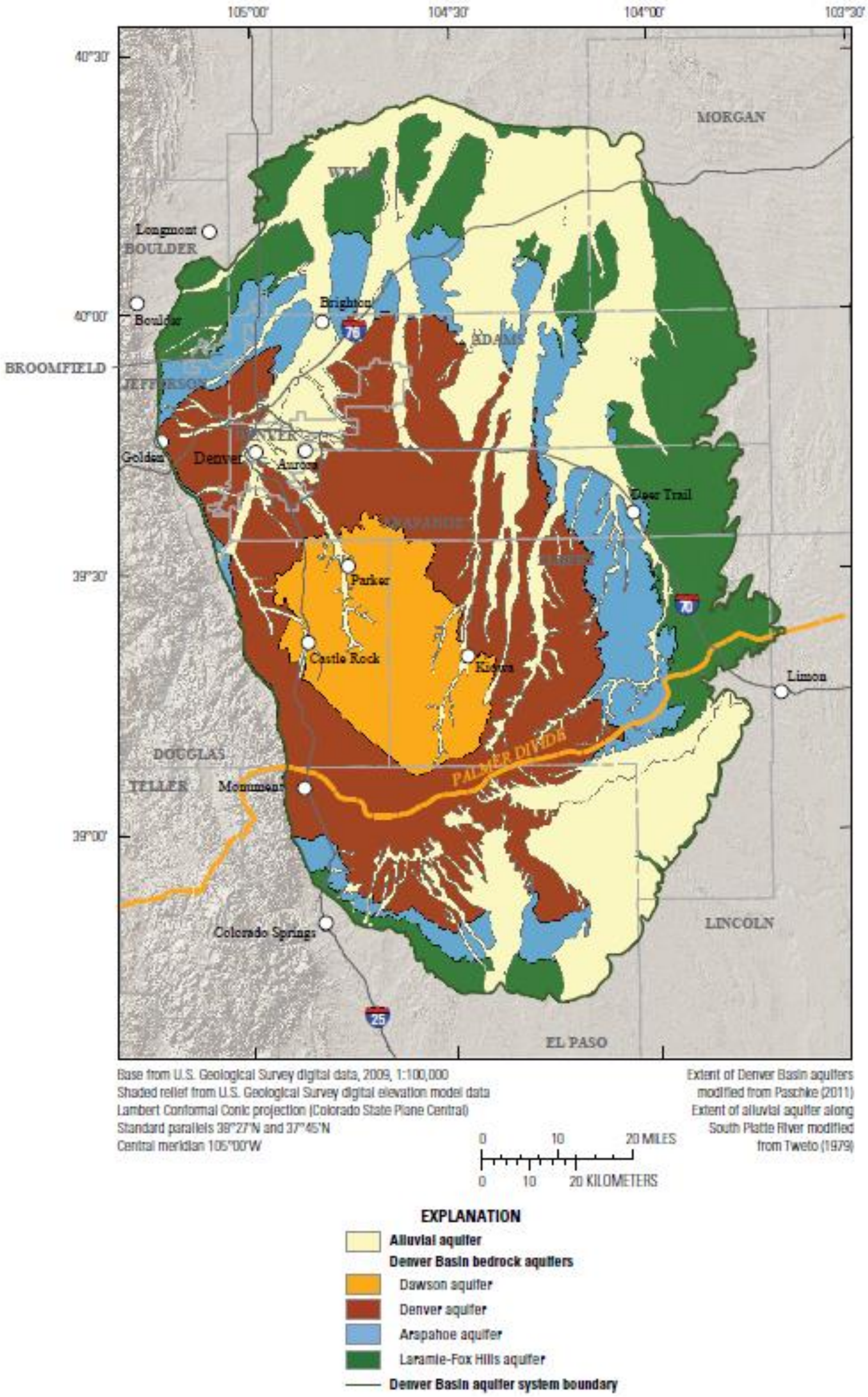


Figure 2-2 Extent of Alluvial and Bedrock Aquifers, Denver Basin Aquifer System (Musgrove et al. 2014)

2.2.1.2 Laramie-Fox Hills Aquifer

The Laramie-Fox Hills aquifer is the oldest, deepest, and most extensive of the bedrock aquifers underlying the area, and its extent defines the limit of the Denver Basin aquifer system. The Laramie-Fox Hills aquifer is composed of poorly to moderately consolidated sandstone units of the upper Cretaceous Fox Hills Sandstone and the lower Laramie Formation, and the base elevation map of the Laramie-Fox Hills aquifer reflects the bowl shape and dipping margins of the Denver Basin geologic structure (**Figure 2-1**).

The deepest part of the Laramie-Fox Hills aquifer base, and therefore also the deepest part of the Denver Basin aquifer system, occurs in Douglas County just north of Parker, Colorado, at an elevation of approximately 3,410 feet. Depth to the base of the Laramie-Fox Hills aquifer near the structural center of the basin is approximately 2,200 to 2,300 feet below land surface, and the total thickness of the aquifer system reaches a maximum of approximately 3,200 feet beneath the topographic high of the Palmer Divide. The Cretaceous upper Laramie Formation, composed of gray to black shale, coal seams, and minor amounts of siltstone and sandstone, overlies the Laramie-Fox Hills aquifer and forms a confining unit that separates the Laramie-Fox Hills aquifer from the overlying aquifers. The Laramie confining unit forms a wedge-shaped layer that thins from a mountain-front thickness of as much as 700 feet to less than 100 feet on the eastern margin of the basin.

2.2.1.3 Arapahoe Aquifer

The Arapahoe aquifer consists of a 400- to 600-foot-thick sequence of interbedded conglomerate, sandstone, siltstone, and shale of Cretaceous age. In the southern two-thirds of the basin, extensive conglomerate and coarse-grained sandstone units were deposited as alluvial fans along the mountain front during the Laramide Orogeny. These coarse-grained sandstones of the lower Arapahoe aquifer are thickest and the most conductive in Douglas and El Paso Counties where they form a productive bedrock aquifer that is heavily used for municipal and domestic water supply.

The base elevation of the lower Arapahoe aquifer ranges from 6,200 feet along the southwest basin margin to approximately 4,100 feet at the basin center just north of Parker, Colorado. Depth to the base of the lower Arapahoe aquifer near the structural center of the basin is approximately 1,700 feet below land surface, and the maximum depth to the base of the aquifer is approximately 2,600 feet below land surface at the Palmer Divide.

2.2.1.4 Denver Aquifer

The Denver aquifer and confining units consists of a 600- to 1,200-foot-thick heterogeneous sequence of interbedded shale, claystone, siltstone, sandstone, coal, and volcanic ash deposits of Cretaceous to Tertiary age. The Arapahoe, Denver, and lower Dawson aquifers represent the synorogenic deposition of sediments in the Denver Basin during Laramide uplift of the Rocky Mountain Front Range. The well-formed alluvial fans mapped in the western part of the basin for the lower Arapahoe aquifer also are observed in the Denver sequence. However, in other parts of the basin, the Denver sequence is, in general, finer grained than the underlying Arapahoe aquifer sequence and is composed of isolated channel sandstones contained in extensive fine-grained deposits. The Cretaceous-Tertiary boundary occurs in the upper part of the Denver aquifer sequence and is closely established by vertebrate fossils.

Despite poor correlations between Denver-aquifer sandstones in some parts of the basin, the base-elevation maps of the Denver aquifer and confining units depict the regional structure of the Denver Basin and provide reasonable representations of layering within the Denver sequence. Elevation of the Denver sequence base ranges from approximately 4,600 to 6,300 feet, and the maximum depth of the sequence is approximately 2,100 feet below land surface at the Palmer Divide. The greatest silt-plus-sand thickness in the Denver aquifer (400 to 600 feet) occurs along the western basin margin in southern Douglas County. The Denver confining units are thin (mean thicknesses of 50 feet) compared to the thickness of the Denver aquifer (mean thickness of 550 feet).

2.2.1.5 Dawson Aquifer

The Dawson aquifer sequence consists of a 100- to 1,100-foot-thick heterogeneous sequence of Tertiary-age, fluvial conglomerate, sandstone, siltstone, and shale. In the northern two-thirds of the Dawson extent, a clay and shale confining layer is present and the Dawson aquifer is administratively separated into upper and lower aquifers. The lower Dawson aquifer forms the upper part of the Laramide synorogenic sequence and separation of the lower Dawson aquifer from the underlying Denver aquifer sequence.

The base elevation of the lower Dawson aquifer ranges from 5,400 feet at the northern edge of its extent to 6,800 feet on the southern edge of its extent. The base is 1,100 feet below land surface at the Palmer Divide. The greatest silt-plus-sand thickness (200 to 375 feet) is in the west-central part of the basin along the Douglas-El Paso County line, like the Denver and Arapahoe aquifers. The Dawson confining unit consists of a shale-rich layer at the top of the lower Dawson sequence. The upper Dawson aquifer consists of arkosic (i.e., a detrital sedimentary rock, specifically a type of sandstone containing at least 25 percent feldspar), coarse-grained, poorly consolidated sandstones with some interbedded overbank mudstone deposits in a distribution pattern quite different from that of the underlying sediments.

Sandstones of the upper Dawson aquifer are more uniform in composition than those from the underlying layers and were likely derived from the Pikes Peak area to the south, rather than from the Front Range source area to the west. Paleochannels at the base of the lower Dawson aquifer are evident from the base-elevation configuration map, and one such paleo-channel aligns with the present-day course of Cherry Creek.

2.2.1.6 Aquifer Permeabilities

Permeabilities of the different Denver Basin bedrock aquifers are highly variable and reflect the variable nature of the depositional structure of the Denver Basin during formation. The permeabilities reflect differences in the lithologic characteristics of the fine-grained sediments such as grain-size, clay mineralogy, and compaction that relate to position in the basin.

A summary of hydraulic conductivity values for the bedrock aquifers, compiled from pumping tests and used by USGS for the development of their Regional Denver Basin conceptual groundwater flow model, indicates that the Arapahoe aquifer is the most permeable of the bedrock units, with a median permeability of 1.8 feet per day (ft/d) and a geometric mean of 1.6 ft/d. The next most permeable aquifer is the Dawson, with a median permeability of 0.8 ft/d and geometric mean of 0.7 ft/d. The Denver aquifer has a median permeability of 0.45 ft/d and geometric mean of 0.42 ft/d, while the Laramie-Fox Hills aquifer has a median permeability of 0.4 ft/d and geometric mean of 0.4 ft/d.

Estimates of specific yield values were compiled from previous studies. Mean specific yield values of 15.2 percent for the Dawson aquifer, 13.3 percent for the Denver aquifer, 17.8 percent for the Arapahoe aquifer, and 18.6 percent for the Laramie–Fox Hills aquifer are reported by the current study and are used in the groundwater flow simulations. A summary of the Denver Basin aquifer characteristics is shown in **Table 2-1**.

Table 2-1 Stratigraphic, Hydrogeologic, and Lithologic Characteristics of the Denver Basin Aquifers, Colorado (Adapted from Paschke 2011, and Robson et al. 1998)

Age	Stratigraphic Unit	Hydrogeologic Unit	Hydrogeologic Description	Lithologic Description	Median Hydraulic Conductivity (ft/day)	Range of Thickness (ft)	Additional Information
Quaternary	Alluvial, flood plain, terrace, colluvial, and eolian sand, gravel, and clay deposits	Alluvial aquifer	Productive unconfined alluvial aquifer where saturated	Unconsolidated sand and gravel with clay lenses; primarily along present-day stream channels; igneous and sedimentary rock fragments.	479	0-175	No confining unit separates the alluvial aquifer and Dawson aquifer.
Tertiary (Paleocene to Eocene)	Dawson Arkose	Dawson aquifer	Productive unconfined to confined aquifer	Channel sandstones, overbank mudstone/ claystone deposits; upper sequence of coarse-grained arkosic sandstones; granitic sediments source of U and Rn to groundwater. Upper and lower Dawson aquifers separated by paleosol claystone in northern part of Dawson extent. Lower Dawson: mixed arkosic and andesitic fluvial sand-stone with interbedded claystone, lignite, and volcanics.	0.80	100-1,100	Underlain by fine-grained confining unit (1- to 150-ft thick) of upper Denver Formation.
Late Cretaceous	Denver Formation	Denver aquifer	Confined to unconfined aquifer	Alluvial fan, swamp, overbank deposits; andesitic fluvial sandstone with volcanic ash deposits, coal, lignite, mudstone/ claystone; Fe-rich sediments; sediments source of Se and U to groundwater.	0.45	280-1,100	Underlain by fine-grained confining unit (5- to 150-ft thick) predominantly composed of claystone with andesitic fluvial sandstone.
Late Cretaceous	Arapahoe Formation	Arapahoe aquifer	Productive confined aquifer	Fluvial environment, alluvial fan deposits near mountain front; conglomerates, sandstone, siltstone, shale; pebbles and cobbles with granite, chert, metamorphic rocks, and quartzite; shale more prevalent in northern part of basin.	1.8	400-600	Thick confining unit (100 to 500 ft) of gray to black shale, coal, siltstone, and sandstone below Arapahoe aquifer limits downward movement of water from Arapahoe to Laramie-Fox Hills aquifer; wedge-shaped confining unit thins to the east.
Late Cretaceous	Laramie Formation and Fox Hills Sandstone	Laramie-Fox Hills aquifer	Productive confined to unconfined aquifer	Laramie Formation: swamps, deltas, overbank deposits; claystone, coal, fluvial channel sandstone; contains coal and lignite beds. Fox Hills Sandstone: marine beach and delta-front environment; sandstone, thin siltstone and claystone beds; contains marine fossils.	0.40	100-500	A 5- to 20-ft-thick shale bed generally separates the Laramie and Fox Hills; aquifer underlain by Pierre Shale, a thick (5,200 ft), low permeability, marine shale that forms base of aquifer system.

ft/day = feet per day; ft = feet; U = uranium; Rn = radon; Se = selenium; Fe = iron

The Arapahoe aquifer has often been identified as the most suitable of the three deep bedrock aquifers due to its favorable hydrogeology and water quality. The Arapahoe aquifer is relatively thick and has favorable hydraulic conductivity. This in combination with good water quality makes if very suitable for both groundwater withdrawals as well as ASR. Most wells drilled into the Denver Basin have been primarily focused on groundwater supply and have been retrofitted for ASR. Although the Arapahoe aquifer has been focused on for dual purpose wells, the Denver and Laramie-Fox Hills aquifers tend to show favorable conditions for injecting and recovering water depending on the location and the site-specific conditions.

2.2.2 Available Recharge Head and Drawdown

With the increased reliance on the Denver Basin aquifers in the south Denver metropolitan area, the production from these aquifers exceeds the natural recharge, and water levels have dropped. These reductions in water levels have been subject to much study and since 2010 an annual report has been prepared by the Colorado Division of Water Resources (CDWR) summarizing the historical water-level data for wells in the four Denver Basin bedrock aquifers (Dawson, Denver, Arapahoe, and Laramie-Fox Hills) for the entire basin. The most recent report published in 2016 indicates highly variable changes in aquifer conditions, both spatially and within the different bedrock aquifers. The water levels presented in this report are based on interpretation of the available data. The water levels are obtained in specific locations from wells screened for varied ranges based upon the site-specific geology. The water levels may vary from location to location since the aquifer is not homogeneous and has interlaying sand-silt and clay layers. In addition, some water level measurements may be affected by other nearby wells.

These variations in aquifer water levels makes interpretation difficult. **Table 2-2** has been modified from the CDWR 2016 report and summarizes the estimated average change for each aquifer during the last 10 years. Data in the latest report indicate that water levels for all four aquifers on average have continued to show declines, however the trends are not straightforward, with some years showing increases. The detailed maps that accompany the CDWR report also show areas with both increases and declines in aquifer water levels in aquifers near each other.

Table 2-2 Average Changes in Denver Basin Bedrock Aquifers Water Levels over a 1-Year, 5-Year, and 10-Year Period

Aquifer	1-Year Water Level Change 2015–2016	5-Year Water Level Change 2011–2016	10-Year Water Level Change 2006–2016
Dawson	-1.43	14.65	-28.6
Denver	4.42	-13.83	25.34
Arapahoe	-6.14	-18.52	11.38
Laramie-Fox Hills	-0.58	-8.76	-46.00

Source: CDWR Groundwater Levels in the Denver Basin Bedrock Aquifers 2016
Note: negative sign indicates groundwater level decline

A similar evaluation has been completed by USGS in cooperation with the Rural Water Authority of Douglas County. This study began in 2011 with the primary aim of monitoring changes in the groundwater levels within rural areas of Douglas County. More than 500 manual and 213,900 automated water-level measurements were collected from the 36 domestic-well network between April 2011 and June 2013. Water level data collection from these sites during this period showed water level declines in all wells. Over the 2-year monitoring period, average declines of approximately 0.4 foot per year were observed in the upper Dawson aquifer, declines of over 2.6 feet per year were observed in the lower Dawson aquifer, declines of about 3.2 feet per year were observed in the Denver aquifer, declines of about 1.9 feet per year were observed in the Arapahoe aquifer, and declines of about 9.9 feet per year were observed in the Laramie-Fox Hills aquifer.

The condition of an aquifer impacts both the selection of suitable ASR locations and the viability of recovering the recharged water. One key recharge objective for ASR is the restoration of groundwater levels, therefore identifying those aquifers and locations where the greatest declines are occurring may be important.

Of greater importance, however, is identifying the depth of the water levels (or piezometric head) relative to the top of the aquifer units. When water levels decline to below the top of an aquifer, the aquifer condition transitions from a confined and fully saturated state to unconfined, with increasing desaturation of the aquifer. When this occurs, oxygen is introduced into the aquifer and several undesirable impacts are possible.

The first potential negative impact is air binding. Air makes its way into a formation and is trapped and cannot easily be released. When this occurs, the formation permeability is reduced, sometimes irretrievably.

The second potential negative is a change in the aquifer reduced anoxic (redox) condition. Unconfined or water table aquifers are typically in an oxic or suboxic condition, meaning they already contain some dissolved oxygen and oxidative reactions have and are occurring. In contrast, deeply confined aquifers are in a redox condition. Redox processes can alternately mobilize or immobilize potentially toxic metals associated with naturally occurring aquifer materials and generate undesirable byproducts such as dissolved manganese (Mn2+), ferrous iron (Fe2+), hydrogen sulfide (H_2S), and methane (CH_4) when in a reduced condition. So, when an aquifer that has previously not been exposed to oxygen is exposed, oxidative reactions facilitated by a variety of microorganisms occur. These and other geochemical reactions are outlined in more detail in Section 2.3, Geochemical Compatibility, but note that pumping a well with water levels that decline below the top of the aquifer (or well screen) is typically undesirable.

2.3 Geochemical Compatibility

2.3.1 Recharge Water Quality

The water quality of different recharge waters is a key component for determining the success of an ASR system. There are several considerations including geochemical compatibility, the potential for plugging the recharge interval due to excess turbidity, entrained air or adverse geochemical reactions, and ensuring the water quality of the source water being recharged meets regulatory requirements.

A related consideration is water quality variability. Significant care must be taken not to characterize the recharge water from just a single water quality analysis. Factors such as seasonal variations and the type of source water being recharged should be considered when determining the frequency and duration over which water quality data is evaluated. For example, potential exists for much greater variability for a partially treated river water source compared with a fully treated groundwater source.

An important water quality consideration is the total suspended solids concentration. Most aquifer systems are vulnerable to plugging. Exceptions to this include highly permeable karst aquifer systems with solution cavities and wide fractures that allow more turbid water to migrate away from the well bore without plugging. However, in most cases, care must be taken not to plug the formation; therefore, pretreatment for sediment removal is commonly required. It also should be recognized that sometimes there are plant “upsets,” allowing turbidity spikes or peaks to occur. If this is anticipated, then it may be appropriate for some form of additional pretreatment at the ASR wellhead.

Geochemical compatibility issues, including the redox state (described in more detail in the section that follows), are an important consideration but ensuring the recharge water quality meets regulatory requirements is also key. For most states, water that is recharged into an underground source of drinking water (USDW), defined as aquifers with total dissolved solids (TDS) concentrations less than 10,000 milligrams per liter (mg/L), must meet primary drinking water standards. Specifically, EPA regulations (40 Code of Federal Regulations [CFR] 144.12) provide that “no owner or operator shall construct, operate, maintain, convert, plug, abandon, or conduct any other injection activity in a manner that allows the movement of fluid containing any contaminant into underground sources of drinking water, if the presence of the contaminant may cause a violation of any primary drinking water regulation under 40 CFR part 142 or may otherwise adversely affect the health of persons.” As outlined in Section 2.6, Colorado requires permits that satisfy the groundwater rules.

2.3.2 Native Groundwater Quality and Rock-Water Interaction

A key part of determining the likely success of ASR is initially gained by understanding the potential for geochemical reactions with the aquifer rock and native groundwater and the degree of mixing with the native groundwater. During the period when water is recharged into the aquifer, stored, and then recovered, the water quality of the source water may change as it equilibrates with the groundwater and minerals in the aquifer.

To determine these potential changes in water quality, a good understanding of the native groundwater quality, presence of reactive minerals, and the redox condition and pH are all required. Once known, geochemical models are a useful tool for obtaining an initial understanding of the potential changes in water quality.

As part of their national water quality assessment program, the USGS summarized the quality of groundwater in the Denver Basin aquifers in their report entitled *Quality of Groundwater in the Denver Basin Aquifer System, Colorado, 2003–2005* (Musgrove et al. 2014). This investigation included the installation and sampling of two monitoring well networks beneath agricultural (31 wells) and urban (29 wells) land uses at or just below the water table in either alluvial material or near-surface bedrock. More relevant to ASR development is the data obtained from existing domestic and municipal supply wells completed in the bedrock aquifers. A total of 79 samples were collected and analyzed for inorganic, organic, isotopic, and age-dating constituents and tracers so that baseline water quality could be established. Some of the relevant findings are summarized below.

Generally, the groundwater quality in the Denver Basin bedrock aquifers is good, however, the geologic source material, the presence or absence of oxygen (redox condition), and pH does affect the occurrence and concentrations of some constituents. The most common exceedances of drinking water standards in the basin are for uranium, radium, arsenic, selenium, and manganese.

It is worth noting that these naturally occurring trace elements behave differently. For example, uranium dissolves when groundwater is oxic and precipitates when groundwater is anoxic. Conversely, other trace elements such as iron or manganese precipitate under oxic conditions and dissolve under anoxic conditions. For this reason, uranium is detected most commonly in the shallow oxic groundwaters, but as the groundwater moves deeper into the aquifer system and conditions become more anoxic, the dissolved uranium can adsorb to aquifer sediments or precipitate as insoluble uranium minerals and become undetectable.

Groundwater samples collected from the Denver Basin aquifer system are primarily oxic (dissolved oxygen concentration of at least 0.5 mg/L) at shallow depths and anoxic (dissolved oxygen concentrations less than 0.5 mg/L) at deeper depths, which reflects the groundwater circulation patterns. As oxic water moves deeper along groundwater flow paths, redox conditions commonly change because of biological use of dissolved oxygen and other redox-sensitive constituents by microbes. The Dawson aquifer is mostly oxic, while the other bedrock aquifers were mostly anoxic. The downward movement of young, oxic groundwater from the shallow system however, has resulted in the presence of dissolved oxygen deeper in the Denver Basin aquifer system. Excess irrigation water, heavy pumping, and the injection of oxic surface water during aquifer storage and recovery operations can accelerate this downward movement, which is very slow under natural conditions.

The solubility, transport, concentration, and chemical form of many water quality constituents in groundwater are also affected by pH. Some redox-sensitive trace elements such as iron and manganese are more soluble under low pH and/or anoxic conditions. Other trace elements such as arsenic and selenium are more mobile when the pH is higher. The formation of arsenic minerals, for example, is inhibited as groundwater pH increases. The majority (94 percent) of pH values in Denver Basin groundwater are between 6.5 and 8.5. Values of pH outside of this range can affect the concentration of many constituents.

A summary of the well completion information, physiochemical properties, and select geochemical parameters for the Denver Basin aquifers is provided in **Table 2-3**. This table is a useful summary extracted directly from the USGS Report 2014–5051 (Musgrove et al. 2014).

Table 2-3 Summary of Well Completion Information, Physiochemical Properties, and Select Geochemical Parameters for the Denver Basin Aquifers (Musgrove et al. 2014)

Constituent	Units	Benchmarks MCL, SMCL, or HBSL (MCL unless otherwise noted)	Water Table Wells					
			Agriculture Land Use (n=31 unless otherwise noted)			Urban Land Use		
			Median	Range (min.-max.)	Exceedances (%)[1]	Median	Range (min.-max.)	Exceedances (%)[1]
Well depth	feet	na	73.3	18.7–113	na	42.3	18.9–81.7	na
Screened interval length	feet	na	9.8	9.6–10.0	na	9.8	9.5–9.8	na
Dissolved oxygen	mg/L	na	7.2	0.4–17.4	na	1.6	0.1–11.1	na
pH	standard units	6.5–8.5 (SMCL)	7.3	6.5–8.0	0	7.0	5.9–8.0	10
Specific conductance	µS/cm	na	1,140	271–6,200	na	1,150	408–4,900	na
Temperature	°C	na	16.7	12.6–22.5	na	13.6	11.5–17.0	na
Turbidity	FNU	na	2.4	0.3–490	na	2.0	0.2–57	na
Total dissolved	mg/L solids	500 (SMCL)	807	182–5,190	61	717	294–4,410	66
Calcium	mg/L	na	120	36.4–609	na	159	53.7–706	na
Magnesium	mg/L	na	27.6	5.6–203	na	24.5	6.0–120	na
Potassium	mg/L	na	5.07	1.36–40.6	na	4.95	0.79–12.9	na
Sodium	mg/L	na	64.4	8.2–930	na	46.5	16.3–748	na
Alkalinity	mg/L as CaCO	na	210	79–832	na	200	22–535	na
Bicarbonate	mg/L	na	256	96–1,010	na	244	27–652	na
Bromide	mg/L	na	0.49	0.05–4.51	na	0.45	0.06–7.43	na
Chloride	mg/L	250 (SMCL)	37.4	3.95–542	10	58.0	3.38–638	10
Fluoride	mg/L	2 (SMCL), 4	0.32	<0.17–3.20	3, 0	0.64	0.17–1.39	0, 0
Silica	mg/L	na	20.7	9.3–27.4	na	23.6	10.3–55.9	na
Na/Cl	molar ratio	na	3.9	1.0–14.2	na	2.2	0.60–11.1	na
(Ca+Mg)/HCO	molar ratio	na	0.92	0.40–4.7	na	0.97	0.49–12.9	na

Constituent	Units	Benchmarks MCL, SMCL, or HBSL (MCL unless otherwise noted)	Water Table Wells					
			Agriculture Land Use (n=31 unless otherwise noted)			Urban Land Use		
			Median	Range (min.-max.)	Exceedances (%)[1]	Median	Range (min.-max.)	Exceedances (%)[1]
Na/(Ca+Mg)	molar ratio	na	0.69	0.31–4.8	na	0.64	0.16–1.7	na
Cl/Br	molar ratio	na	70	48–167	na	95	50–242	na
Ammonia	mg/L as N	na	<0.04	<0.04–1.43	na	<0.04	<0.04–0.17	na
Nitrate plus nitrite	mg/L as N	na	6.42	<0.06–31.9	na	4.02	<0.06–24.2	na
Nitrate	mg/L as N	10	6.42	<0.060–13.8	19	4.02	<0.060–24.2	17
Nitrite	mg/L as N	1	<0.008	<0.008–0.795	0	<0.008	<0.008–0.282	0
Organic	mg/L	na	<0.09	<0.05–2.3	na	<0.01	<0.01–0.48	na
Orthophosphate	mg/L as P	na	0.030	<0.2–0.28	na	0.012	<0.006–0.228	na
Dissolved organic carbon	mg/L	na	2.98	0.58–81.9	na	4.46	1.32–20.2	na
δ18O	per mil (‰)	na	-13.73 (n=8)	-16.79 to -12.52	na	-13.39 (n=5)	-14.69 to -12.79	na
δD	per mil (‰)	na	-104 (n=8)	-126 to -97.9	na	-102 (n=5)	-110 to -99.2	na
δ13C	per mil (‰)	na	--	--	--	--	--	--
Aluminum	µg/L	50–200 (SMCL)	2.2	<3.2–7.1	0	1.4	<1.6–27	0
Barium	µg/L	2,000	54.3	9.71–243	0	44.0	10.7–306	0
Beryllium	µg/L	4	<0.060	<0.060	0	<0.060	<0.060–0.145	0
Cadmium	µg/L	5	0.021	<0.037–0.23	0	<0.040	<0.040–E0.037	0
Chromium	µg/L	100	1.0	<0.8–5.6	0	<0.8	<0.8–0.8	0
Cobalt	µg/L	na	0.379	0.113–7.040	na	0.623	0.15–9.65	na
Copper	µg/L	1,300 (action level)	1.9	0.04–31.5	0	2.0	E0.3–10.3	0
Iron	µg/L	300 (SMCL)	1.0	<10–3,880	3	5.0	<6.4–27,300	21
Lead	µg/L	15 (action level)	<0.080	<0.080–0.089	0	<0.080	<0.080–0.138	0

Constituent	Units	Benchmarks MCL, SMCL, or HBSL (MCL unless otherwise noted)	Water Table Wells					
			Agriculture Land Use (n=31 unless otherwise noted)			Urban Land Use		
			Median	Range (min.-max.)	Exceedances (%)[1]	Median	Range (min.-max.)	Exceedances (%)[1]
Lithium	µg/L	na	27.0	9.35–137	na	29	5.95–131	na
Manganese	µg/L	50 (SMCL), 300 (HBSL)	2.87	<0.18–2,500	32, 10	71.9	0.24–663	52, 17
Molybdenum	µg/L	na	2.50	0.417–9.48	na	1.32	<0.80–10.4	na
Nickel	µg/L	na	3.91	1.8–35.3	na	2.49	<0.06–19.7	na
Silver	µg/L	100 (SMCL and HBSL)	<0.200	<0.200–<0.600	0	<0.200	<0.200–<0.600	0
Strontium	µg/L	4,000 (HBSL)	1,340	381–12,400	19	1,910	527–12,300	14
Thallium	µg/L	2	<0.041	<0.041–<0.041	0	<0.040	<0.040–0.099	0
Vanadium	µg/L	na	1.8	0.3–10.7	na	0.6	0.1–14.6	na
Zinc	µg/L	2,000 (HBSL), 5,000 (SMCL)	2.1	<1.0–16.3	0, 0	1.4	<0.6–19.9	0, 0
Antimony	µg/L	6	<0.300	<0.300–0.62	0	<0.200	<0.200–<0.200	0
Boron	µg/L	na	61	27–771	na	59	19–292	na
Selenium	µg/L	50	6.2	<0.5–408	16	9.7	<0.4–696	21
Radon	pCi/L	300; 4,000 (alternative MCL)	--	--	--	--	--	--
Uranium	µg/L	30	6.8	0.13–146	19	19.8	0.105–941	34
Arsenic	µg/L	10	1.5	E0.2–15.6	3	1.2	<0.2–87.5	14

MCL = maximum contaminant level; SMCL = secondary maximum contaminant level; HBSL = health-based screening level; n = number; min. = minimum; max. = maximum; % = percent; Na = sodium; Ca = calcium; Mg = magnesium; Cl = chlorine; Br = bromine; N = nitrogen; P = phosphorus; mg/L = milligrams per liter; µg/L = micrograms per liter; pCi/L = picocuries per liter; < = less than; na = not applicable

Constituent	Units	Bedrock Aquifers											
		Dawson Aquifer (n=30 unless otherwise stated)			Denver Aquifer (n=10 unless otherwise stated)			Arapahoe Aquifer (n=29 unless otherwise stated)			Laramie-Fox Hill Aquifer (n=10 unless otherwise stated)		
		Median	Range (min.-max.)	Exceedances (%)[1]	Median	Range (min.-max.)	Exceedances (%)[1]	Median	Range (min.-max.)	Exceedances (%)[1]	Median	Range (min.-max.)	Exceedances (%)[1]
Well depth	feet	384	190–790	na	669	441–1,150	na	501	130–2,149	na	858	515–1,450	na
Screened Interval Length	feet	110	40–120	na	70 (n=6)	40–300	na	102	20–460	na	127.5 (n=8)	80–205	na
Dissolved	mg/L	3.8	M–9.4	na	0.3	0–1.0	na	0.1	0–9.2	na	0.1	0–1.3	na
pH	Standard Units	7.0	6.2–7.9	13	8.2	7.5–9.3	30	8.2 (n=28)	6.9–9.4	21	8.8	7.3–9.4	80
Specific Conductance	µS/cm	211	78–934	na	330	212–706	na	497	172–2,640	na	758	167–1,230	na
Temperature	ºC	11.7	8.3–16.5	na	15.7	12.0–21.0	na	16.5	12.3–30.1	na	17.2	14.0–22.1	na
Turbidity	FNU	0.2	0.1–15	na	0.6	0.2–3.9	na	0.3	0.1–14	na	1.1	0.1–4.5	na
Total Dissolved Solids	mg/L	151	81–610	7	207	148–459	0	314	106–1,180	34	425	102–746	40
Calcium	mg/L	23.6	6.1–	na	19.6	1.4–	na	14.3	1.4–	na	1.6	0.7–20.8	na
Magnesium	mg/L	2.5	0.3-18.8	na	1.5	0.2-5.3	na	1.3	0.03-44.1	Na	0.3	0.1-2.7	na
Potassium	mg/L	2.43	0.72–6.90	na	1.96	0.53–4.42	na	1.91	0.30–12.2	na	1.03	0.30–5.50	na
Sodium	mg/L	11.9	6.0-50.3	na	57.0	17.7-151	na	95.9	4.1-349	na	173	8.3-307	na
Alkalinity	mg/L as $CaCO_3$	76 (n=28)	31–239	na	133	66–214	na	143	62-427	na	271	72-539	na
Bicarbonate	mg/L	92 (n=28)	38–290	na	161	80-255	na	171	76-516	na	318 (n=9)	95-653	na
Bromide	mg/L	0.06	0.01–0.35	na	0.08	0.04–0.24	na	0.06	0.02–1.39	na	0.22	0.01–0.81	na

Constituent	Units	Bedrock Aquifers											
		Dawson Aquifer (n=30 unless otherwise stated)			Denver Aquifer (n=10 unless otherwise stated)			Arapahoe Aquifer (n=29 unless otherwise stated)			Laramie-Fox Hill Aquifer (n=10 unless otherwise stated)		
		Median	Range (min.-max.)	Exceedances (%)[1]	Median	Range (min.-max.)	Exceedances (%)[1]	Median	Range (min.-max.)	Exceedances (%)[1]	Median	Range (min.-max.)	Exceedances (%)[1]
Chloride	mg/L	2.40	1.13-91.6	0	2.45	1.51-10.1	0	4.38	<0.20–231	0	13.3	0.57-79.3	0
Fluoride	mg/L	0.47	0.09–1.36	0, 0	1.13	0.51–2.29	10, 0	1.47	0.44–3.62	24, 0	1.15	0.47–3.81	20, 0
Silca	mg/L	36.4	11.0-54.9	na	13.3	10.3-19.4	Na	11.6	8.3-34.7	na	11.3	10.0-13.5	na
Sulfate	mg/L	16.0	2.57-261	3	25.4	10.2-124	0	35.8	<0.90–655	24	1.1	<0.18–426	20
Na/Cl	molar ratio	7.4	0.5–33	na	25	8.3–65	na	23	2.3–	na	18	6.0–54	na
(Ca+Mg)/HCO	molar ratio	0.48 (n=28)	0.11–2.8	na	0.21	0.02–0.55	na	0.14	0.01–2.4	na	0.01 (n=9)	0.00–0.34	na
Na/(Ca+Mg)	molar ratio	0.73	0.16–8.3	na	4.5	0.80–63.7	na	11	0.20–107	na	153	0.61–239	na

µS/cm = microSiemens per centimeter; °C = degrees Celcius; FNU = Formazin Nephelometric Unit; HCO = bicarbonate

CDM Smith

Constituent	Units	Bedrock Aquifers											
		Dawson Aquifer (n=30 unless otherwise stated)			Denver Aquifer (n=10 unless otherwise stated)			Arapahoe Aquifer (n=29 unless otherwise stated)			Laramie-Fox Hill Aquifer (n=10 unless otherwise stated)		
		Median	Range (min.-max.)	Exceedances (%)1	Median	Range (min.-max.)	Exceedances (%)1	Median	Range (min.-max.)	Exceedances (%)1	Median	Range (min.-max.)	Exceedances (%)1
Cl/Br	molar ratio	42	22–262	na	43	13–106	na	55	38–189	na	81	33–107	na
Ammonia	mg/L as N	<0.04	<0.04–0.65	na	0.11	0.05–0.50	na	0.28	<0.04–1.28	na	0.53	<0.04–0.90	na
Nitrate plus nitrite	mg/L as N	0.25	<0.06–5.79	na	<0.06	<0.06–<0.06	na	<0.06	<0.06–15.9	na	<0.06	<0.06–<0.06	na
Nitrate	mg/L as N	0.25	<0.060–5.79	0	<0.06	<0.054–<0.060	0	<0.06 (n=28)	<0.06–15.9	3	<0.06	<0.060–<0.060	0
Nitrite	mg/L as N	<0.008	<0.008–0.092	0	<0.008	<0.008–0.020	0	<0.008	<0.008–0.535	0	<0.008	<0.008–<0.008	0
Organic nitrogen	mg/L	<0.01	<0.01–0.12	na	<0.002 (n=8)	<0.002–<0.04	na	<0.01 (n=23)	<0.01–E0.64	na	<0.01	<0.01–<0.13	na
Orthophosphate	mg/L as P	0.016	<0.006–0.340	na	E0.005	<0.006–0.080	na	<0.006	<0.006–0.109	na	0.054	<0.006–0.197	na
Dissolved organic carbon	mg/L	0.55	<0.33–3.24	na	0.53 (n=9)	<0.33–1.09	na	0.58	<0.33–4.39	na	0.53	<0.33–0.96	na
δ13C	per mil (‰)	-14.10 (n=26)	-15.52 to 10.30	na	-13.88 (n=9)	-14.38 to -11.04	na	-13.83 (n=26)	-15.06 to -10.19	na	-12.51	-14.95 to -9.61	na
δD	per mil (‰)	-107 (n=26)	-117 to -78.8	na	-104 (n=9)	-109 to -83.7	na	-102 (n=26)	-113 to -75.1	na	-90.1	-114 to -71.3	na
δ13C	per mil (‰)	-13.41 (n=9)	-18.98 to -.966	na	-10.88 (n=8)	-13.07 to -5.92	na	-10.37 (n=12)	-13.82 to -5.29	na	-10.73	-19.06 to -4.42	na
Aluminum	µg/L	<1.6	<1.6–2.5	0	<1.6	<1.6–2.0	0	1.4	<1.6–7.6	0	2.3	<1.6–5.3	0
Barium	µg/L	53.1	6.7–318	0	58.8	12.1–127	0	35.4	1.53–163	0	17.5	3.29–51.1	0
Beryllium	µg/L	0	<0.060–0.432	0	<0.060	<0.060–0.126	0	<0.060	<0.060–0.265	0	<0.060	<0.060–0.095	0
Cadmium	µg/L	<0.040	<0.040–E0.031	0	<0.040	<0.040–0.1	0	<0.040	<0.040–E0.037	0	<0.040	<0.040–E0.030	0
Chromium	µg/L	<0.8	<0.8–1.1	0	0.05	<0.04–0.18	0	<0.8	<0.8–E0.4	0	0.04	E0.03–0.13	0
Cobalt	µg/L	0.083	E0.01–0.585	na	0.015	<0.040–0.066	na	0.033	<0.014–0.35	na	<0.040	<0.040–E0.024	na
Copper	µg/L	4.2	<0.4–40.3	0	0.4	<0.4–10	0	0.4	<0.4–13.9	0	0.1	<0.4–1.9	0
Iron	µg/L	2.1	<6.0–595	10	35	<6.0–555	10	18	<6.0–4,100	17	18	<6.0–2,360	20

Constituent	Units	Bedrock Aquifers											
		Dawson Aquifer (n=30 unless otherwise stated)			Denver Aquifer (n=10 unless otherwise stated)			Arapahoe Aquifer (n=29 unless otherwise stated)			Laramie-Fox Hill Aquifer (n=10 unless otherwise stated)		
		Median	Range (min.-max.)	Exceedances (%)[1]	Median	Range (min.-max.)	Exceedances (%)[1]	Median	Range (min.-max.)	Exceedances (%)[1]	Median	Range (min.-max.)	Exceedances (%)[1]
Lead	µg/L	0.200	<0.080–0.985	0	0.103	<0.080–0.620	0	0.048	<0.080–2.26	na	0.030	<0.080–1.13	0
Lithium	µg/L	13	3.44–122	na	10	1.67–22.9	na	19	4.29–86.1	na	18	6.62–41.3	na
Manganese	µg/L	4.05	<0.20–508	23, 7	18.8	5.24–108	20, 0	12.6	0.23–868	24, 7	4.98	2.42–46.9	0, 0
Molybdenum	µg/L	0.95	<0.400–4.53	na	2.13	1.29–3.96	na	1.77	<0.400–12	na	1.12	E0.326–3.3	na
Nickel	µg/L	0.31	<0.06–4.24	na	0.14	<0.06–0.99	na	0.41	0.06–4.87	na	0.09	<0.06–0.27	na
Silver	µg/L	<0.200	<0.200–<0.200	0	<0.200	<0.200–<0.200	0	<0.200	<0.200–<0.200	0	<0.200	<0.200–<0.200	0
Strontium	µg/L	248	63.1–1,150	0	177	22–446	0	180	12.9–1,480	0	43	9.01–177	0
Thallium	µg/L	<0.040	<0.040–E0.028	0	<0.040	<0.040–<0.040	0	<0.040	<0.040–0.09	0	<0.040	<0.040–<0.040	0
Vanadium	µg/L	0.15	<0.10–9.3	na	<0.10	<0.10–1.2	na	0.20	<0.10–2.0	na	<0.10	<0.10–0.16	na
Zinc	µg/L	14.9	0.9–1,070	0, 0	3.7	E0.4–112	0, 0	6.2	<0.6–560	0, 0	6.1	<0.6–193	0, 0
Antimony	µg/L	<0.200	<0.200–0.135	0	<0.200	<0.200–<0.200	0	<0.200	<0.200–E0.170	0	<0.200	<0.200–<0.200	0
Boron	µg/L	26	10–66	na	57	44–73	na	58	12–438	na	174	15–643	na
Selenium	µg/L	0.8	<0.4–18.6	0	<0.08	<0.08–10.9	0	<0.4	<0.08–118	3	<0.08	<0.08–0.23	0
Radon	pCi/L	1,545	300–25,500	97, 7	--	--	--	460	70–1,470	90, 0	--	--	--
Uranium	µg/L	0.81	<0.040–20.3	0	0.040	<0.040–1.78	0	0.023	<0.040–7.31	0	0.040	<0.040–E0.030	0
Arsenic	µg/L	1.7	<0.2–10.7	3	<0.12	<0.12–0.42	0	<0.2	<0.2–6.7	0	<0.12	<0.12–0.15	0

CDM Smith

Limited geochemical modeling has been performed to date to determine the potential geochemical reactions from injection of drinking water in an ASR system. However, preliminary modeling has been performed for the Arapahoe aquifer during an earlier phase of the regional ASR study and suggests that for this aquifer, there is a limited potential for adverse geochemical reactions to occur that would impact the water quality of the recovered water. This evaluation is briefly summarized below.

The analysis was performed for the conditions at the Rangeview Well A-20 and source water quality anticipated from Aurora. Modeling of the treated water and Arapahoe groundwater was performed using USGS's PHREEQC model (Parkhurst and Appelo 1999). PHREEQC is an equilibrium speciation model that considers ionic complexing, activity effects, and the temperature and pressure conditions of the water being modeled to predict the saturation state of various minerals.

The mixing evaluation looked at potential precipitation and dissolution reactions that could affect the quality of the water or the permeability of the aquifer. The processes of potential concern, the results of the evaluation, and the possible mitigation measures are presented in **Table 2-4**.

Table 2-4 Summary of Concerns, Results, and Possible Mitigation Measures Identified during the Evaluation of Treated Aurora Water and Arapahoe Aquifer Groundwater Water Quality

Concern	Results	Possible Mitigation Measure
Precipitation of iron minerals	Predicted to occur but not likely to be a problem due to low iron concentrations (0.05 mg/L or less)	na
Precipitation of manganese oxide minerals	Not predicted to occur based on modeling	na
Precipitation of carbonate minerals	Not predicted to occur unless degassing of carbon dioxide (CO_2) occurs	Could be mitigated by pH adjustment using an acid
Dissolution of arsenic-bearing pyrite	Based on previous ASR projects within the Arapahoe Formation (i.e., Willows Well A-6A), no increase in arsenic is observed as a result of pumping oxygenated treated water into the formation	na
Dissolution of uraninite	Not predicted to occur based on modeling results	na

Note, although not fully considered in this evaluation, the potential for bio-fouling should also be considered. Bio-fouling is not common with the injection of treated water with a residual chlorine level, but issues were observed during recent ASR cycle testing of a Laramie-Fox Hills aquifer well.

2.3.3 Target Storage Volume

TSV is the volume of water required to be in storage at all times to meet the recovery goals for the project, and includes the sum of the water that will be recovered and the volume of water held as a buffer between the native groundwater and the stored water. It is a simplistic approach for calculating the size of an ASR system or recharge bubble.

Figure 2-3 illustrates the principles of a TSV with a cross section of an ASR well used for both injection and recovery phases. As shown on this figure, water is stored underground in an aquifer between two confining layers. The stored water is separated from the native groundwater by water in the buffer zone.

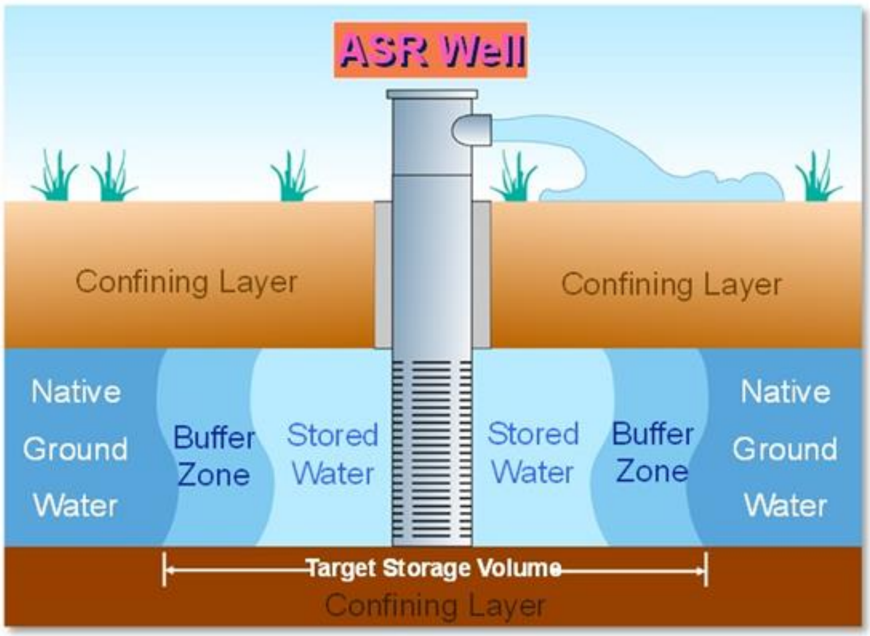


Figure 2-3 Example ASR Well Used for Both Injection and Recovery, Illustrating TSV

When there are no significant differences in the water quality between the stored recharge water and the native groundwater, including redox condition, then no buffer zone is required and only the volume that needs to be recovered needs to be recharged; however, this situation is uncommon. For example, even if the dissolved mineral concentrations are similar, when oxygenated water is recharged into an aquifer that is suboxic or anoxic, potential exists for the mobilization of metals and other constituents due to the oxidation reactions that then occur.

To avoid recovering elevated concentrations of metals and other constituents due to these oxidation reactions, the increasingly more common approach is to initially recharge for an extended period so that a buffer zone is developed and moved away from the ASR well. The buffer zone includes water that is mixed with the native groundwater and the recharge water, along with any mobilized minerals that are located in the zone as the redox state transitions from oxic back to suboxic or anoxic conditions. This change in redox and geochemistry is described in more detail in Section 2.3.2, Native Groundwater Quality and Rock-Water Interaction.

The volume of water required to be held in the buffer zone is variable. For example, for karst, brackish, limestone aquifers, the buffer zone volume is typically about half of the TSV; however, for relatively fresh, confined, sandstone aquifers such as those in the Denver Basin, the buffer zone will most likely be considerably less. The best way to think of the buffer zone is like the walls of a ground storage tank. To build the walls a volume is recharged once and then left in place to provide an adequate buffer. It is then usually possible to subsequently recharge and fully recover the target recovery volume on a consistent basis.

It is less acceptable however to recover the buffer zone volume once it is in place and established. Continued pumping may be possible once the target recovery volume is removed, but there are several key risks associated with removing the buffer zone water. Firstly, increased deterioration in water quality is likely as this water is brought back towards the ASR well, which means full retreatment of this water is likely required to meet drinking water standards. Secondly, experience has demonstrated that as poorer quality water is brought back into the storage zone that had previously been "conditioned" by the oxidized recharge water, remixing occurs and elevated concentrations of metals and other constituents that were previously oxidized are likely remobilized resulting in potentially reduced recovery capacity during subsequent recharge and recovery cycles. Recovery capacity is defined as the volume of water that may be recovered meeting a predetermined water quality standard.

The development of a buffer zone and determining the volume required for a buffer zone is not an exact science. Aquifer simulation modeling including geochemical modeling are tools that can help with the estimation of the buffer zone volume. The bottom line, however, is operational testing or cycle testing must be performed with careful water quality monitoring during recovery phases to determine how the system is really behaving because every ASR system is slightly different due to unique and variable hydrogeology, microbiology, and geochemistry. This can be monitored over time based upon water quality or by using tracers.

2.4 Existing and Proposed Infrastructure

2.4.1 Wells

The most successful ASR wells are those that have been specifically designed for both recharge and recovery. There are some subtle and some not-so-subtle differences in the way a well behaves when in recharge mode compared to conventional withdrawal. For example, there are differences in hydraulic behavior, particularly in wells that intersect unconsolidated sediments and/or require well screens with gravel packs. Gravel packs are prone to plugging during recharge, therefore the screen and gravel pack design must be sized to allow adequate back flushing or well development to remove any accumulated fines that would otherwise reduce the well performance.

Fortunately, potential exists for the retrofit of existing wells in the Denver Basin primarily because the wells intersect competent bedrock aquifers with groundwater quality not that dissimilar to the recharge water quality being contemplated. However, the following design considerations should still be considered. One of the primary reasons for considering the retrofit of wells is because the cost of a drilled ASR well, constructed to the depths and diameters required, can be significant. Nevertheless, it should be recognized that if retrofitted wells are used and the casing material is conventional carbon steel, then the asset life of the well will potentially be much shorter than if it were used only for conventional supply.

Some of the design considerations summarized below include:

- Casing material
- Casing diameter

- Casing strength (collapse and pressure rating)
- Mechanical integrity of the casing and annular grout seal
- Screen design
- Recharge interval
- Well condition

2.4.2 Casing Material

Depending on the types of recharge water and the salinity of the target storage zone (e.g., brackish groundwater zones), different casing materials other than mild steel are more appropriate in ASR wells. Conventional carbon steel is common in water supply wells, but for lower permeability formations, care must be taken that rust from the casing does not plug the well. Rusting of mild steel can be triggered either by the salinity of the target recharge aquifer, or more commonly, from the chlorine residuals in the recharge water (especially when treated drinking water is injected). Also, because of repeated wetting and drying during recharge and recovery, the casing is more prone to corrosion over an extended cased interval.

To mitigate, alternate casing materials are typically used in ASR wells and include polyvinyl chloride for shallow well applications, 304 or 316 stainless steel, other corrosion resistant alloys and fiberglass reinforced plastics (FRP); although not all FRP casing manufacturers currently have their product approved by the National Science Foundation for potable water use. Some proponents also suggest epoxy-coated steel casing, and although these coatings can substantially reduce or eliminate the surface area of steel that is subject to rusting, extreme care is required to not damage the coating during well construction or during installation of pumps and pump columns and any other well inspection. For butt-welded casing, damage to the coating in proximity to the weld is inevitable. It only takes several exposures of the steel surface (due to damaged or missing coating) for corrosion to preferentially attack that zone and cause the well casing to fail.

2.4.3 Casing Diameter

It is assumed that any existing well being considered for retrofit has been designed with inside casing diameters sufficient to accommodate the required pump and flow rates. It is also assumed that the well has been constructed with appropriate verticality (plumbness and alignment), particularly if vertical line shaft turbine pumps are being installed, which have lower tolerances for “bends” or “dog legs” in the casing.

The selection of pump may be dictated by the existing well casing diameter, but one aspect to consider is the maximum pumping rate that can be achieved compared to the recharge or injection rate. Typically, due to well hydraulics, the recharge rate will be less than the pumping rate. However, as a rule of thumb, it is important that the installed pump is capable of pumping at least 140 percent of the recharge rate so that the well may be periodically backflushed to waste using the installed pump and developed to remove any solids that may have been carried into the well during recharge. Higher pumping rates mean that the horizontal well velocities are greater and extend further into the formation, increasing the probability that fines can be mobilized and removed. Therefore, if the well diameter restricts the size of the pump, it is recommended that the recharge rate is reduced accordingly.

Another aspect to consider is the installation of injection tubes and downhole control valves, which are outlined in more detail in the next section, Section 2.5, Wellhead Facilities. Due to the smaller casing diameters of many installed Denver Basin bedrock wells, the use of separate injection tubes in addition to the pump column will likely not be possible. Therefore, the preferred design will be the use of downhole flow control valves, appropriately sized for the anticipated range of recharge rates.

2.4.2 Casing Strength

Care is always required for the correct selection of casing strength, as measured by tensile strength, yield strength, and collapse resistance. These criteria are particularly important for new well construction. For example, it is important that the tensile strength is high enough to support the weight of a suspended long casing string before it is cemented in place. Collapse resistance is also important, because if high lift cement stages are proposed during cementing of the annulus between the casing and drill hole or outer casing strings, extreme care must be taken that the casing does not collapse. This can occur if the differential pressure between the inside and outside of the casing is higher than the collapse pressure due to the fluid or live load weight of cement prior to it curing.

Although casing strength characteristics are most important for new well construction, they should still be considered for retrofitted wells. During recharge, it is possible that the well may become over-pressurized or the pressure heads may be greater than originally designed for, therefore, it is important that the yield strength (measured in pounds per square inch [psi]) is sufficient and there are no mechanical integrity issues. If for any reason the annulus inside the well (the head space between the water level and top of casing) goes into vacuum following recharge due to inadequate vacuum pressure control on the wellhead if the wellhead is sealed, then potentially, the vacuum pressure could exceed the collapse resistance. Theoretically, the bond with the cemented annulus should offset this, but casing strings, particularly on older wells, are not always adequately cemented and any additional weakness on the casing (for example due to corrosion) could cause issues.

2.4.5 Mechanical Integrity

Regardless of the regulatory requirements for Class V ASR wells in Colorado (some states with primacy who administer the EPA Underground Injection Control [UIC] Program rules require mechanical integrity testing of ASR wells, similar to that conducted for Class I injection wells), it is still prudent that the mechanical integrity of a retrofitted well is checked prior to recharge testing.

Testing does not necessarily need to include all of the components normally associated with mechanical integrity testing such as radioactive tracer surveys and mechanical pressure tests using downhole inflatable packers. Less costly methods are still possible such as full video surveys using forward view and side scan cameras and cement bond logs (CBLs). CBLs determine the presence of cement behind casings, and for well diameters less than approximately 12 inches, the cement bond between the casing, cement, and formation. Tools and CBL software have now been developed so that the presence of cement can be determined behind much larger casing strings, up to at least 30 inches in diameter.

In some well designs, the final casing string is a telescoped well design where the upper-cased section is a larger diameter to accommodate larger pumps, while the lower section is a smaller diameter pipe that is lowered or telescoped into position and then cemented in place. The two casing sections overlap with a variable overlap, from just tens of feet to sometimes over 100 feet, at a depth below the anticipated maximum pump setting depth. The reason for highlighting this design, which is believed to be uncommon in the Denver Basin, is because the overlap can sometimes fail and leak. For a conventional supply well this is less critical, but for a recharge well it is highly critical because potential exists for injected water to leak at the transition and enter a higher zone than intended. A CBL is one way of determining the likely adequacy of the seal.

2.4.6 Screen Design

To maximize injection and recovery capacity, the screen design for ASR wells typically differ from a conventional supply well. In summary, the screen slot size, gravel pack gradation, and, if possible, the screen diameter and gravel pack thickness, are all slightly larger. For recharge, it is important that hydraulic resistance or well loss is minimized and the potential for clogging reduced. One of the ways to achieve this is to reduce the entrance velocities.

The most common well screens used for ASR wells are wire wrap screens, and for deep well applications, the screen may be installed over a perforated pipe base to increase the strength and collapse resistance. One of the advantages of wire wrap screens for ASR applications is they typically have higher percent open areas (i.e., a greater percentage of the screen is open to water flow). Additionally, it is easier to develop the gravel pack behind the screen and rehabilitate, if necessary. These features are important because often ASR recharge intervals are located within deeper, thinner confined aquifers requiring the highest well efficiency possible. Note for recharge zones located within brackish groundwater aquifers, the screens should always be located at the top of the interval because the fresher recharge water will typically migrate to the top of the interval due to buoyancy or density effects.

Well screens should be constructed of noncorrosive materials. For the same reasons as outlined for casing material design, carbon steel is typically not recommended due to the higher potential for corrosion. Most wells utilize 316 or 304 stainless steel casing.

The gravel pack design is an equally important component of the screen design. Options include natural collapse packs, prepacked gravel screens, and graded filter gravel placed via tremie pipe immediately following installation of the screen assembly. In some cases, the formation is competent and no gravel pack is used, however, in these cases, the effectiveness for retaining sand from the formation is limited to the slot size of the screen.

Natural collapse packs have successfully been used for some ASR sites such as in Las Vegas, Nevada. When the screen is installed, the well is then developed with sufficient energy so that the formation collapses around the screen. However, it is important that the formation collapses uniformly and forms a continuous pack without voids around the screen, otherwise fine material can bypass the gravel pack and pass through the screen. Generally, this type of gravel pack is less efficient than other methods.

Prepacked gravel screens have been used and are well suited for deep screen placement or situations where it is difficult to place the gravel pack. However, generally, the well efficiency is lower, the thickness of the gravel surrounding the screen limited, and the ability to develop the formation outside the assembly is also restricted.

A recent innovation in gravel pack design is the use of round glass beads or SiLibeads®. These beads are manufactured by German manufacturer Sigmund Lindner GMBH and offer advantages over conventional mineral gravel packs. SiLibeads® are perfectly round beads with uniform grading (same size) in a variety of sizing to match the formation characteristics. The packing properties of SiLibeads® are superior to mineral gravel packs resulting in greater pore volume and permeability, which translates to a more efficient gravel pack and therefore lower well loss. The manufacturer also claims that the scaling of glass bead packs is delayed when compared with mineral gravel packs with identical grain sizes. This feature is important because scaling (with, for example, iron precipitates) is a common problem during recharge cycles. Finally, because of the greater and more uniform pore space between the beads compared with a natural mineral gravel pack, the pack may more easily be redeveloped and remove any accumulated fines during backflushing. To date, only several ASR wells have had SiLibeads® installed partly because the product itself has only been available since 2007; however, reports on well performance using this technology are favorable.

2.4.7 Recharge Interval

Defining the recharge interval or target storage zone is an important consideration for ASR wells where the native groundwater quality is significantly different from the quality of the recharged water. Aquifers are rarely homogenous and vertical changes in permeability, hydraulic head, and water quality frequently occur. These changes mean injected water will preferentially recharge zones with the greatest permeability and lowest hydraulic head or resistance. Intervals with low permeability and/or high hydraulic head will not receive the same recharge volumes, and in some cases, the native groundwater of lesser water quality is not even displaced by the high-quality recharge water. This can result in poor recovery characteristics or poorer water quality being pumped during a recovery cycle.

For water supply wells, the primary aim is to achieve the highest yield with suitable water quality. However, for ASR wells, much greater emphasis is placed on controlling the water quality of the source water and recovered water. One of the methods used to control the recharge and recovery of water in these situations is to restrict the recharge interval to thinner or more discrete zones. For this approach, zones of poorer water quality are avoided, but if selected, the poorer quality native groundwater is displaced by the higher quality recharge water in a much more controlled manner. If greater well yields are required, then one option is to “stack” ASR wells; that is, several ASR wells are constructed at the same location with a single recharge zone in each well stacked above each other.

It is typically advantageous to locate the top of a recharge zone immediately below a confining layer so that any vertical flow in the recharge zone is restricted. For situations where poorer native groundwater quality exists beneath the targeted recharge interval, it is also advantageous to locate low permeability confining layers beneath the recharge zone to prevent or reduce the potential for upconing of the poor water quality during recovery.

The native groundwater quality for the Denver Basin bedrock aquifer units is generally very good, which is fortunate because most of the wells in the Denver Basin in the Denver South Metro area are constructed with multiple well screens over intervals that can total hundreds of feet and therefore, as constructed, offer limited control for the recharge of water. However, in many cases retrofitting these wells for use as ASR wells should work, but prior to conversion, an understanding of the vertical changes in native groundwater should be investigated. This is because variations in water quality do occur, with approximately 1 in every 10 Denver Basin wells used for drinking water yielding groundwater having a water quality parameter that exceeds a human-health benchmark. The most common exceedances are for manganese, radon, arsenic, uranium, and selenium, all of which are derived from the natural leaching of the formations.

As discussed in Section 2.3.2, Native Groundwater Quality and Rock-Water Interaction, a detailed investigation of the quality of groundwater in the Denver Basin aquifer system was completed by USGS (Musgrove et al. 2014) with water quality samples collected during the period 2003–2005. This report notes that the shallow portions of the Dawson and Denver aquifers do have concentrations of nuisance constituents (chloride, dissolved solids, fluoride, iron, manganese, and sulfate), while exceedances for manganese and dissolved solids were the most common for the deep groundwater.

2.4.8 Well Condition

Not unlike conventional supply wells, it is important that the condition of an ASR well is periodically assessed. This is particularly important prior to commencing any recharge cycles and even more critical when retrofitting a pre-existing well. The retrofitted well may not be designed for higher pressure heads; there may be corrosion issues with the casing strings or a lack of cement behind casing that is required to ensure the well has mechanical integrity, or it may be possible for the well to become overpressurized if the well is partially clogged.

The typical approach is to first perform a desktop evaluation, looking at all historical well records and gathering all available construction and testing data including well logs, geophysical logs, well pump tests, and any prior well inspection reports. Depending on the level of pre-existing information available, subsequent well inspections and testing may then be required.

At a minimum, video surveys are normally performed using forward- and side-view cameras so that a visual inspection of the well casing may be made along with other key features of the well such as the production intervals or well screens and gravel packs. Following inspection, redevelopment of the well may be needed to ensure optimum well performance. Sometimes excessive buildup of scale, bio growths, and accumulated sediment restricts adequate inspection, so following well rehabilitation and redevelopment, a follow-up video inspection is then performed. If there are any concerns with the production screened intervals, vertical flow profiles can be completed to more clearly determine preferential flow zones and ensure screened intervals are not plugged.

Following the video inspection and any well development, a series of baseline well performance tests are appropriate. This includes pump-out tests to determine the specific capacity (typically measured as flow in gpm for every foot of drawdown), and with appropriate permits, injection or recharge tests so that the specific injectivity may be determined. These tests ensure that the benchmark performance of the well is determined up front and subsequent tests can then be used to measure any change in performance. Using this data is particularly important for recharge cycles as any well plugging issues can be identified early. With a proactive well development, backflushing to waste, or rehabilitation program, appropriate steps are undertaken in a timely manner and are more likely to ensure the well does not suffer from a permanent loss of performance.

2.5 Wellhead Facilities

Downhole flow control is one of the most important elements of an ASR wellhead design. This is particularly so for the Denver Basin bedrock aquifers because the water levels in the aquifers are now significantly below the surface; in fact, they are among the lowest or deepest in the United States with water levels approaching 1,000 feet below surface.

Cascading occurs when the water level in the recharge pipe does not rise to the surface during recharge. Cascading and allowing water to fall freely into the well from the surface is not advisable because the entrained air can lead to air binding in the storage zone and promote adverse geochemical reactions and bacterial activities that lead to clogging. Cascading can also potentially lead to cavitation damage to pipes, valves, and fittings. Several options are available for cascade control, but for the Denver Basin, there really are only a few viable options. These are either dedicated injection tubes that extend below the lowest anticipated water level or pump column recharge.

2.5.1 Injection Tubes

Dedicated injection tubes with a fixed diameter (e.g., 2 inches internal diameter) may either be installed to restrict the flow rate and keep the injection tube pipe full, or some form of downhole flow restrictor may be added to the bottom of a larger tube. Small-diameter injection tubes with or without a nonadjustable downhole flow constrictor (orifice plate) can be relatively inexpensive, however there are several major drawbacks.

Firstly, injection tubes typically cannot be installed in a retrofitted well or smaller diameter ASR well because space does not permit the installation of both a pump column and an injection tube. Secondly, they offer no operational control over flow rates, and often during start-up of an ASR well for the first time, the real hydraulic performance during recharge is not reliably known. This may be partially overcome by installing several tubes of different sizes, providing the option of using either one or both injection tubes to meet the desired range of flows. However, close attention during the operation of the ASR well is required during recharge because not only can the available hydraulic head at the surface change, but the well hydraulics also change as the recharge or pressure head increases as recharge proceeds. Finally, it is important that cascading and air entrainment during initial filling and at the end of a recharge cycle do not cause serious problems, so the application of injection tubes is better suited to long continuous recharge cycles. The latter two issues are largely eliminated when an adjustable downhole flow control valve is installed.

2.5.2 Pump Column Recharge

Pump column recharge is the preferred method of recharge for wells with deep water levels, using either vertical turbine line shaft pumps or deep well submersible pumps. However, for wells with deep water levels, large variations in recharge flow rate and pressures can be experienced, exacerbated because the riser or pump column is sized for the recovery rate.

The preferred approach to recharge under these conditions is to install a downhole flow control valve, either at the base of the pump column for wells with vertical turbines installed, or above the submersible pump with a check valve installed between the control valve and pump so flow during recharge does not run backwards through the pump. Most submersible pumps are not designed to reverse-turbine so under this scenario, damage to the pump will occur.

Several downhole flow control valve options are available that include:

- Baski InFlex™ Flow Control Valve (FCV™)
- 3R valve
- Variable orifice selective monitored artificial recharge throttle valve (VoSmart)
- Variable orifice valve (VoV)

Each valve has different advantages and disadvantages. The subsections below summarize the advantages and disadvantages, with information provided from the valve manufacturers. Note any claims concerning the performance of these valves are those made by the manufacturer and not CDM Smith.

2.5.2.1 Baski InFlex FCV

Baski, Inc. made the world's first downhole flow control valve in 1992, which was installed in Highlands Ranch, Colorado for CWSD. Since then, Baski has manufactured over 180 FCVs, which have been installed mostly in the western United States. Their InFlex FCV is a fluid-actuated valve that permits pumping water to the surface or regulating the flow of water from the surface into the well while using the same column pipe and maintaining a column of water in it at all times. The InFlex FCV may be used in conjunction with a submersible pump or a vertical turbine pump.

The manufacturer states that because of its unique design features including no sliding seals to fail, it is the most durable and versatile valve on the market. The key to the successful control of the injection water through this valve is its long, adjustable, annular-gap flow path through a series of circular annular orifices. This flow path provides noncavitating head loss that is easily controlled by changing the gap between the annular orifices and the rubber element. Stainless steel channels are a part of the adjustable flow system and stabilize the rubber element as it is pushed down and stretched by the inflation liquid. By design, there is no place for sand to collect; therefore, it is impossible for the rubber element to "stick" at any time during pumping or injection as there are no sliding surfaces to become stuck due to sand-locking. The InFlex FCV is extremely wear-resistant due to its rubber control element, similar to slurry pumps, which are rubber-lined to reduce wear. Due to its low-velocity, cavitation-free flow, the InFlex FCV resists sand and silt far better than conventional valve designs. Conventional valves have all of their pressure loss (at high velocities) across only one orifice stage, leading to wear from suspended solids and erosion with cavitation.

Included with the valve is an automatic or manual control panel, which is designed to allow a single user to adjust the inflation pressure of the FCV either remotely with a programmable logic controller (PLC) or SCADA control system, or manually with the incorporated needle valves. For automatic control, there are two solenoid valves on the panel that can be tied into the user's existing PLC or SCADA control system. Paired with both solenoid valves are two metering valves with vernier handles. These metering valves can be used in conjunction with the solenoid valves to fine-tune the control of the inflation pressures. Essentially, the metering valves determine how much nitrogen gas is passed through for each pulse of the solenoid valve. This allows for different rates of inflation and deflation.

For manual operation, large needle valves are positioned in a parallel path to the solenoid valves, which allow the user to control the inflation and deflation right at the panel. Manual control is often convenient during start up and/or diagnostic testing of the operations. A large, 4.5-inch pressure gauge installed on the panel allows the operator to read the downhole inflation pressure while making any manual adjustment, or to double check against other digital readouts from the PLC or SCADA control system.

2.5.2.2 3R Valve

The design of the 3R valve allows the user to control the flow of water flowing down a pump column by activating two hollow, single-acting hydraulic cylinders that move an ultra-high molecular weight (UHMW) internal sleeve in front of a group of small holes that allows the water to then move from the inside of the valve through the holes to the outside and out into the aquifer. The small-diameter holes are located around the valve in a slight upward spiral pattern, so as the UHMW sleeve moves, it exposes only a few holes at a time. This allows the controller to regulate the flow of water more precisely. The small discharge holes in the valve also allow the water that is surrounding the valve to dissipate the energy of the water that is flowing out of the holes, and in turn, reduces the hydraulic mining that might occur inside the borehole. The valve is constructed out of stainless steel and does not screw together like other valves on the market. This one-piece construction will not allow the valve to unscrew and fail. The 3R valve also has no moving parts that are on the outside of the valve body that can rub against the borehole or allow rocks or other object to interfere in the operation of the valve. The 3R valve does not use any rubber boots, which are subject to wear and can cause the valve to fail, to control the flow. The 3R valve can be ordered with an option that allows the valve to close if there should be a hydraulic failure in the valve’s control line. 3R valve also makes a recharge-only valve that allows the operator to control the flow of water back into the aquifer.

2.5.2.3 VoSmart and VoV

VOV Enterprises, Inc., a company incorporated in Nevada and California, specializes in industrial valve manufacturing with a focus on valves for flow control and downhole flow control for dedicated recharge, salt water barrier, water banking, and ASR wells. They offer two products: VoSmart (or V-Smart) and VoV.

The VoSmart is a hydraulically actuated, near-linear flow control device that permits the operator to adjust the flow rate using a PLC or SCADA control system. The valve functions efficiently in ASR wells in conjunction with either a submersible or vertical turbine pump. The design features provide this valve with cavitation-free operation.

At startup and during recharge, the valve is set in the closed position allowing the recharge pipe to fill with water. The air in the pipe is then evacuated through an air-vacuum valve at the wellhead ensuring the elimination of cascading water. The recharge rate may then be set using a manual or electric hydraulic control valve with local and/or SCADA control. Flow may be adjusted using a null loop, a dead band, or a magnetic flow meter and the dynamic water level, along with a PLC to control the water flow through the "D" ports for near-linear control. The valve is designed to smoothly start a recharge well, adjust the flow linearly, and place the water into the formation gently under laminar conditions.

The VoV is a hydraulically actuated, near-linear flow control device that also permits the operator to adjust the flow rate using a PLC or SCADA control system. The VoV also functions quite efficiently in ASR wells along with other well options requiring near-linear flow control. In wells, the VoV is typically set just above the well screen, and at startup, the valve is set in the closed position (closed or 20-30 gpm flow) allowing the drop pipe to fill with water. The air in the pipe is evacuated through an air-vacuum valve at the wellhead. The range in flow settings means the VoV is designed to provide full closure or trickle flow to maintain the bubble of recharge water in the formation.

The VoV may be sized to meet the specific design requirement. One of the advantages of this valve is it is available in small diameters, starting at 3 inches up to 12 inches, with maximum flow ranges for the different-sized valves from 170 gpm to 2,650 gpm, with a dynamic water level of 100 feet below land surface.

2.5.3 Energy Recovery

Energy recovery may be possible during recharge cycles using a downhole power generation unit. Significant potential exists to drive a unit with the surplus recharge head available due to the deep-water levels. If demonstrated to be economically viable, this technology could assist with offsetting the energy costs for operating an ASR well during recovery. The technology is still in development, but there are at least two documented cases of its successful application. Downhole power generation has also been subject to at least one research thesis in the United States, and the approach is currently under review by others in cooperation with Colorado State University (CSU). Several patents for the technology also exist.

The two known documented test cases are at the Northern California Power Agency (NCPA) Geysers Geothermal site in California, and Madison Farms in Echo, Oregon. At the NCPA site, a test generator was installed into an existing injection well to a depth of 1,800 feet. An off-the-shelf 400-horsepower (HP) downhole electrical submersible geothermal pump was modified to operate as a turbine generator pump and was tested at injection flow rates between 800 and 1,300 gpm. The generator resulted in a sustainable generation of 250 kilowatts, and the estimated payback period for the system was just 3 years. The tests were completed in 2009 with the assistance of a grant from the California Energy Commission. Further studies to better determine the energy efficiency are currently underway.

In 2011, Kent Madison of Madison Farms tested the concept using regenerative drive technology at a shallow well location. Financial assistance for the test was provided by The Energy Trust of Oregon with a research and development grant that was used for the purchase of the regenerative module. Full details of the tests are outlined on the 3R Valve website, a downhole control valve patented by Kent Madison. The 3R valve was originally developed for use on his own ASR well. Some of the highlights from the test are extracted below. Note the details are the subject of a patent.

The source water for the power generation was a shallow pit supplied by a 40-HP pump delivering 542 gpm at 47 psi to the inlet of the regenerating pump. The regenerating pump and line shaft turbine was located in a 20-foot deep shallow well. The regenerating pump was set on top of 15 feet of 6-inch column, with four 6-inch bowls and a water level 5-feet below ground surface. A U.S. Drives, Inc. AC Line Regenerative Module, model number RG-0400-0060-N1, rated at 50 HP, was used to capture the direct current line voltage created during the regenerative process. The regenerative module was connected to a 125-HP, U.S. Drives, Inc. Phoenix variable frequency drive, model number D4-0125-N1.

During the test, the pump was allowed to spin backwards, being driven by the 542 gpm of water flow and the 118 feet of head that was available at the pump bowls. A 5-hertz reverse input was then applied to the drive, magnetizing the stator and causing the rotor of the motor to slow down from 46 hertz to 5 hertz. This electronic braking action caused the direct current bus to produce energy that the U.S. Drive regenerative module then converted to alternating current power and supplied back to the utility line at 480 volts (three phase).

A 100-HP pump was installed in the same well as the line shaft turbine and was pumped at a continuous rate into the irrigation system. The reason this pump was installed and operated was in lieu of placing power back onto the utility grid. The energy required to operate the test system was 12,015 watts, of which 5,800 watts were recovered during regeneration; therefore, demonstrating that 48 percent of the energy needed to deliver water to the regeneration site was recovered. Note the focus on the Madison Farms test case was reducing the energy requirements for recharging water into the well. For ASR wells with much deeper groundwater levels, significantly greater energy recovery is expected, with some researchers suggesting at least 70 percent.

2.5.4 Water Utility Infrastructure

The ideal hydrogeological location for siting ASR wells may not necessarily occur where existing water utility infrastructure is located. The cost of moving water can be expensive, therefore well siting needs to take these factors into consideration. Although the cost of drilling ASR wells can also be expensive, the overall project cost may still be less with an additional ASR well to make up for any loss in well yield, rather than installing additional pipelines to convey the recharged and recovered water.

There are several other factors to consider. These include any pretreatment requirements for the recharged water, power availability, and the likely recovery efficiency for the wells. When recharging into an aquifer with similar water quality to the recharge water, and with no adverse geochemical reactions (which results in excellent recovery efficiency), it may be possible to space ASR wells further apart and colocate wells in proximity to existing (strategic) water mains (i.e., along the line of the water main). This situation provides the greatest flexibility and can be very cost effective. However, for sites with recharge into poor or brackish native groundwater, it becomes increasingly important that ASR wells are spaced more closely together so that individual recharge bubbles coalesce. Under this scenario, additional conveyance pipelines may be required to optimize the wellfield layout.

In most cases, the recharge source water is treated drinking water, therefore consideration needs to be given to the most cost-effective way of distributing that water to individual ASR wells and then recovering the water back into supply. When utilizing treated water mains to convey the water (as compared to raw water mains associated with a conventional wellfield), it is a requirement that adequate backflow prevention is in place to ensure the stored water does not enter the treated water supply main without meeting all the regulatory requirements. For some ASR facilities, a simple solution is to also provide disinfection at the ASR well site (assuming all other water quality parameters meet drinking water standards) so that stored water when recovered may simply be disinfected prior to going into supply. At other facilities, the recovered water may need to be directed via raw water mains to a dedicated treatment facility for treatment.

Whenever existing water mains are used, it is important that residual water pressures are sufficient to be able to recharge the ASR wells, and dependent on the arrangement, some combination of pressure control or flow control may also be required to balance pressures and flows for both the well and the water main. For downhole flow control valves such as the Baski valve designed to control recharge rates and avoid cascading water, a residual pressure in the recharge line, typically in the range 10 to 30 psi, will be required at the wellhead. If pressures are too low, dedicated inline booster pumps at each ASR well or a booster pump station are required.

These are just some of the high-level considerations for the design and operation of ASR systems. ASR is more than just a dual purpose well; the entire water utility infrastructure should be considered in parallel so that the ASR system is fully integrated with the water supply system and is developed in a cost-effective way. For demonstration projects where initially, a single ASR well is constructed and tested, water utility infrastructure requirements can be even more critical to reduce the cost of implementation, and often test demonstration projects are collocated on water treatment facilities where there is typically good access to power and land, and relatively short distances to convey the water are required.

2.6 Permitting

There are unique regulations and permits that must be obtained to construct or retrofit an existing well for ASR. These permits may vary based on location and the purpose of injection. For ASR in the Denver area, permits must be obtained from CDWR, the Colorado Department of Public Health and Environment (CDPHE), and EPA.

2.6.1 Colorado Division of Water Resources

The CDWR has specific rules for artificial recharge extraction from the Denver Basin (2 CCR 402-11). These rules govern the permitting and use of waters artificially recharged into the Dawson, Denver, Arapahoe, and Laramie-Fox Hills aquifers and gives the state engineer authority to administer the orderly withdrawal of any artificially recharged water. Highlights of these rules include:

- The water at the time of injection is required to be fully consumable and/or reusable, or decreed for storage, or legally and physically available for storage. Totalizing flow meters are required for both injection and extraction.
- A report summarizing the current hydrological conditions in the existing well and the decreed rights and permitted or registered wells of record within 1 mile of the extraction site.
- Once granted, the permit shall continue indefinitely as long as a valid permit is applicable to the existing well and the applicant complies with the reporting requirements in the rule.
- Remote extraction from a confined aquifer is limited to 5 miles from the injection site within the same contiguous extraction parcel, and 1,000 feet in an unconfined aquifer.
- The maximum amount of recharged water that may be extracted through any one well, in any one calendar year, is five times the maximum amount of water injected in any one calendar year, and in no case shall the amount of water extracted exceed the total amount of water injected.
- Each calendar year water level data as well as permanent records on both injection and extraction activities (maintained on a weekly basis) shall be submitted to the state engineer.

For current and additional information on well permitting, see the Colorado Division of Water Resources Well Permitting page at: http://water.state.co.us/groundwater/wellpermit/Pages/default.aspx.

2.6.2 Colorado Department of Public Health and Environment

The Safe Drinking Water Enforcement Group of the CDPHE has specific responsibilities for water that is used for drinking supply. During initial pilot testing of an ASR well, if the recovered water is discharged to waste and is not used as a source of water for drinking supply, then there are no CDPHE requirements or permits that need to be met or obtained. However, when recovered water from an ASR well is ultimately used for drinking water, a new source characterization must be performed under their engineering requirements because the source of a water utilities supply will have changed. These engineering requirements are presented on the CDPHE website (https://www.colorado.gov/cdphe).

The Water Quality Control Division regulates the discharge of pollutants into the state's surface and groundwater under the provisions of the Colorado Water Quality Control Act of 1974. The protection and maintenance of water quality is achieved by issuing permits specifying the types and amounts of pollutants that may be discharged without violating the state water quality standards. The Water Quality Control Commission addresses Colorado's standards for groundwater in:

1. Regulation 41, basic standards for groundwater: https://www.colorado.gov/pacific/sites/default/files/41_2016%2812%29.pdf

2. Regulation 42, site-specific water quality classification and standards for groundwater: https://www.colorado.gov/pacific/sites/default/files/42_2017%2812%29.pdf

2.6.3 U.S. Environmental Protection Agency

ASR wells in Colorado are permitted under the UIC program of EPA Region 8. The UIC regulatory framework was originally set up pursuant to the 1974 Safe Drinking Water Act, and rules were promulgated by EPA in 1981. Thirty-nine states have been granted primacy by EPA, providing them responsibility for implementing the UIC program. However, Colorado is not included and therefore the UIC program is implemented directly by EPA. The primary focus of the UIC program is to protect USDW from contamination, defined as aquifers with TDS concentrations less than 10,000 mg/L.

The wells used to inject water for storage in an ASR project are classified as Class V injection wells. This class of wells includes wells not included in other classes and includes a wide range of wells, although most common are shallow disposal systems. Some types of Class V wells have the potential for groundwater contamination or degradation, and while they may still be permitted, a permit is required. Other Class V wells including ASR wells are usually allowed to operate under authorization by rule once information has been submitted in accordance with 40 CFR 144.26.

Specific information submitted to evaluate whether a permit or rule authorization will be issued include the source of injectate (including flow rate, volume, and pressure), site location and hydrogeology, existing well locations within a 1-mile radius, receiving formation characteristics, and water quality of both the injectate and receiving aquifer and potential adverse geochemical interactions. The complete list of required information to be submitted in support of operating an ASR under authorization by rule is contained in the interim report in **Appendix A**.

Permitting an ASR well in Colorado can vary depending on the agency and type of system that is being operated. It will generally take longer to permit a new ASR well or ASR system than to permit a new well for an existing ASR system. In addition, as ASR becomes more common in Colorado, regulatory agencies are assessing their rules and regulations. Thus, it is important to check the latest rules and regulations prior to submitting applications for permitting an ASR well.

Additional information and updates to EPA's regulation can be found on the EPA's Region 8 Underground Injection Control website: https://www.epa.gov/uic/underground-injection-control-epa-region-8-co-mt-nd-sd-ut-and-wy.

Section 3

Summary of ASR in the Denver Basin

As discussed in Section 1, the objectives of the ASR study were revised as the study progressed into Phase II. This section focuses on the Phase II ASR study objective to summarize the ongoing and planned ASR projects in the Denver Basin/South Metro area. Since completion of Phase I, several entities have embarked on their own ASR studies and programs. To gain a better understanding of each entity's ASR program, CDM Smith, on behalf of SMWSA, reached out to each member entity through a series of phone calls, surveys, and meetings. The information obtained through this process is important in assessing the viability of ASR as part of the water supply solution for each water provider in the South Metro area.

3.1 Overview of Data Collection Process

A three-step approach was utilized for conducting a survey of ASR projects throughout the SMWSA membership. The purpose of this approach was to establish which members are currently operating, piloting, or seriously considering ASR as part of their water resource portfolio in the future; to collect specific details on existing and planned programs; and to follow up for additional clarification and details. An overview of this approach is shown in **Figure 3-1** and described in more detail below.

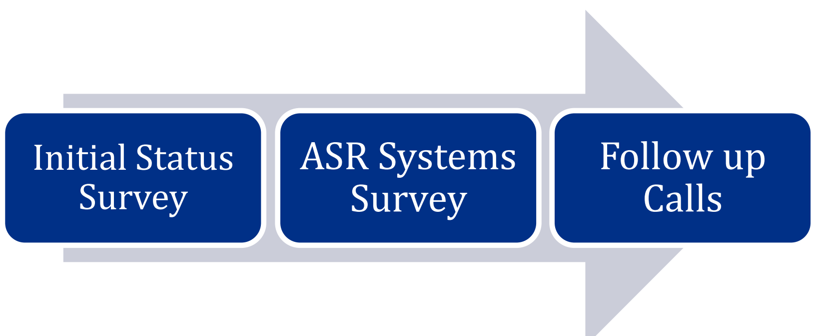


Figure 3-1 ASR Status Survey Workflow

First, an initial status survey was conducted via email, phone, or in person to identify existing ASR operations or plans for ASR amongst all thirteen SMWSA water provider members. The service areas of the members and results of this initial outreach are shown on **Figure 3-2** and include:

- Arapahoe County Water and Wastewater Authority (ACWWA)
- Castle Pines North Metropolitan District (CPMD)
- Centennial Water and Sanitation District (CWSD)
- Cottonwood Water and Sanitation District (W&SD)
- Dominion W&SD

- East Cherry Creek Valley Water and Sanitation District (ECCV)
- Inverness W&SD
- Meridian Metropolitan District (MD)
- Parker W&SD
- Pinery Water and Wastewater District (W&WD)
- Rangeview
- Stonegate Village MD
- Town of Castle Rock

Second, following initial outreach, an ASR system survey was solicited from members who are currently operating or planning to operate an ASR system. This supplemental survey was more detailed and focused on gathering specific information related to source water, well quantity, system capacity, opportunities, and lessons learned. The completed ASR system surveys can be found in **Appendix B**. Lastly, follow-up calls and meetings were held to clarify any responses and collect available data.

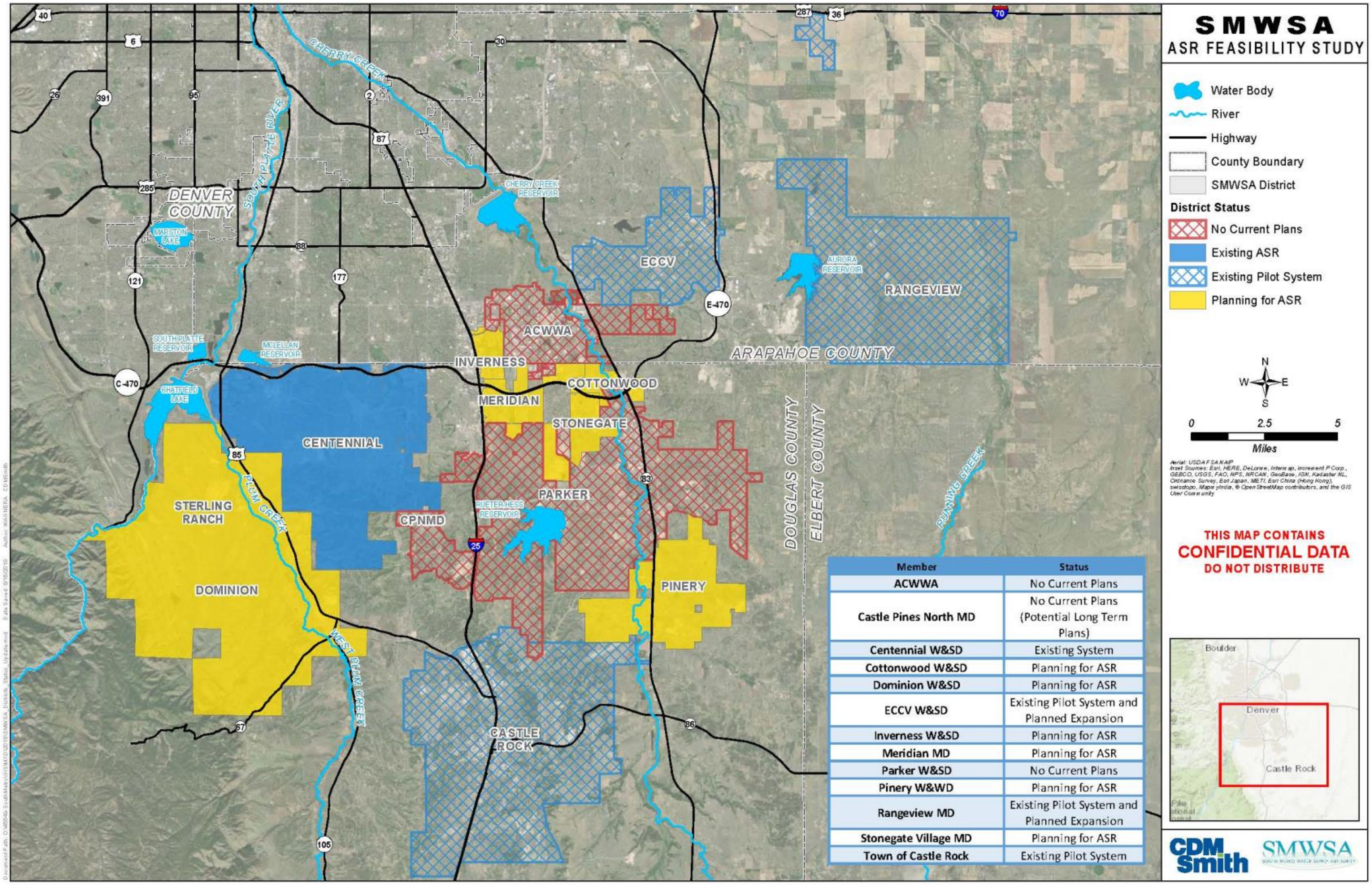


Figure 3-2 SMWSA ASR Status by Member

3.2 Survey Results

Survey results are summarized in the sections below. SMWSA members were grouped based on the current status of their ASR operation. These groups include:

- Entities currently operating or piloting ASR
- Entities currently planning for ASR

SMWSA members who currently have no plans for implementing ASR are not included in this section; however, a survey response (if received) is included in **Appendix B**.

3.2.1 Entities Currently Operating or Piloting ASR

This section includes a summary of ASR systems for those members that are either currently operating or at the pilot stage. An overview of their system is provided in **Table 3-1**, with more detail provided below including the challenges, lessons learned, and opportunities that each member identified in their survey response.

Table 3-1 Overview of Existing and Pilot ASR Systems in SMWSA

Member	Status	Source Water	Number of ASR Wells
CWSD	existing system	South Platte River	33
ECCV	existing pilot system and planned expansion	Northern Water Supply Project	1 (pilot)
Rangeview MD	existing pilot system and planned expansion	WISE	1 (pilot)
Town of Castle Rock	existing pilot system and planned expansion	WISE, Plum Creek surface water and alluvial water, treated reuse water	2 (pilot)

3.2.1.1 Centennial Water and Sanitation District

CWSD has 33 wells equipped for ASR utilizing both injection and production in the same wells for a total injection rate of 6.38 MGD. Their system is designed for drought supply. The source water for their ASR system is the South Platte River and they inject treated water from their surface water system. The recovered water is treated in one of their two groundwater treatment plants. Post recovery treatment includes greensand and anthracite filtration to remove iron and manganese, sodium hypochlorite for disinfection, and caustic soda for pH adjustment.

<u>*Challenges*</u>:

- The primarly challenge the cost of operations, including the cost of initial surface treatment and pumping and the cost of recovery pumping

<u>*Lessons Learned*</u>:

- Production wells should be pumped occasionally (monthly) during the injection cycle to backwash any solids off the face of the well gravel pack, similar to backwashing a sand filter

Opportunities:

- Extending the life of aquifers for water supply

3.2.1.2 East Cherry Creek Valley Water and Sanitation District

ECCV is currently pilot testing one Arapahoe aquifer well, injecting 80 gpm or 0.11 MGD. The district plans to expand their ASR operations with up to 13 wells ultimately equipped with ASR capabilities. Their system is designed for drought supply. The water source is from the Northern Water Supply Project (South Platte River) near Barr Lake. The source water is treated at a reverse osmosis plant then blended with their well water prior to injection. The extracted water is disinfected but no further treatment is needed at this time.

Challenges:

- Automating the ASR operations through SCADA
- EPA permitting
- Shorting of the level transducers due to a lightning strike

Lessons Learned:

- ASR operations are viable, even in lower-transmissivity aquifers
- Switching from manual controls to an automated control panel, and using stainless steel cables to secure transducers to avoid binding and sticking to the side of the well, have made operations run smoother

Opportunities:

- Significant advantages exist in longer term storage of water to meet drought demands when surface waters may be out of priority. Additionally, there are benefits due to minimal evaporation of water stored underground, potential for short-term and long-term storage, operational flexibility, and the ability to optimize water operations.

3.2.1.3 Rangeview Metropolitan District

Rangeview currently has one well equipped for ASR. They began pilot testing on this well in early 2017 and plan to expand their system in the future. Their planned capacity is 1.5 MGD, spread across eight Denver Basin wells, and will be using WISE water as the source.

Challenges:

- Source water cost

Lessons Learned:

- None identified at this time

Opportunities:

- Additional water storage in their system

3.2.1.4 Town of Castle Rock

The current planned system capacity for ASR includes four wells equipped for ASR. Currently, two wells are equipped and are in pilot testing. Two additional wells are planned for 2018. This will give the Town of Castle Rock the ability to inject approximately 860 gpm (1.24 MGD). The town will inject excess renewable water as it is available during nonpeak demand months. The town will determine future ASR sites based on the results of the two initial sites and the availability of excess renewable water. The ASR wells will be used as a seasonal supply and/or drought supply depending on the amount of renewable supply available for recharge. Their water sources include WISE water, treated Plum Creek surface water and alluvial groundwater, treated reuse water (originated from the Denver Basin aquifers), and future imported water supplies that the town is working on procuring.

Challenges:

- Equipment issues and failures and pilot testing timing

Lessons Learned:

- Ensure that operators and plant mechanics are properly trained on the ASR system
- Prepare an operating and maintenance manual that is readily available and utilized by staff
- Have a plan and communicate with all parties involved

Opportunities:

- The ability to store excess renewable water during the nondemand season with limited retreatment and evaporative loss and the potential for regional partnerships

3.2.2 Entities Currently Planning for ASR

This section includes a summary of ASR systems for those SMWSA members that are currently planning on implementing ASR in the future but do not yet have active systems or pilot testing. An overview is provided in **Table 3-2**, with more detail provided below including the challenges, lessons learned, and opportunities that each member identified in their survey response. For some members, the survey is still being completed. This is indicated by a "survey response in progress" designation in **Table 3-2**.

Table 3-2 Overview of Planned ASR Systems in SMWSA

Member	Status	Source Water	Number of ASR Wells
Cottonwood W&SD	Permitting for ASR	Cherry Creek, WISE, and Denver Basin groundwater	3
Dominion W&SD	Planning for ASR and partnering with Castle Rock	WISE	Currently unknown

Member	Status	Source Water	Number of ASR Wells
Inverness W&SD	Permitting for ASR	Denver Water, Denver Basin groundwater, WISE, and Cherry Creek (when developed)	4
Meridian MD	Permitting for ASR	Denver Basin groundwater and WISE	1 to 2
Pinery W&WD	Planning for ASR	WISE and Cherry Creek alluvial well water	Up to 9

3.2.2.1 Cottonwood Water and Sanitation District

Cottonwood W&SD is planning to use ASR to store three quarters of its WISE yearly volume, if delivered during the winter months, to firm up its summer supplies. The district's plan is to use it for seasonal ASR during most years. However, during years when the district's supplies in Cherry Creek are not limited, the plan will be a combination of aquifer storage (multi-year) and seasonal ASR. Cottonwood W&SD is planning to retrofit three Arapahoe wells for ASR.

Challenges:

- Getting through the permitting process

Lessons Learned:

- Getting through the permitting process takes time

Opportunities:

- Provides an increased potential for a permanent solution for aquifer decline
- Opportunity to recharge the aquifer during average years when renewable supplies have the ability to offset the use of both the existing Denver Basin and the stored supplies from the ASR process
- ASR eliminates water losses typically observed in open storage reservoirs, including high costs for re-treatment. In addition, it eliminates large capital costs for open storage reservoir/treatment capacity ownership, including any additional infrastructure needed to deliver the excess supply to and from the open storage reservoir
- Treatment costs for ASR supply is anticipated to be more cost effective than treating supplies from open storage reservoirs

3.2.2.2 Dominion Water and Sanitation District

Dominion W&SD is planning a conjunctive water supply system that is primarily renewable water with nontributary groundwater to be used as a back-up and a firming supply. Dominion is excited about the prospect of ASR to assist in optimizing its water supplies in the future. However, rather than developing their own wellfield at this early phase in its system development, Dominion partnered with Castle Rock for retiming and firming of 700 ac-ft of Dominion's WISE water. Dominion has an additional 625 ac-ft of subscription of WISE water. ASR will be considered for any wells that Dominion develops in the future. Dominion's planned system capacity and the need for additional wells is still in the early stage.

Challenges:

- None identified at this time

Lessons Learned:

- None identified at this time

Opportunities:

- Partnering with Castle Rock to retime and firm WISE supplies while Dominion determines needs for future wells

3.2.2.3 Inverness Water and Sanitation District

Inverness W&SD is planning to store its full WISE yearly allocation (assuming those are delivered during the winter months in some years) to firm up its summer supplies. Inverness is planning to retrofit four of their Arapahoe wells for ASR. The plan would be to use the wells for seasonal supply as well as a drought supply in dry years. Inverness plans to use its existing supplies (Denver Water, Denver Basin groundwater, and WISE) as well as planned supplies from Cherry Creek to supply water for ASR.

Challenges:

- Getting through the permitting process

Lessons Learned:

- Getting through the permitting process takes time

Opportunities:

- Provides an increased potential for a permanent solution for aquifer decline
- Opportunity to recharge the aquifer during average years when renewable supplies have the ability to offset the use of both the existing Denver Basin and the stored supplies from the ASR process
- ASR eliminates water losses typically observed in open storage reservoirs, including high costs for retreatment; it eliminates large capital costs for open storage reservoir/treatment capacity ownership, including any additional infrastructure needed to deliver the excess supply to and from the open storage reservoir
- Treatment costs for ASR supply is anticipated to be more cost effective than treating supplies from open storage reservoirs

3.2.2.4 Meridian Metropolitan District

Meridian MD is planning on equipping one or two wells with ASR to provide 0.27 MGD on a monthly water basis. The water source will be WISE water.

Challenges:

- Getting through the permitting process

Lessons Learned:

- None identified at this time

Opportunities:

- Retrofitting wells for ASR will prove economical given the amount of storage it can potentially provide in their system

3.2.2.5 Pinery Water and Wastewater District

Pinery W&WD plans to utilize ASR in their Arapahoe aquifer wells. Currently, Pinery has nine Arapahoe aquifer wells that will be retrofitted with an average production capacity of 300 gpm and plan on using these wells to meet peak seasonal demand. Additionally, they plan to use one well in the winter to obtain the greatest reuse benefit in their augmentation plan. Their water supply for ASR will be Cherry Creek alluvial groundwater and WISE water.

Challenges:

- None identified at this time

Lessons Learned:

- None identified at this time

Opportunities:

- Excess water storage and the potential to slow the decline of water levels in the aquifer

3.3 Regional Entities and ASR

Other entities in the greater Denver metro area are also considering ASR. As part of this project, CDM Smith interviewed Denver Water and Aurora Water staff to gain a better understanding of their ASR plans. While outside the scope of this study, regional partnerships for ASR may prove beneficial in the future. Below is a brief description of current ASR planning by Denver Water and Aurora Water.

3.3.1 Denver Water

Denver Water is undertaking a feasibility study of ASR within the bounds of the City and County of Denver. The primary objective of the project is focused on data collection, since hydrogeologic information within the city and county is not as prevalent as other areas of the Denver Basin. The project consists of drilling eight boreholes, collecting core samples, and evaluating the hydrogeologic properties of the core. Denver Water is looking at ASR as a viable alternative to future, increased surface storage; however, preliminary results of the study show an ASR program within the city and county may be limited due to the properties of the Denver Basin aquifers within the city's boundaries, and land access concerns as Denver continues to urbanize and experience infill.

3.3.2 Aurora Water

Aurora Water is considering ASR as a future storage option that would primarily serve as drought supply. Currently, the utility is not conducting any formal studies; however, they have added technical staff that will be exploring the potential for ASR in more depth in the near future. Also, the City of Aurora, as part of their annexation process, obtains the rights to Denver Basin groundwater as their service area grows. In addition, Aurora Water's Peter D. Binney Purification Facility, located near Aurora Reservoir, serves as the primary treated water supply for WISE water and serves as a source of injection water for Aurora Water as well as WISE participants.

Section 4

ASR Tools and Resources

This section focuses on the Phase II SMWSA ASR study objectives of developing tools and resources for water providers to assess ASR for their respective communities. The development of tools and resources is valuable for the assessment of ASR in the Denver Basin due to the potential program scale and interrelated technical issues that must be considered. The tools developed allow for user-specified inputs to assist in the performance and economic comparisons of ASR facilities in different sites and configurations, and for comparisons with other storage and management approaches.

To assess ASR feasibility, common water system planning, design, and operation parameters are required to be input into the tool. These parameters include:

- Hydrogeology
- Aquifer yield
- Pumping requirements
- Construction requirements for retrofitting existing wells or constructing new wells
- Operating schedule
- Water available to be put into storage
- Wellfield performance

Development of a hydrogeological conceptual model is a valuable means of establishing the parameters identified above. Conceptualization of the groundwater system is also the first step in analytical/numerical model development, calibration, and application. Models can be used for gaining an understanding of subsurface water movement and flow, and the potential hydraulic influence of implementing ASR within basin aquifers. However, experience has shown that lack of data and uncertainties frequently render regional models to be of limited value due to insufficient data to calibrate and verify model performance. Model development during the planning stage must either be limited to those areas with sufficient available data (wellfield-scale) or be delayed until such time that site-specific data are collected from exploratory well programs. In the context of this study, the former approach was available and selected. Analytical models were developed to simulate and predict the water levels in the Denver Basin for selected wellfields to demonstrate the feasibility of this approach. The locations selected depended on the available data collected by SMWSA members to allow for comparison of the estimated aquifer parameters with actual performance data. More widespread application of analytical and numerical modeling can be undertaken, if desired, as more exploratory and operational data are collected.

This section summarizes the ASR tools and resources developed for this study and includes:

- Methods for resolving wellfield-scale geology and hydrogeology to examine ASR potential
- Estimates of typical aquifer parameters
- Methods for predicting groundwater levels in the Denver Basin
- Spreadsheet tool for estimating life cycle, capital, O&M, and present value costs at a screening level associated with Denver Basin ASR programs

In addition to the conceptual hydrogeological model presentation, case studies are used to illustrate the effectiveness of the methods, estimates, and tools presented.

4.1 Hydrogeologic Conceptual Model

Fundamental to a successful ASR program is having favorable hydrogeological conditions underlying the wellfield. The conceptual understanding of the Denver Basin aquifers has recently undergone modification as new and unpublished data have been evaluated. This section will describe the results from two case studies that illustrate this and have contributed to a better understanding of basin hydrogeology and how it might integrate with a potential ASR system.

4.1.1 General Denver Basin Geological and Hydrogeological Conceptual Models

The aquifers of interest from an ASR perspective in the Denver Basin are comprised of sediments of late Cretaceous to early Tertiary age that resulted from uplift and erosion of the Rocky Mountains. The resulting downwarping of the sediments east of the Rocky Mountains allowed for a north-northeast trending basin to form. These sediments, formed as alluvial fans during deposition, were subsequently deeply buried and altered into well-cemented rock units. Refer to Section 2.2, Hydrogeology, for a complete description of these units and their characteristics.

The hydrogeologic conceptual models of the Denver Basin aquifers are based on existing reports and provide a basis for evaluating ASR opportunities. While the scope and the scale of the published reports provide an excellent overview, for the purposes of the South Metro study area (boundaries provided in **Figure 3-2**), the data contained therein lacks the detail needed to resolve the merits of specific locations for ASR facilities on a wellfield scale. A more robust approach is therefore required that considers unpublished hydrogeologic data from the South Metro area in specific areas of user interest where there is potential for water resource development. Compilation, integration, and interpretation of lithological, geophysical logging, and aquifer test data from these areas allows the development of wellfield-scale geologic cross sections and maps, with better definition of geologic architecture using spatial statistics (Sale et al. 2017). This approach provides for an advanced basis to screen ASR potential by infilling data gaps and providing greater resolution at a user wellfield scale.

Under an agreement with CDM Smith and the SMWSA, CSU (Sale et al. 2017) and Hemenway Groundwater Engineering developed a report on determining the validity of applying the approach described above. The resulting report compiled and analyzed unpublished data, synthesized it into maps and cross sections, and applied a geostatistical model to a SMWSA member Denver Basin wellfield to demonstrate its validity in identifying and mapping intervals favorable for ASR. This report is provided as **Appendix C**; refer to the appendix for the details of this approach.

4.1.2 Wellfield-Scale Hydrogeological Model Demonstration of Approach

In the Sale et al. (2017) report, the authors compiled several case studies that demonstrate the value of integrating lithologic, aquifer testing, and geophysical logging data (Cannan 2016) into the development of models to better characterize hydrogeology on a wellfield scale and identify geologic units with favorable storage characteristics. The following subsections are extracted from this report and advance the utility of this approach.

4.1.2.1 Centennial Water and Sanitation District Case Study

Cannan, in her 2016 master's degree thesis that Sale et al. (2017) cited, had several primary objectives that are relevant technically and geographically with the goals of the SMWSA study and demonstrate the value of an integrated data analysis approach. In previous ASR potential evaluations of the Denver Basin bedrock aquifers, it was often the case that the role of heterogeneity was not considered fully. The prevailing regional interpretation was that geologic layers were deposited uniformly across the basin. Cannan sought to more fully understand the influence that the combination of transmissive and nontransmissive interbeds resulting from discontinuous layers could have on ASR performance. She identified that cross sections constructed used to evaluate hydrogeology are effectively two-dimensional (2D) representations of the subsurface aquifer data, and therefore provide a spatially limited, simplistic portrayal of the transmissive zones within the basin. To evaluate if an application of a three-dimensional (3D) aquifer analog could derive further insight into wellfield and regional subsurface heterogeneity and ASR potential, multiple point geostatistical stochastic model simulations were performed.

CWSD's Highlands Ranch, Colorado wellfield was used as the basis for evaluation as there is a well- developed set of geologic and hydrogeologic data. Groundwater flow simulations for these aquifer models were subsequently performed to evaluate ASR cycles of recharge, storage, and recovery and to assess heterogeneity's influence on the performance of aquifer storage and recovery operations. Refer to **Appendix C** for a detailed description of the analytical methodology.

A key result from the 3D realizations in the subsurface of the Highlands Ranch wellfield vicinity is better definition of continuity and definition of aquifer storage zone limits. The transmissive zones in the wellfield form a continuum through geologic formations that were not shown in the more simplistic 2D portrayals of the hydrogeology.

4.1.2.2 Castle Rock Case Study

As reported in the Sale et al. report (2017), Castle Rock, Colorado applied a similar analytical approach using 2D geologic cross sections to assess hydrogeologic potential in the area (see **Appendix C**). The cross sections allowed for evaluating the heterogeneity and continuity of geologic material in the Denver Basin near Castle Rock. Using this approach allowed for revisiting previous hydrogeological interpretations and assessing groundwater resource development and storage potential in subsurface areas that are near to demand.

For example, the evaluation of cross section D-D' (**Figure 4-1**) revealed a previously unidentified buried alluvial fan that is in direct contact with crystalline rock. These features have significant economic benefits, as it identified the opportunity of upland recharge from the Front Range watersheds to the goundwater system. Historically, development of groundwater resources in this area of the Denver Basin was hampered by the economic limitations imposed by having large distances between where the water sources and water demands are located in the basin. Similar reassessments were done in other parts of the basin near Castle Rock that concluded a reasonable potential for groundwater resources development and ASR in this area. The morphology of the geologic units had large fractions of coarse sand bounded by lower permeability shale and siltstone units, which is a hydrogeologic configuration with good ASR development potential.

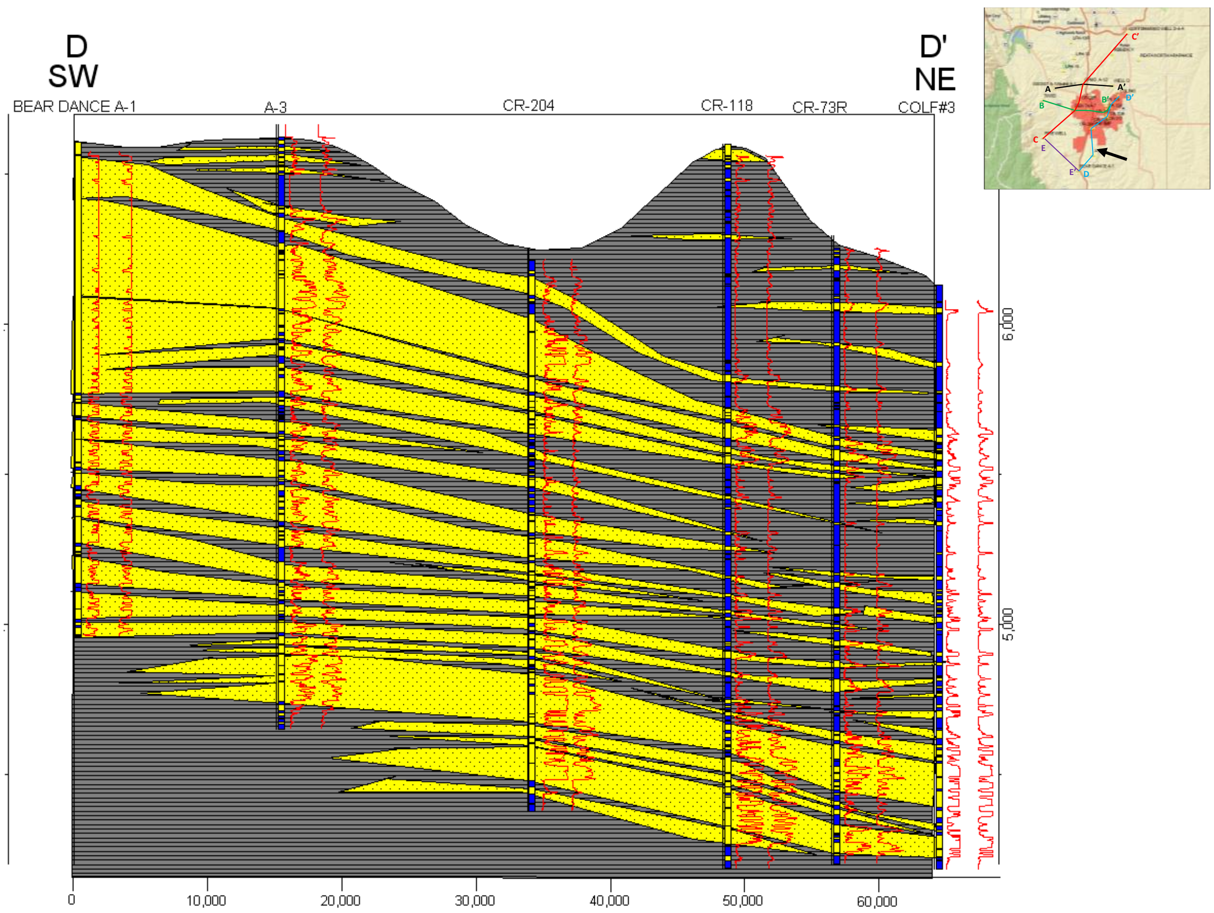


Figure 4-1 Cross Section D-D' SW to SE through Castle Rock, Colorado (Source: Sale et al. 2017)

4.2 Water Level Prediction Tool

In the context of ASR site screening, water level prediction tools are beneficial for simulating recharge mounding and localized aquifer-level responses to recharge and recovery. Fundamental to applying predictive tools is to have reasonable initial estimates of aquifer parameters (e.g., transmissivity, storage coefficients, and water levels) that match historical data and achieve the desired degree of correspondence between the model simulations and observations of the groundwater flow system. Lewis et al. (2016) developed an approach that utilized derivative analysis of water-level time series to estimate aquifer parameters. Using the analytical Theis wellfield superposition model to estimate transmissivity and storage coefficients, these estimates were compared to existing wellfield test data to demonstrate the utility of this approach. Sale et al. (2017) further built upon the work of Lewis et al. by implementing Matlab™ and applying it to individual storage and recovery wells operational data. The following section, extracted from the Sale et al. work done under contract for this project with SMWSA and CDM Smith, briefly describe the methodology used and the study results. Overall, the results demonstrate the utility of using the methods of Lewis et al. and the refinements of Sale et al. to estimate aquifer response at and near individual wells during ASR operations. Refer to **Appendix C** for a detailed description of the data used and methodology.

4.2.1 ASR Wellfield Methodology and Model

Historical (observed) groundwater head data provided by CWSD at each of the district's Arapahoe aquifer wells were evaluated using an analytical model based on the Theis superposition approach. The model accounts for well interference effects and the influence of recharge and recovery on local water levels. It also provides an option to incorporate two well loss coefficients at each well to account for different recharge and recovery rates. It is common in ASR systems to see a significant head change during recharge and recovery operations and the latest version of the model accounts for this.

Model calibration was achieved by adjusting transmissivity, storativity, and well loss coefficients until the simulated groundwater heads closely matched observed groundwater heads during recharge and recovery. This not only yields reasonable estimates of aquifer hydraulic properties and well loss data but also enhances the credibility and reliability of the model for simulation of potential conditions with the SMWSA ASR wellfields. Potential uses of the model include evaluation of:

- Recharge and recovery flow rates
- Screening locations for ASR wells in wellfields
- Resolution of storage and recovery schedules
- Resolution of pumping heads in support of estimating ASR operation costs

4.2.2 Results

Using the information described, the results below were noted for the CWSD data.

Calibration: For periods of nonpumping, a good fit between simulated and observed levels was achieved with the differential being generally less than 5 meters. During periods of pumping (recovery), larger discrepancies of 5 to 25 meters (50 to 250 feet) on average were apparent. This is believed to result from the model's flow rate averaging scheme (detailed daily variations in discharge are not explicitly modeled) and from the simplified approach used to calculate well loss effects. **Figure 4-2** presents an example of hydrographs used to evaluate the calibration between observed and simulated water levels. The hydrographs for the other wells and tabular calibration data are provided in **Appendix C**. Simulated heads are depicted by the solid red line and historical (observed) head data by black data points.

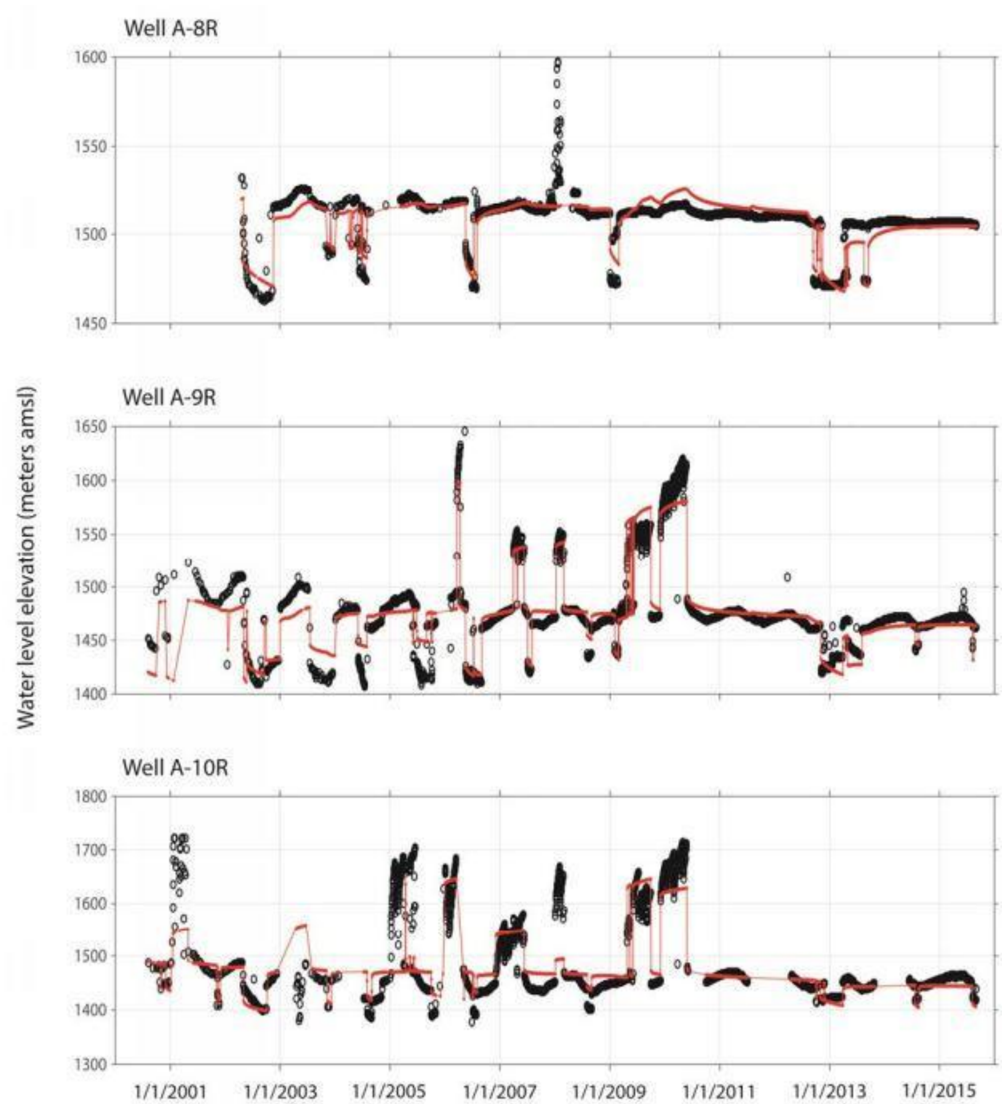


Figure 4-2 Example of Well Hydrographs Showing Observed (black) and Modeled (red) Water Levels, Highlands Ranch Wells A-8R, A-9R, and A-10R (Source: Sale et al. 2017)

Background water level trend analysis of the hydrographs also provided useful information on the status of background water levels in the Denver Basin. Water levels during periods of storage, when pumping or injection are not taking place, can be evaluated through time to determine if there are any discernible trends. These trends can be useful to assess background water levels and their level of decline or recovery. **Table 4-1** provides a summary of the water level slopes noted in the hydrographs provided in **Appendix C**. Eight of the 12 wells evaluated had a negative drift-line slope across the water level time series data set indicating a decline in hydraulic heads over the period evaluated. The average slope was -0.32 meters per year, indicating a background water level decline in the wellfield of approximately of 1 foot per year. **Figure 4-2** demonstrates an example of this trend in the data from each well. The water level decline noted in the

Highlands Ranch wellfield data is consistent with that reported by Everett (2014) for the Arapahoe aquifer in Douglas County, Colorado.

Table 4-1 Best-Fit Recoverable Water Levels Obtained Using the Wellfield Model – Highlands Ranch Wellfield

Well	h_o		Slope	
	(meters amsl)	(feet amsl)	(meters/yr)	(feet/yr)
A1	1,472.13	4,829.82	0.02	0.07
A2	1,492.50	4,896.65	-1.06	-3.48
A3	1,537.69	5,044.91	4.52	14.83
A5R	1,482.04	4,862.34	0.06	0.20
A6R	1,511.47	4,958.89	-0.41	-1.35
A7R	1,455.11	4,773.98	2.39	7.84
A8	1,528.01	5,013.16	-1.35	-4.43
A9R	1,489.91	4,888.16	-1.47	-4.82
A10R	1,489.79	4,887.76	-2.83	-9.28
A11R	1,517.09	4,977.33	-0.79	-2.59
A12R	1,525.20	5,003.94	-0.91	-2.99
A13R	1,509.02	4,950.85	-1.98	-6.50
Average	**1,500.83**	**4,923.98**	**-0.32**	**-1.04**

H_o = best fit recoverable water levels; amsl = above mean sea level; meters/yr = meters per year; feet/yr = feet per year

Spatial distribution of drawdown: One of the important results of this modeling is defining the radius of influence (ROI) from ASR activities in the Arapahoe aquifer at the wellfield scale and its potential to influence the well spacing distances. To evaluate ROI, spatially distributed drawdowns using the Theis superposition model during recharge and recovery were graphically plotted using Matlab (**Figure 4-3**). The conclusions from these results indicate that hydraulic head changes tended to be localized around individual wells, with the exception of during periods of extended recovery where well interference effects were noted. For wellfield design exclusively for ASR purposes, the potential exists for closer well spacing than that typically used for wellfields that are solely used for water supply. This is primarily due to a relatively low aquifer transmissivity in combination with intermittent ASR well operation.

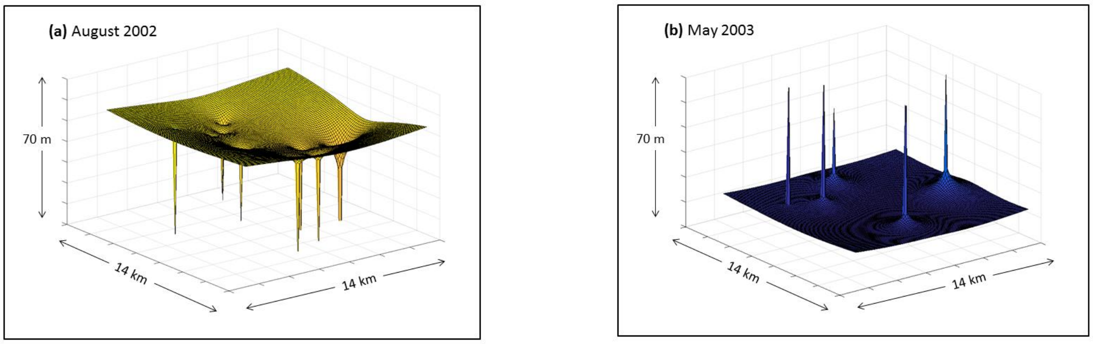


Figure 4-3 Spatially Distributed Drawdowns During Recharge and Recovery – Graphic Representation from Theis Wellfield Superposition Analytical Model (Sale et al. 2017)

Collectively, the results from the analytical model applied show reasonable agreement with the observed data. The results support the validity of using this approach in developing aquifer parameter estimates to resolve the impacts of ASR activities on a wellfield scale and allow for initial site screening and system cost estimates.

4.3 Economic/Costing Tool

This section summarizes the work done in developing a tool to allow SMWSA users to estimate screening level costs for evaluating ASR alternatives in the Denver Basin. Cost estimating is one of the most important steps in the site screening process. A cost estimate allows for economic comparison of competing approaches selected to address a specific design objective, for comparing different configurations of design alternatives, and establishing the baseline of the project cost at different stages of development (Hendrickson 1998). However, due to relatively low levels of project definition at the concept screening level, the accuracy of the estimate can range from -50 percent to +100 percent of the bid/tender estimate (American Association of Cost Engineering 2005).

The costs to the owner of a constructed facility include both the initial capital cost and the subsequent operation and maintenance costs. Each of these two major cost categories consists of a number of component costs. In the context of ASR facility site screening, capital costs to be considered include:

- Drilling and equipping new wells
- Retrofitting existing wells
- Well testing
- Pumps
- Wellhead piping, valving, and other appurtenances

- Water transmission piping to convey source water and recovered water
- Water treatment or filtering should it be necessary

Over the project life cycle of ASR facilities, the following operation and maintenance expenses must be included in the cost estimate:

- Staffing
- Facility maintenance
- Monitoring
- Consumable materials
- Equipment replacement and rehabilitation
- Financing costs
- Power consumption

The magnitude of each of these cost components depends on the nature, size, and location of the project as well as the organizational management, labor, and physical assets the user considering ASR has. For example, whether a user needs to acquire land to develop ASR facilities in an urban area can have a significant impact on the project capital cost.

The development of the cost estimating tool for this study was done through the agreement with CSU, SMWSA, and CDM Smith, and builds on the previous CSU work. Under the agreement, CSU applied the cost tool to the CWSD Highlands Ranch Denver and Arapahoe ASR wellfields. As with previous evaluation work done using Highlands Ranch's operating history, data were available to compare model estimates with historical conditions and costs. The following sections discuss the cost estimate model basis, structure, input requirements, and expected outputs. These sections are extracted from the Sale et al. 2017 work. A detailed description of the model can be found in **Appendix C**. For this report, the tool was modified to simplify some of the user input parameters and these modifications are likewise described in the following sections.

4.3.1 CSU Costing Tool and Modifications for SMWSA Users

The costing tool was developed using Microsoft Excel. The spreadsheet tool estimates capital, operation and maintenance, and life cycle costs for ASR projects associated with conditions in the Denver Basin. The spreadsheet consists of nine worksheets which are configured as follows: one requires user inputs on the definition of the proposed ASR system, three require user conceptual design inputs, and the remaining five display outputs (plots and calculations).

4.3.1.1 User Definition (Input Sheets)

An example of the user definition inputs is presented in **Figure 4-4**. For this worksheet, the user is required to define the unit costs, wellfield operating parameters, and the duration of the project. These are coupled with the values entered in the user design tabs to calculate the present value cost. The user-defined inputs provided in the tool were examples of costs from CWSD. The user is free to modify the unit cost estimates as required to better represent their circumstances.

The input parameters, with a brief description after each, include:

- Interest rate: This input represents a specified rate of return used to discount future cash flows or a sum of money based on the date of valuation. In the context of the cost tool, it is the rate that is used to convert the life cycle cost to a present value cost. Since the alternatives being considered for ASR and other water management strategies do not all occur within the same time frames, using a present value approach allows for comparisons between projects with different start dates and durations.

- New ASR well: The capital cost of constructing a new well. Included in this estimate are associated well costs of pump, motor, wellhead piping, and appurtenances.

- ASR well replacement cost: The capital cost of construction for a new well, should that option be selected.

- ASR well life expectancy: The expected useful life of either a new or replacement ASR well.

- ASR well rehabilitation cost: The cost to rehabilitate, as part of required ongoing maintenance.

Inputs		
Interest rate	3	%
ASR well replacement cost	1,000,000	USD per well
ASR well life expectancy	30	years
ASR well rehabilitation cost	50,000	USD per well
ASR well rehabilitation frequency	10	years
New well	1,500,000	USD per well
ASR Retrofit w Baski Valve	100,000	USD per well
Non-Construction & Contingency	20	% to the total cost
Power cost	0.08	USD/kWh
Injection treatment cost	0.005	USD/1000 gallon
Labor	1	Number of people operating the field
Cost of each labor annually	100000	USD per labor
O&M	1	% from the capital cost
Injection TDH from source to ASR wells	500	ft

Pipes		
Pipes cost	$/ft	** total cost (USD/ft)
<6"	50	69.5
6"	55	78.95
8"	65	85.25
10"	71	91.55
12"	79	99.95
16"	112	134.4
18"	142	166.1
20"	158	182.9
24"	191	217.55

Easement for pipes	17	USD/ft

User Input	
Calculation	

Non-Construction and Contingency Costs	%
Construction contingency	10
Mobilization, bonds, and construction	2
Field exploration and design	2
Permitting	2
Legal and administrative	2
Construction management and QA	2

Wellfield Operating Parameters	
Projected operations period (years):	15
Well pump efficiency	85%

	Well Location Name					
	A-2	A-3	A-5R	A-6R	A-7R	A-8
Flow Rates						
Recovery (gpm)	300	80	300	280	250	300
Injection (gpm)	300	80	300	280	250	300
Recovery TDH Baseline (ft)	1000	1500	1500	1000	1000	1000

Operating Schedule (days) — Anticipated Schedule for Operating Days/Well/Year to Recover Design Demand per Well

Year 0 Recovery						
Injection	0.0	0.0	180.0	0.0	0.0	0.0
Year 1 Recovery	**0.0**	**0.0**	**120.0**	**0.0**	**0.0**	**0.0**
Injection	180.0	180.0	180.0	180.0	180.0	180.0
Year 2 Recovery	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**
Injection	180.0	180.0	180.0	180.0	180.0	180.0
Year 3 Recovery	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**
Injection	180.0	180.0	180.0	180.0	180.0	180.0
Year 4 Recovery	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**
Injection	180.0	180.0	180.0	180.0	180.0	180.0
Year 5 Recovery	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**
Injection	180.0	180.0	180.0	180.0	180.0	180.0
Year 6 Recovery	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**
Injection	180.0	180.0	180.0	180.0	180.0	180.0
Year 7 Recovery	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**
Injection	180.0	180.0	180.0	180.0	180.0	180.0
Year 8 Recovery	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**
Injection	180.0	180.0	180.0	180.0	180.0	180.0
Year 9 Recovery	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**
Injection	180.0	180.0	180.0	180.0	180.0	180.0
Year 10 Recovery	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**
Injection	180.0	180.0	180.0	180.0	180.0	180.0
Year 11 Recovery	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**
Injection	180.0	180.0	180.0	180.0	180.0	180.0
Year 12 Recovery	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**
Injection	180.0	180.0	180.0	180.0	180.0	180.0
Year 13 Recovery	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**
Injection	180.0	180.0	180.0	180.0	180.0	180.0
Year 14 Recovery	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**
Injection	180.0	180.0	180.0	180.0	180.0	180.0
Year 15 Recovery	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**	**120.0**
Injection	180.0	180.0	180.0	180.0	180.0	180.0

Guidance for Well Operating Model Inputs

Key assumptions: Recovery Well Operating Schedule, recovery well flow rate, pump degradation factor, pump efficiency, and pumping water leve

Recovery well flow rate - estimate from other wells in the area or Colorado Division of Water Resources Well Database

Pumping water level - estimate from other wells in the area or Colorado Division of Water Resources Well Database

Pump efficiency - typical pump efficiencies in good operating condition range from 75% to 85%

To estimate the Recovery Schedule Per Wel

Estimate annual demand that will be served by ASR well facilities

Estimate recovery flow rate per well (gpm) from historic data or Colorado DWR database

Based on each well's recovery capacity, distribute Year 1 annual demand throughout the wellfiel

Determine the number of days of pumping required to meet annual demand target per wel

Figure 4-4 Example of User-Defined Unit Cost Input Sheet

Page intentionally left blank.

- ASR well rehabilitation frequency: The frequency and duration between well rehabilitation events.
- ASR retrofit w/Baski valve: The capital cost for retrofitting an existing well by furnishing and installing a downhole flow control valve and other appurtenances. Baski, Inc. is a manufacturer of equipment and products related to fluid control and management during ASR well operations.
- Non-construction and contingency costs: This input is derived as a percentage of the total cost (capital and O&M) and can be varied based on the user's experience, expected project difficulty, or industry standards on similar projects. This category contains allowances for unexpected conditions, schedule adjustments, mobilizations, bonds, permitting, engineering, and legal and administrative.
- Power cost: The unit cost per kilowatt hour (kWh) to produce and convey source or recovered water.
- Injection treatment cost: The operating cost for the treatment of recharged water on a per 1,000 gallons basis.
- Labor and cost of each unit of labor: The number of full-time equivalent personnel assigned to the project and the cost of that labor including salary and benefits.
- Operation and maintenance (O&M): Operation and maintenance costs not accounted for in labor and power categories as a percentage of the capital cost.
- Injection total dynamic head (TDH): This value represents a combination of elevational differences between aquifer, wellhead, and friction losses resulting from water transmission in pipes and valves from the source to the ASR well. TDH is multiplied by the unit power cost to calculate total cost for the injection of water. This calculation is one component of operating cost.
- Pipe: The capital cost for furnishing and installing, on a per linear foot basis, pipe having diameters from less than 6 inches to 16 inches.
- Easement for pipes: The cost to secure easements for the installation of piping on a per linear foot basis.

The Wellfield Operating Parameters Table requires the input of several elements. These include:

- Projected operations period (years): The number of years of anticipated operations.
- Well pump efficiency (%): This is due to energy loss and leakage and typically ranges between 75 to 85 percent.
- Well locations: The user inputs the name or designation of each well.

- Recovery (gpm): This is the recovery or extraction pumping rate that can be derived from historical wellfield data or can be estimated by querying the Colorado Division of Water Resources' (DWR's) database to get an estimate of flow rate and pumping water level.

- Injection (gpm): This is the rate at which water is injected into the well for storage purposes. As a rule of thumb, the injection rate is typically between 70 and 100 percent of the recovery rate for a well. The user should set this rate based on their local or regional experiences.

- Recovery TDH (feet): To simplify the TDH analysis, the tool requires the user define as one value a combination of elevation head, friction head losses due to piping, valves, and appurtenances, and pressure or elevation head to enter the distribution, storage, or treatment system. The vertical head required for lifting groundwater to the surface elevation for recovery in each well can be estimated in one of two ways: by either using historical water level data from the facility or regionally from the state database, or by using the Theissian wellfield superposition model method developed by CSU described in **Appendix C**. That tool has functionality through a Matlab code linked to the spreadsheet that allows it to calculate TDH. Refer to **Appendix C** for further description of how the code is utilized to calculate TDH. Friction head loss for various wellhead piping and components can be calculated based on reference values found online or texts such as Crane Co. Technical Paper No. 410 "Flow of Fluids Through Valves, Fittings, and Pipe."

- Recovery Operating Schedule (days): The user is required to estimate the number of days each year that the well will operate in recovery mode. The estimated days of recovery operations for each year and TDH per well are used to calculate power costs over the duration of the project. There are various factors that contribute to the length of time for recovery operations. These include the amount of water needed, the amount of water available in storage, regulatory restrictions, and available hydraulic aquifer head above the pump in the well. If there is no historical or planning data available, as a first approximation to establish the recovery schedule, the user can determine how much of the water plant's annual demand will be serviced by the ASR wells. From this, the user can allocate the demand to individual ASR wells based on each's flow rate capacity and available hydraulic head. The number of operating days per year per well can be estimated by dividing the individual well demand by the well's flow rate.

- Injection Operating Schedule (days): The user is required to estimate the scheduled number of days for injection each year. The resulting number of operating days per year are then used by the Recovery and Recharge worksheets to calculate annual operating costs. The primary control on this factor is the volume of water available for injection.

4.3.1.2 User Conceptual Design (Pipes, Well Retrofit, and Well Worksheets)

The user's conceptual project design is required to be entered into three tabs. These include criteria for wellfield layout (wells or well retrofits) and schedules for well modification or construction. These are listed below, along with details on the characteristics of the inputs:

- Wells Retrofit worksheet: If the user plans to retrofit existing wells for ASR purposes, the number of wells and their schedule, by year, for retrofitting need to be determined.

- New Wells worksheet: If the user should determine that constructing new ASR wells is the optimal choice, then the number of wells and their scheduled dates of construction need to be established.

- Pipes worksheet: The user should identify the conceptual pipe routing lengths needed to transmit water from the source to the well and from the well to the distribution network. In addition, the user should determine the hydraulic capacity required based on timing and magnitude of the demand flow and size the pipe diameters, accordingly.

4.3.1.3 Output Results (Recharge/Storage, Recovery, Plots, Calculations, and Present Value Worksheets)

After completing the inputs to the Excel workbook, the program calculates the present value and life cycle costs for the selected duration of the project alternative. The sheets that present these outputs are:

- Recharge/Storage (Qin) worksheet: This sheet calculates the annual volume of water stored in the aquifer (recharge rate multiplied by operating days). The volume is combined with TDH from the Inputs worksheet to calculate the required power cost needed to provide recharge water from a source and treat the water prior to injection for the Calculations worksheet.

- Recovery (Qout) worksheet: This sheet calculates power consumption in kWh. Operating days, TDH, and pump efficiency are brought in from the Inputs worksheet to calculate power consumption. The recovery operating cost is determined by multiplying kWh times the dollar per kWh from the Inputs worksheet.

- Calculations: This sheet brings the user-defined unit costs and design concepts together with the proposed schedule and calculates the different component costs on an annual basis. The annual costs are summed over the project duration, and then further processed on the Present Value worksheet.

- Present Value: This sheet applies the discount rate defined in the Inputs sheet and discounts the annual project component costs over the anticipated life cycle of the project, summing the discounted cash flows.

- Plots: The program presents two plots. The first is a pie chart showing the total and present value project cost and the percentage of each project component relative to the total. The second is a histogram chart comparing life cycle cost and present value cost to a user selected base year. These plots are useful for identifying component cost distribution and schedule impacts, respectively, to the overall project cost. **Figures 4-5** and **4-6** provide examples of these plots.

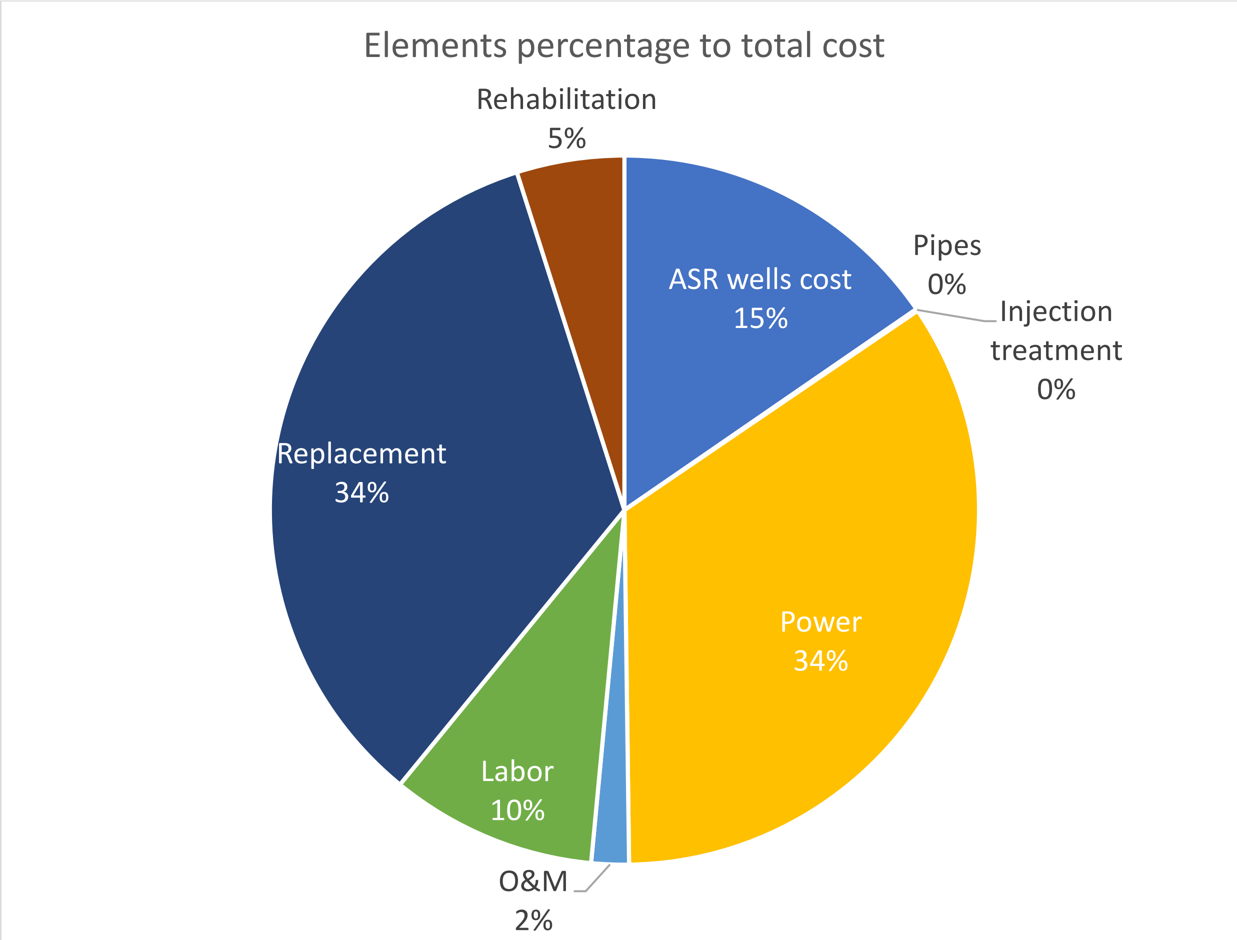


Figure 4-5 Example Output Pie Chart from Costing Tool Showing Percentage of Component Costs

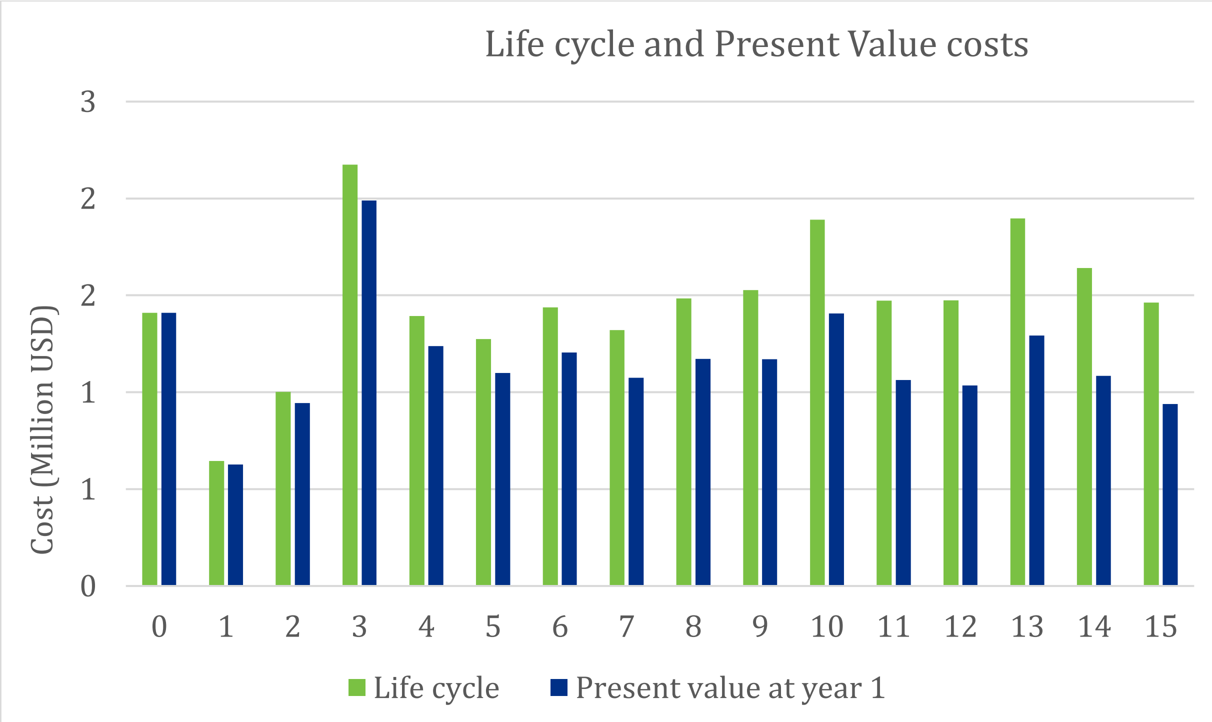


Figure 4-6 Example Histogram Chart from Costing Tool Comparing Life Cycle Costs and Present Value Costs

As part of the study undertaken by CSU as part of the agreement with SMWSA, cost and operating data from CWSD's Highlands Ranch wellfield were input to determine how representative the tool's outputs are relative to historical costs. A review by CWSD indicated that the costs estimated by the tool appeared to be reasonably accurate relative to historical costs.

The estimated cost components are derived from several sources. Specialist reviews based on experience were utilized to estimate drilling, equipping, and rehabilitation costs for the ASR wells and typical operating schedules for an ASR well facility. Units cost estimates for standard water system components are based on checks against a proprietary construction cost estimation database that is trade specific. These estimates were reviewed and confirmed by engineering experience, and are provided for reference. The SMWSA users are free to modify the unit costs and financial factors as necessary to better fit the operator's circumstances.

4.3.2 Other Approaches

The engineering costing model approach described in this report is a standard design type that is commonly done during the screening phase of a project. This method, known as unit cost estimating, uses the summation of individual unit cost estimates to arrive at a total cost estimate for the project alternative under consideration. It is a type of parametric estimating approach that is reliant on the collection of previous project data to develop cost estimating relationships (U.S. Department of Energy [DOE] 2011). The unit cost method is straightforward in principle, useful for preparing early conceptual estimates, but can required a significant amount of work in its application (Hendrickson 1998). It requires the breakdown of the total work process into its component parameters or tasks. Once these have been defined and the quantities assessed, a unit cost can be assigned to each. The product of each quantity and associated unit cost are summed to create a cost estimate.

There are other commonly used techniques for estimating costs at various levels of project development. These other approaches applicable to a project's screening stage are listed below with a brief description of each.

- Analytical Estimating: Similar to the unit cost approach, the estimator identifies the project deliverables and divides them into a series of work packages made up of the project tasks. The estimator then estimates the cost of completing each package and sums these to calculate the project estimate total cost. This method can be similarly time consuming.

- Analogous Estimating: This approach uses known cost and schedule data from projects that are similar in scope to the proposed one under consideration. It is also known as empirical cost estimating. Adjustments are made, as necessary, to account for the relative complexities of performance, design, and operational characteristics (DOE 2011). In cases where the proposed work is of a significantly different scale (e.g., flow or well depth) relative to the historical project data, the ratio or factor method can be applied to account for the deviations from the similar work.

- Expert Opinion: This approach uses the judgement of experienced specialists in a specific area to fill gaps in a project's work process breakdown structure so that it may be better defined. This approach utilizes individual or consensus expert opinions and can be used for either portions of or for entire estimates of activities for which there is no other sound basis (DOE 2011). Relevant to this study, the estimating of ASR well construction costs by an engineer or scientist with specialized experience in this area is an example of where this approach has value. This approach is typically applied early at the feasibility assessment stage of the project.

There are many different cost-estimation approaches available to apply at various phases of project development. Successful cost estimates display accuracy, credibility, and reliability that result from project understanding and using available data effectively. The level of accuracy for the estimate directly varies based on the how well defined the design is and the level of information available. The tool, developed as part of this study by CSU, provides satisfactory results for the purposes of site screening and the input parameters are intuitive for the user.

Section 5

ASR Local and Regional Planning

This section summarizes an approach to local and regional ASR planning. It builds on the guidance and roadmap provided in Section 2, ASR Considerations and Planning. Key evaluation components outlined in Section 2 include:

- Recharge objectives
- Hydrogeology
- Geochemical compatibility
- Existing and proposed infrastructure
- Permitting

For this planning exercise, a preliminary evaluation of the local hydrogeology has been completed using published data and SMWSA member borehole information that was previously provided during earlier studies and a follow up questionnaire as part of this study. A summary of the hydrogeological evaluation is presented in the following section, Section 5.1, Hydrogeology.

The primary recharge objective for all SMWSA members is to store surplus WISE water, as described in Section 5.3, SMWSA WISE Program, so that additional water may be available to offset the use of potentially nonrenewable groundwater. However, it has quickly become apparent that there may be additional recharge benefits beyond storing surface WISE water in different aquifers.

Aquifer water level declines are not uniform across the region, and there are aquifers with locations where water levels are greater than 100 feet below the top of well screens with pumping water levels that are even lower. These are not favorable aquifer conditions for multiple reasons as outlined in Section 2.2.2, Available Recharge Head and Drawdown. Therefore, a key recommended secondary recharge objective is the restoration of aquifer levels. The technical difficulty is the cone of influence (i.e., the radius at which significant rises in aquifer water levels occur) around each well used for recharge is relatively limited. Therefore, to be more effective and provide greater environmental benefit, more closely spaced wells in a single aquifer creating recharge mounds that will locally replenish depleted aquifer heads and allow improved recovery characteristics is likely the preferred approach.

To achieve this secondary recharge goal there are merits in completing regional planning efforts to identify focus areas (or "hot spots") where aquifer recharge is best concentrated, stored, and subsequently recovered and redistributed amongst member utilities, rather than distributing recharge water over a larger area and in multiple aquifers (i.e., local planning, where each member utility pursues their individual recharge goals).

Conceptual outlines for regional and local planning approaches are provided in 5.3, Conceptual ASR Development, with preliminary planning-level costs provided in 5.4, Economics/Costing. The pros and cons of the different planning approaches are briefly outlined in Section 5.5, Alternatives Analysis, which also considers the existing and proposed water utility infrastructure.

Several hot spot locations have tentatively been identified; however, further planning efforts are still required to confirm them primarily because aquifer conditions are more complex than anticipated and data sets provided during this evaluation are incomplete. Additionally, the hydraulic capacities of key distribution mains, including the ability to direct recharge water to individual retrofitted or new ASR wells, and the viability of individual connection points to the WISE water project still need to be fully evaluated. With these considerations, recommended next steps to more thoroughly evaluate potential planning approaches are made and summarized in Section 7, Recommendations.

5.1 Hydrogeology

A description of the regional hydrogeologic setting has been outlined in Section 2.2.1, Target Recharge Zones. This provides an overview of the four primary aquifer units, from oldest to youngest: Laramie–Fox Hills, Arapahoe, Denver, and Dawson.

To identify preferred hydrogeologic locations for ASR in each aquifer, at both local and regional scales, basic aquifer conditions need to be summarized. Broad hydrogeologic criteria to consider include mapping the elevation of the top of each aquifer unit to determine the depths for well completion and provide a reference for available drawups and drawdowns for recharge and recovery; providing aquifer thickness, so that the likely storage potential may be quantified and the total depths for wells determined; providing hydraulic parameters, so that likely recharge and recovery rates may be identified; and determining aquifer condition (water level relative to the top of each aquifer), so that aquifers with depleted groundwater levels may be identified and assessed.

Mapping and summarizing these criteria for each aquifer is not a straightforward proposition. Certainly, at a regional scale it is easier, but as identified in Section 4.1, Hydrogeologic Conceptual Model, the aquifer units are much more complex, with highly variable buried alluvial fans of alternating sands and shales that make identification of aquifer units at a local scale more difficult and explains why there is often so much variability in aquifer hydraulic parameters across relatively short distances. For this reason, once focus areas or hot spots have been identified, further evaluation is encouraged, including the use of the evaluation tools identified in Section 4, ASR Tools/Models, so that any proposed ASR project is adequately scoped.

There is likely sufficient continuity of the more permeable sands to assume that ASR will work at some level across the basin, but the basic key questions to still answer include are there more preferred locations in terms of viability (the ease with which water may be recharged and recovered) and are there locations that would benefit more from recharge to replenish depleted groundwater levels. To answer these initial broad questions, a simplistic approach has been taken and two broad evaluation criteria have been used: aquifer permeability and aquifer condition. The results from this initial planning-level evaluation is summarized below.

5.1.1 Aquifer Permeability

By understanding aquifer permeability, or more specifically, the change in water levels due to pumping or recharge, an assessment can be completed to determine more favorable aquifers and locations for ASR. Higher permeabilities means greater volumes potentially may be recharged and recovered from individual ASR wells. It also potentially means that for aquifers where groundwater levels are depleted to levels close to the top of well screens, that stored water is more likely to be recovered without drawing water levels below top of screens.

Analysis of pumping test data for aquifer permeability, measured as “K” in units of feet per day (ft/day) and transmissivity, measured in square feet per day (ft^2/day), have previously been performed and was summarized in CDM Smith (2010) as part of a technical memorandum that was originally prepared to support SMWSA with an evaluation of potential ASR pilot projects. As part of this assessment, a summary figure was produced to show the range of aquifer permeabilities for the four main aquifers. The figure extracted below (**Figure 5-1**) shows that the Arapahoe aquifer contains sands with the highest permeabilities, and therefore from a permeability perspective, ranks highest as a target aquifer.

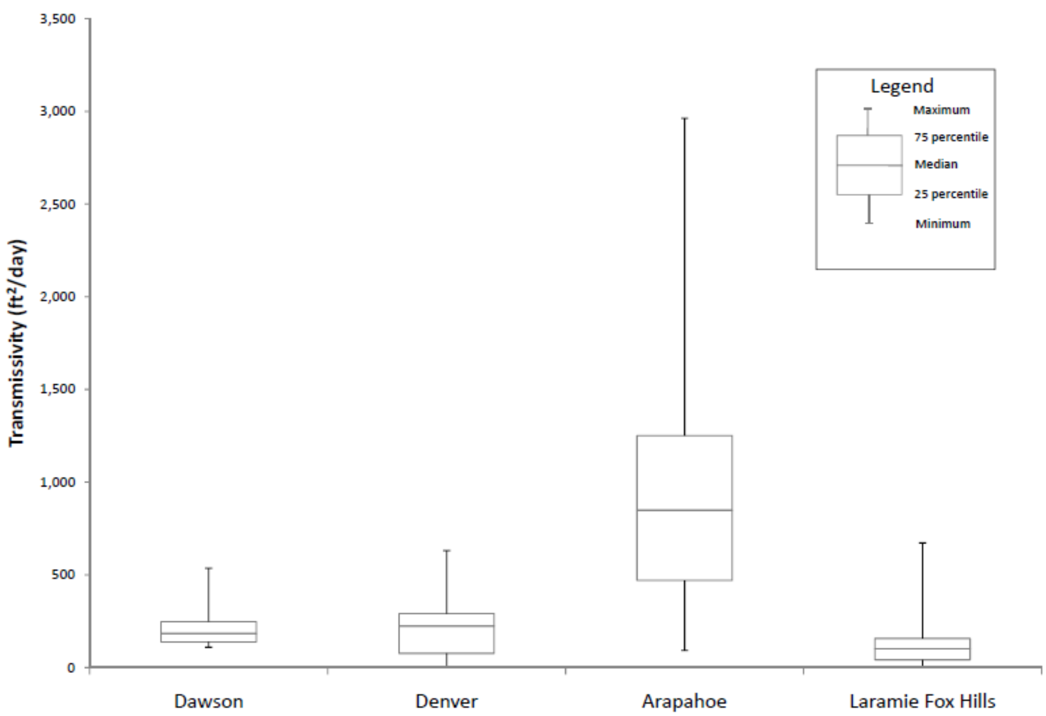


Figure 5-1 Comparison of Aquifer Transmissivities

Since the CDM Smith (2010) report was prepared, efforts have been ongoing to characterize aquifer permeabilities, and CSU as part of their groundwater modelling efforts with others, as reported in Section 4.2, Water Level Prediction Tool, have assessed more than 70 extended well tests. This data has been used to further calibrate their groundwater modelling tool. The model developed is a very useful tool to predict changes in aquifer level due to pumping and recharge and can be used to help with both regional and local level planning efforts.

5.1.2 Specific Capacity

An initial more simplistic approach in lieu of groundwater modelling is to look at specific capacity (SC) data. SC, measured in units of gallons per minute per foot (gpm/ft), is a measure of both well performance and aquifer permeability. The higher the gpm for every foot of drawdown, the higher the performance of the well, which is also particularly important for Denver Basin wells given the very deep static water levels for many wells and the relatively high costs of pumping due to the energy needed to lift water to the surface. Mapping SC data for the different aquifers can therefore be used to identify more favorable aquifers and locations with higher performing wells. Because SC data includes individual well performance (i.e., well losses associated with the well design and any change in performance over time), it is a particularly useful measure for prioritizing existing wells that may be subsequently retrofitted for use as an ASR well.

SC data has been compiled for all member wells, using either previously provided SC data or analysis of recent time series pumping and water level data. Approximately half the member utilities provided detailed water level and pumping records for their wells for periods to the end of 2017, and several beyond. This provided a very useful snapshot for the aquifer condition and performance. By plotting recent time series water level data with the pumping data, suitable pumping periods were identified and interpreted to provide static water level, pumping water level, and pump rate data needed to calculate a reliable SC value. For short-duration pumping tests (i.e., less than 24 hours), pumping water levels in most wells in the Denver Basin do not reach anywhere close to equilibrium, therefore SC tends to be overestimated. By selecting recent periods with both static and pumping water levels with extended pumping periods, accuracy is improved and is more reflective of the likely change in heads during operation.

The compiled SC data for each aquifer is plotted in **Figures 5-2a through 5-5a** and summarized in Section 5.2, Target Aquifers. The data used to compile these figures is contained in **Appendix D**. Note specific injectivity (SI), also often measured in units of gpm/ft, is a similar measure, only for recharge. It is a measure of the increase in heads for a given recharge rate. Available SI data is limited and therefore has not been summarized. Anecdotal information provided by member utilities suggest that SI is approximately 50 percent of SC (i.e., drawups during recharge are approximately twice that of the drawdowns). Elsewhere, 70 percent of SC is common. Given the depth-to-water levels in most Denver Basin aquifers, which allows wells to be recharged using gravity flow and requires the use of downhole flow control valves to prevent water cascading, SI is generally less important.

5.1.3 Aquifer Condition

Understanding the aquifer condition, or rather the aquifer water level relative to the top of each aquifer unit, is key. It defines the potential for aquifer degradation when water levels drop below the top of an aquifer and identifies locations that would benefit the greatest from aquifer replenishment. To determine the aquifer condition, the most recent available static water level data for each aquifer unit has been compared to the top of well screens for each of the member utility production wells, with the methodology for deriving the data described below.

5.1.3.1 Static Water Levels

Interpolating static or rest water levels requires careful data interpretation because the production wells are impacted by intermittent pumping or interference drawdowns from neighboring wells, and monitor wells are not always representative. Unfortunately, it is not possible to pick a single day or week to compare all water levels because in any given week, many wells are pumping. In addition to long-term water level trends (summarized annually by CDWR and outlined in Section 2.2.2, Available Recharge Head and Drawdown), review of the available time-series water level plots also shows a strong seasonal influence for many wells.

Using the available time-series data, the most recent seasonal high static water levels have been compiled for each aquifer. Generally, this data is for late 2017 and provides the best snapshot of the approximate aquifer condition. The compiled static water level data for each aquifer is plotted in **Figures 5-2b through 5-5b** and summarized in Section 5.1.3, Target Aquifers. The data used to compile these figures is contained in **Appendix D**, which includes the actual date used for each measurement.

5.1.3.2 Top of Aquifer

The top of each aquifer unit has previously been compiled and mapped, and the data is considered reasonably reliable at a regional scale. However, of greater importance is the screened interval for each production well, because once water levels drop below the top of the well screen, air can then enter the production interval regardless of the actual top of the aquifer and the aquifer then begins to transition from a confined to an unconfined state. Therefore, as a surrogate for the top of the aquifer, and a likely better indicator of the aquifer condition, the top of the well screen for every well has been compiled and all data corrected to datum.

The compiled top-of-screen data for each aquifer is plotted in **Figures 5-2c through 5-5c**, with the data used to compile these figures contained in **Appendix D**. The data has been contoured to show the approximate surface and highlight any wells with anomalously high or low well screen elevations.

5.1.3.3 Aquifer Condition

The differences between the top of well screen and the static water levels have been mapped and are provided as **Figures 5-2d through 5-5d** for each aquifer. These figures are revealing because they indicate areas or clusters of wells with water levels that are now significantly below the tops of screen. "Significant" is defined as greater than 100 feet, a somewhat arbitrary depth but chosen because of the accuracy of the data used to produce the maps. Negative values indicate water levels below the top of screen, although care is needed with interpreting this data. The figures do not indicate whether water levels are continuing to decline, are stable, or are recovering (rising) as part of a long-term trend (i.e., they are just a snapshot). Nevertheless, they do indicate the most recent aquifer condition using the highest static water levels recorded during 2017, which is the most favorable condition. Under pumping conditions, the aquifer condition deteriorates further for those wells with static water levels already below screen, although given the relatively low permeabilities for the Denver Basin aquifers, the radial extent around each well is expected to be relatively limited.

5.2 Target Aquifers

The most favorable aquifer, in terms of aquifer permeability, is the Arapahoe aquifer. SCs are generally in the range 1.0 to 9.0 gpm/ft, with large areas of the aquifer having SCs significantly over 2 gpm/ft. The highest SC data mapped are located within the central areas of the SMWSA area, although care is needed interpreting this data because the highest SC values are from historical data from when the wells were drilled, and evaluation of more recent water level and pumping data was not possible because the data was not provided.

It is assumed that because the Arapahoe aquifer is the most prolific, water level declines have occurred due to preferred use of this aquifer with historical withdrawals. As a result, this aquifer has the most alarming water levels relative to the tops of screen. Anecdotal information provided by SMWSA members suggests well performance is not being impacted, but further evaluation is warranted.

A brief synopsis for each aquifer unit is provided below, with a summary provided in **Table 5-1**.

5.2.1 Dawson

The Dawson aquifer is the shallowest aquifer in the Denver Basin, and generally SMWSA members only utilize this aquifer in the southeastern part of the region. Almost all aquifer levels are above tops of screen, meaning it is not the highest priority to recharge this aquifer to replenish depleted aquifer levels, although current static water levels are generally less than 200 feet above well screens. Aquifer permeabilities are generally less than 1.3 gpm/ft, and although not the lowest of permeability for the four major aquifer units in the Denver Basin, these SCs are on the low end for successful ASR development.

5.2.2 Denver

The Denver aquifer is utilized by many SMWSA members, second to the Arapahoe aquifer. Aquifer permeability (as measured by SC) is low; with the exception of wells in the southern part of the region, many wells have SCs less than approximately 0.5 gpm/ft. The Denver aquifer wells in the south appear to be more productive, although this may be reflected, in part, by the fact that historical SC data was available for only one-member utility, therefore the values may be an overestimation.

The most alarming factor is the widespread decline in aquifer levels, with many wells having the highest 2017 static water levels still more than 100 feet below top of screen. Pumping water levels are even lower, in many cases several hundred feet lower. Although nowhere as productive as the Arapahoe aquifer, this aquifer would still benefit greatly from aquifer replenishment.

5.2.3 Arapahoe

The Arapahoe aquifer is the most utilized aquifer in the Denver Basin. The large number of wells used means the aquifer attributes can be characterized well. Generally, the Arapahoe Aquifer has the highest SCs for the Denver Basin, in the approximate range of 1.0 to 9.0 gpm/ft, making it the most suitable aquifer for aquifer recharge. The highest SCs occur in the central and southern areas of the SMWSA region.

With the data available, generalized groundwater flow direction from the west to the east can be mapped, although several wells with anomalously high static water levels (SWLs) appear to also be intersecting the overlying Denver aquifer.

A surprisingly high percentage of wells have SWLs below top of screen, with pumping levels much lower. These are not favorable aquifer conditions for sustainable groundwater development, although detailed analysis has not been completed to confirm whether groundwater trends are now stable (i.e., no longer declining). The least depleted groundwaters levels are in the south. Several of the highest declines (greater than 200 feet below top of screen) are associated with higher yielding wells that, despite greater permeabilities, are perhaps being over-pumped.

5.2.4 Laramie-Fox Hills

Utilization of the Laramie-Fox Hills aquifer is low relative to the other Denver Basin aquifers, and the limited number of wells available for evaluation makes analysis more difficult. In general, the SCs in the Laramie-Fox Hills are low (many wells less than 0.5 gpm/ft) which means this aquifer is less suited for ASR because at relatively low (several 100 gpm) recharge and recovery rates, high recharge and low recovery water levels will occur. On a positive note, aquifer heads are generally 500 to 800 feet above the top of screens, meaning this aquifer has the lowest priority for aquifer recharge to replenish depleted groundwater heads. The aquifer could still be used for storage but given the condition of the overlying aquifers and the relatively limited availability of WISE water for recharge, that water is probably best directed to other aquifers.

Page intentionally left blank.

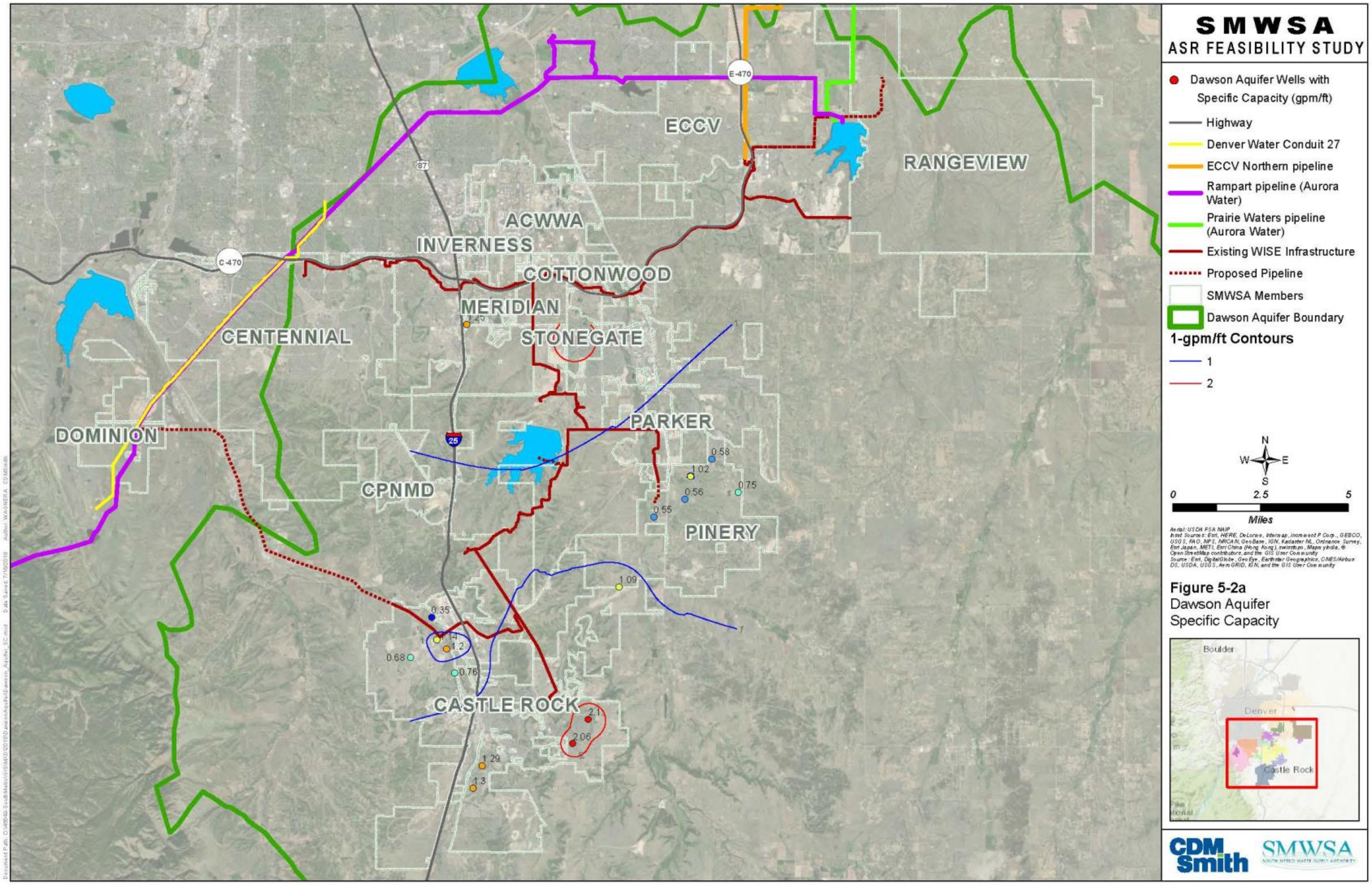


Figure 5-2a Dawson Aquifer Specific Capacity

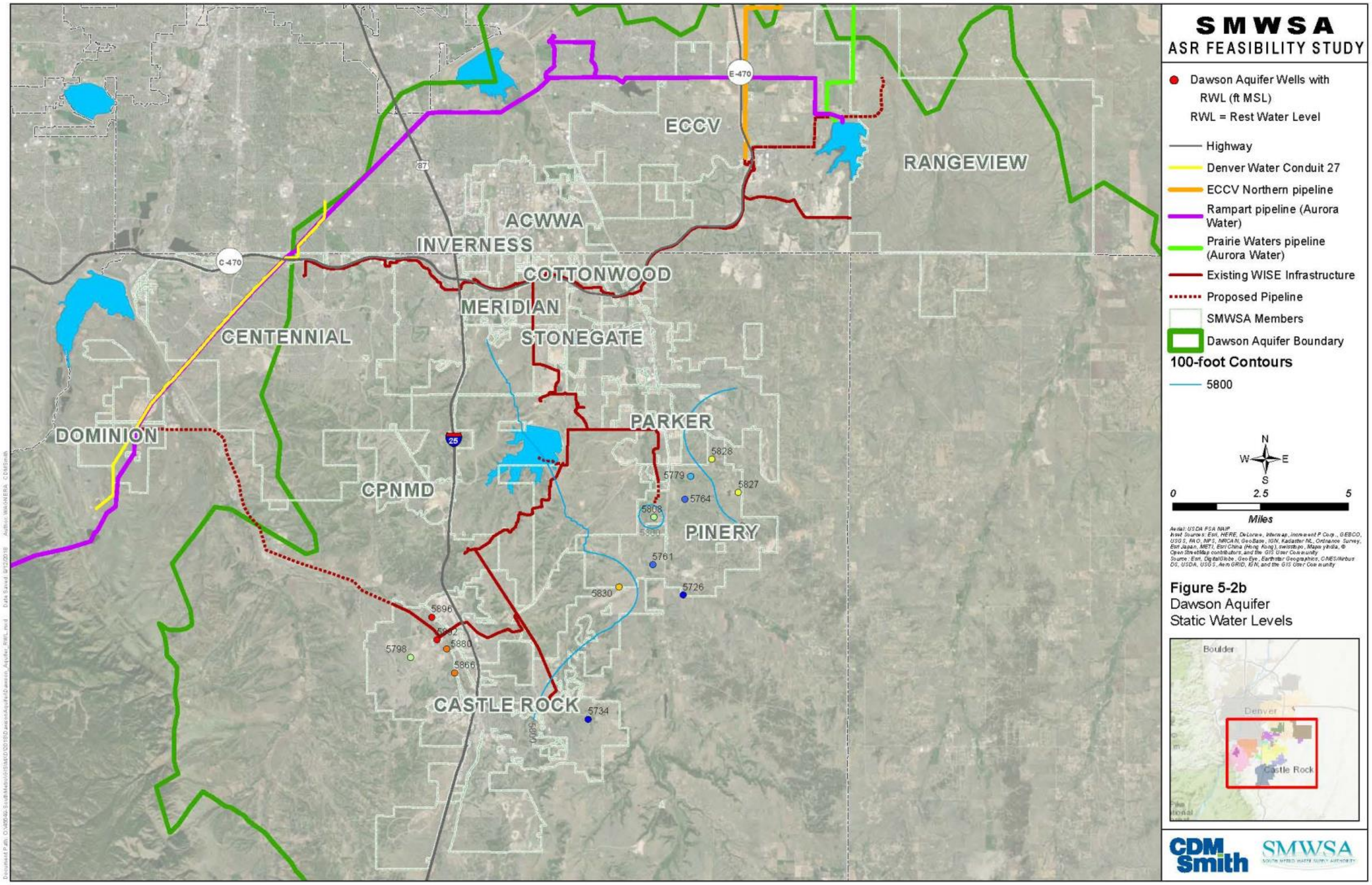


Figure 5-2b Dawson Aquifer Static Water Levels

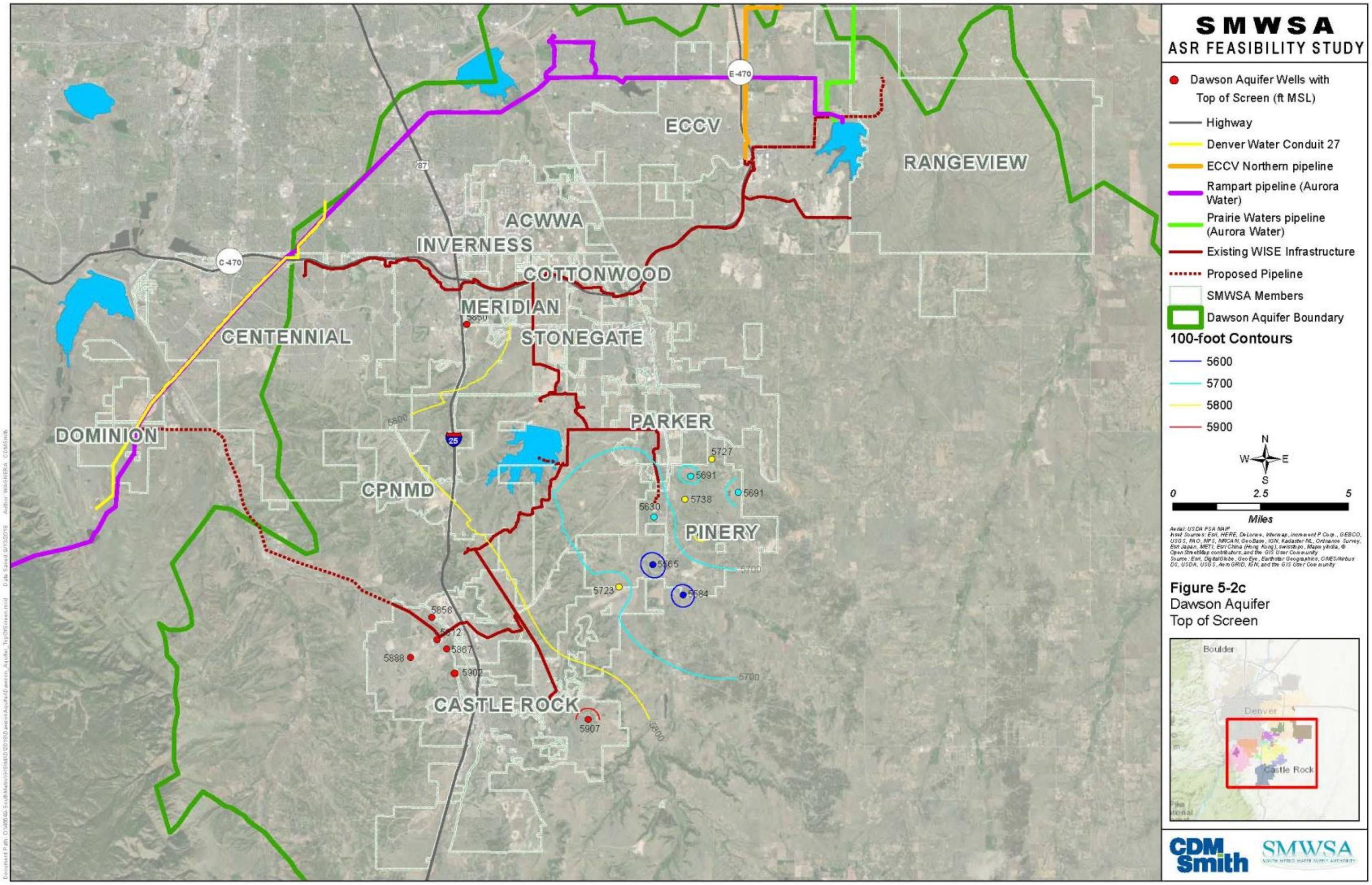


Figure 5-2c Dawson Aquifer Top of Screen

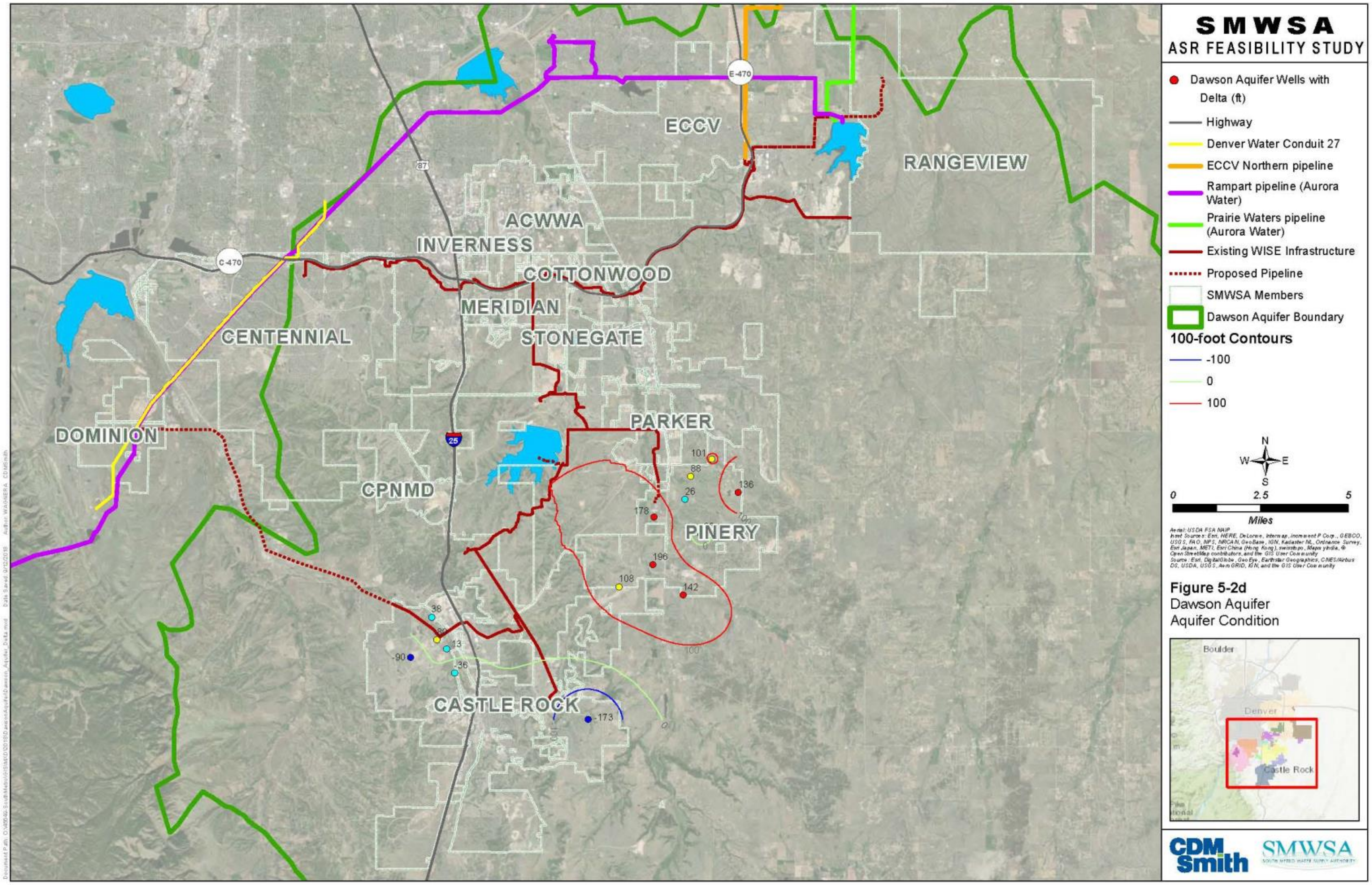


Figure 5-2d Dawson Aquifer, Aquifer Condition

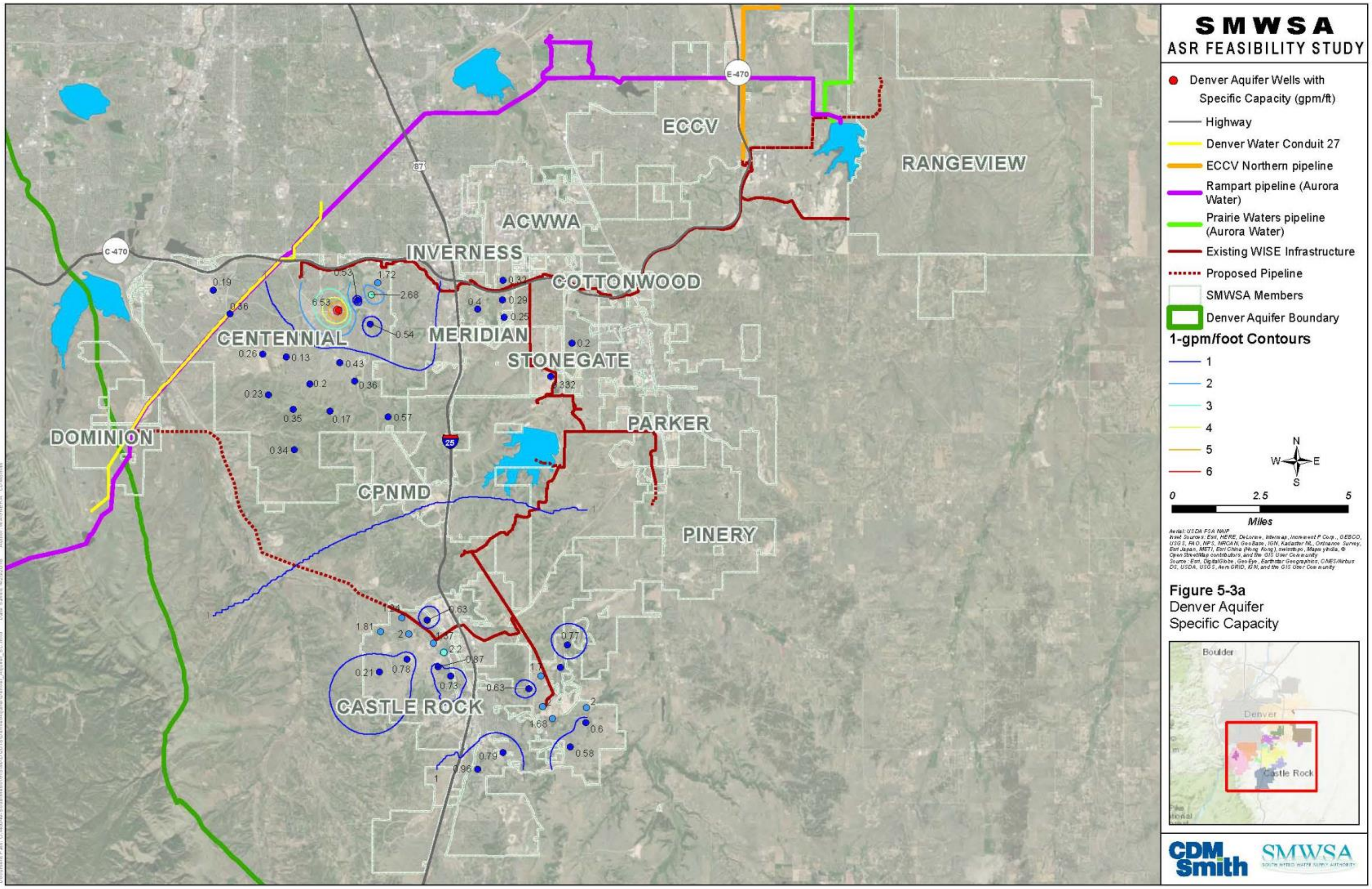


Figure 5-3a Denver Aquifer Specific Capacity

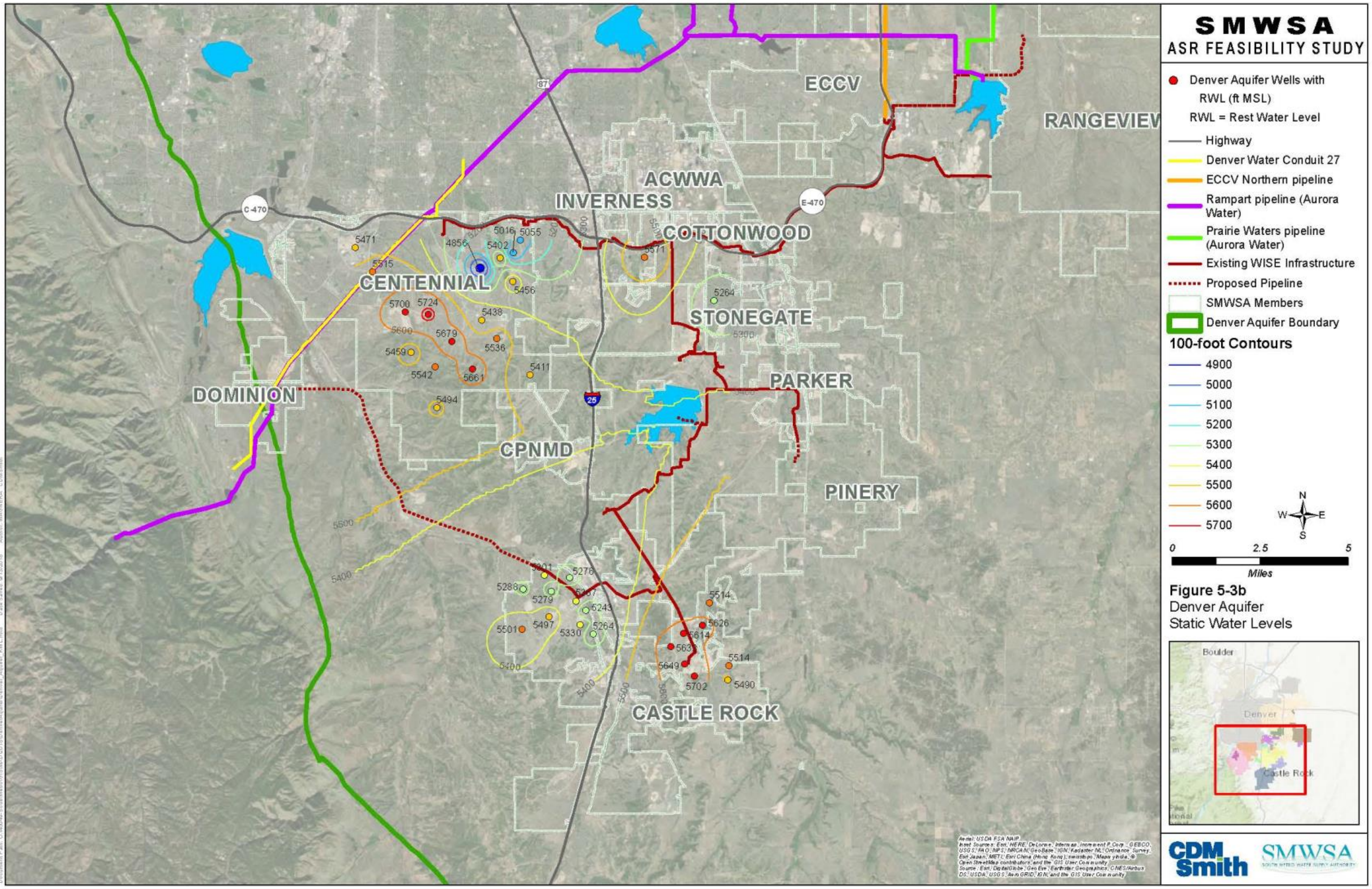


Figure 5-3b Denver Aquifer Static Water Levels

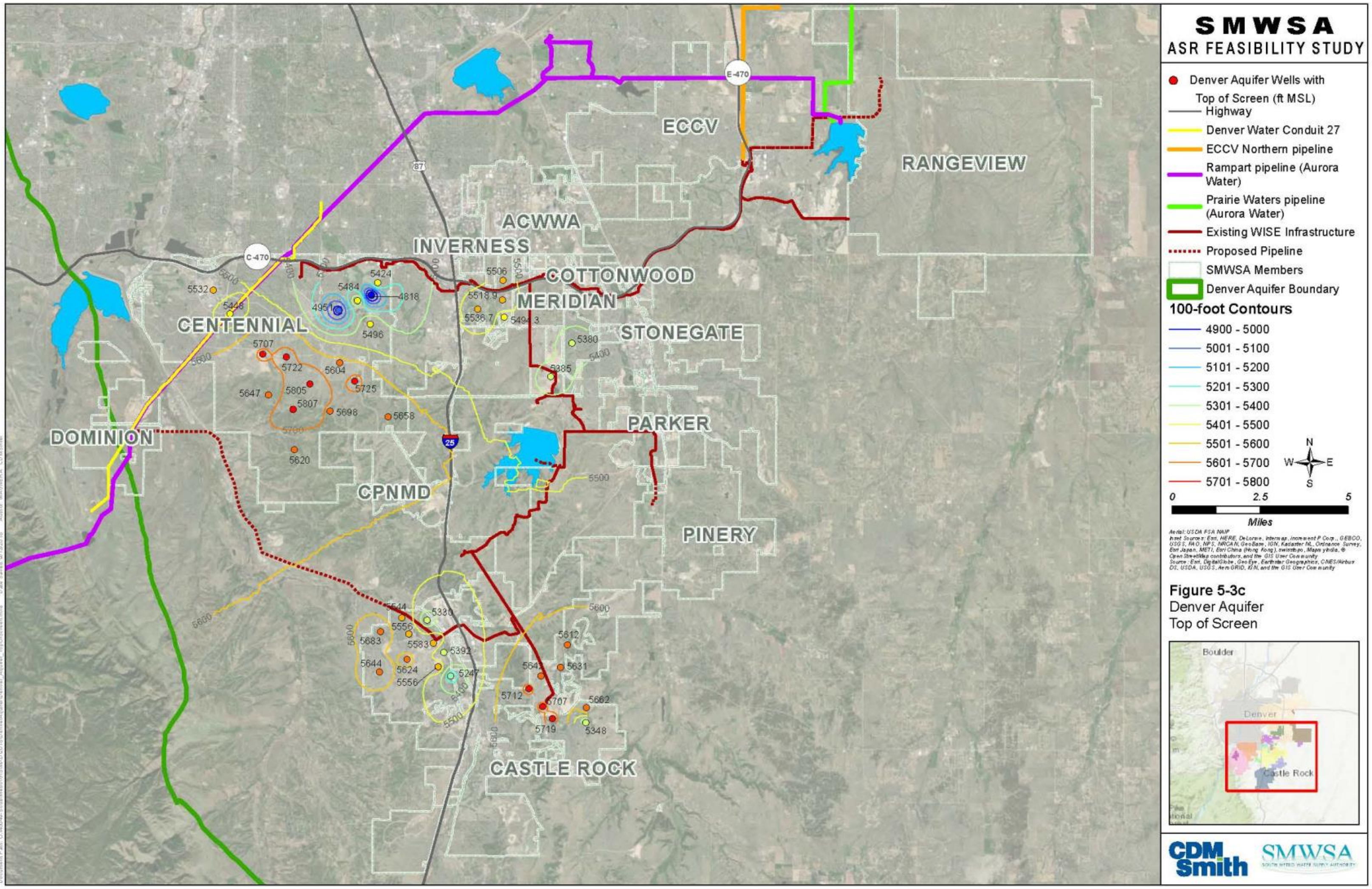


Figure 5-3c Denver Aquifer Top of Screen

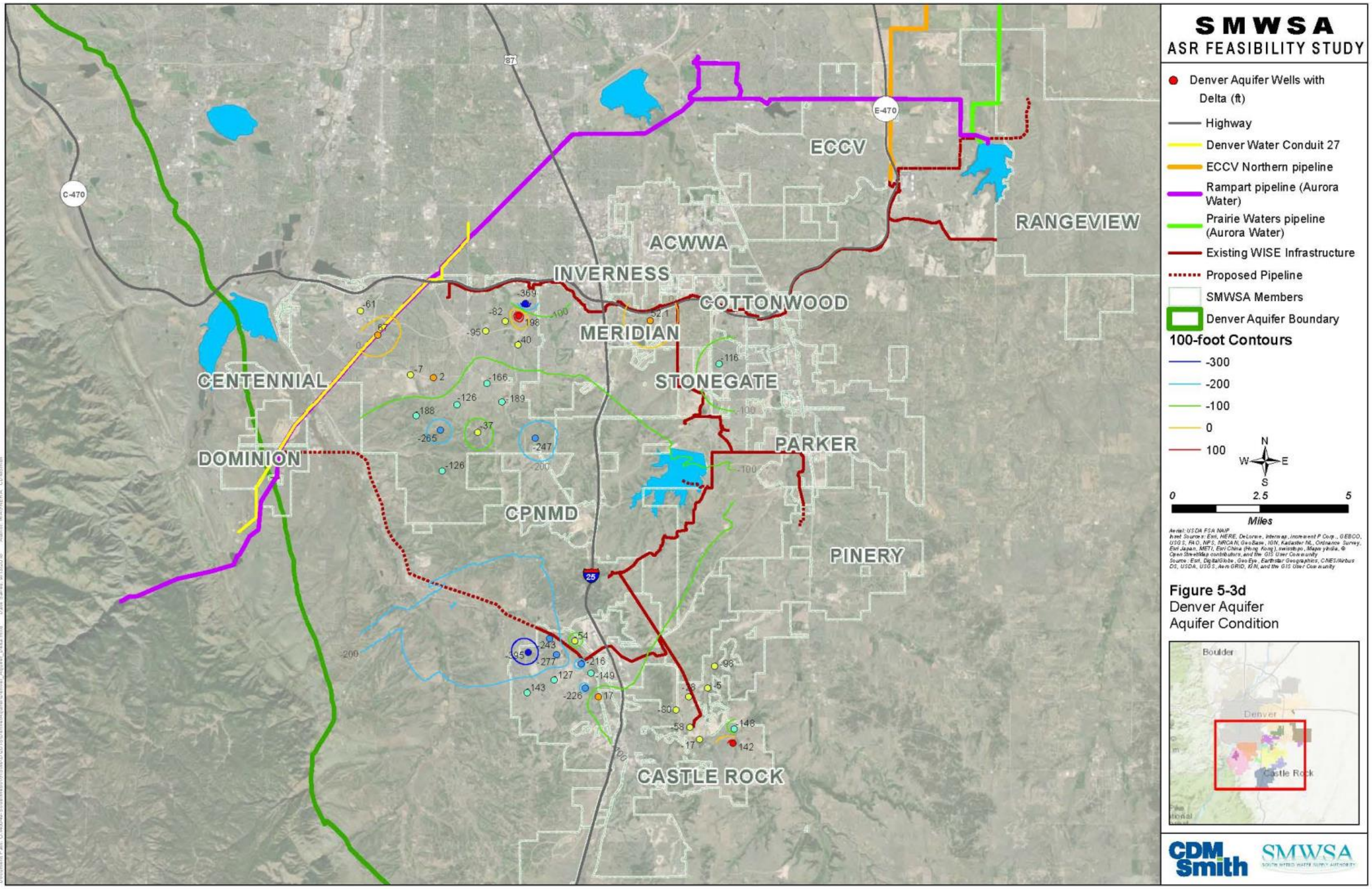


Figure 5-3d Denver Aquifer, Aquifer Condition

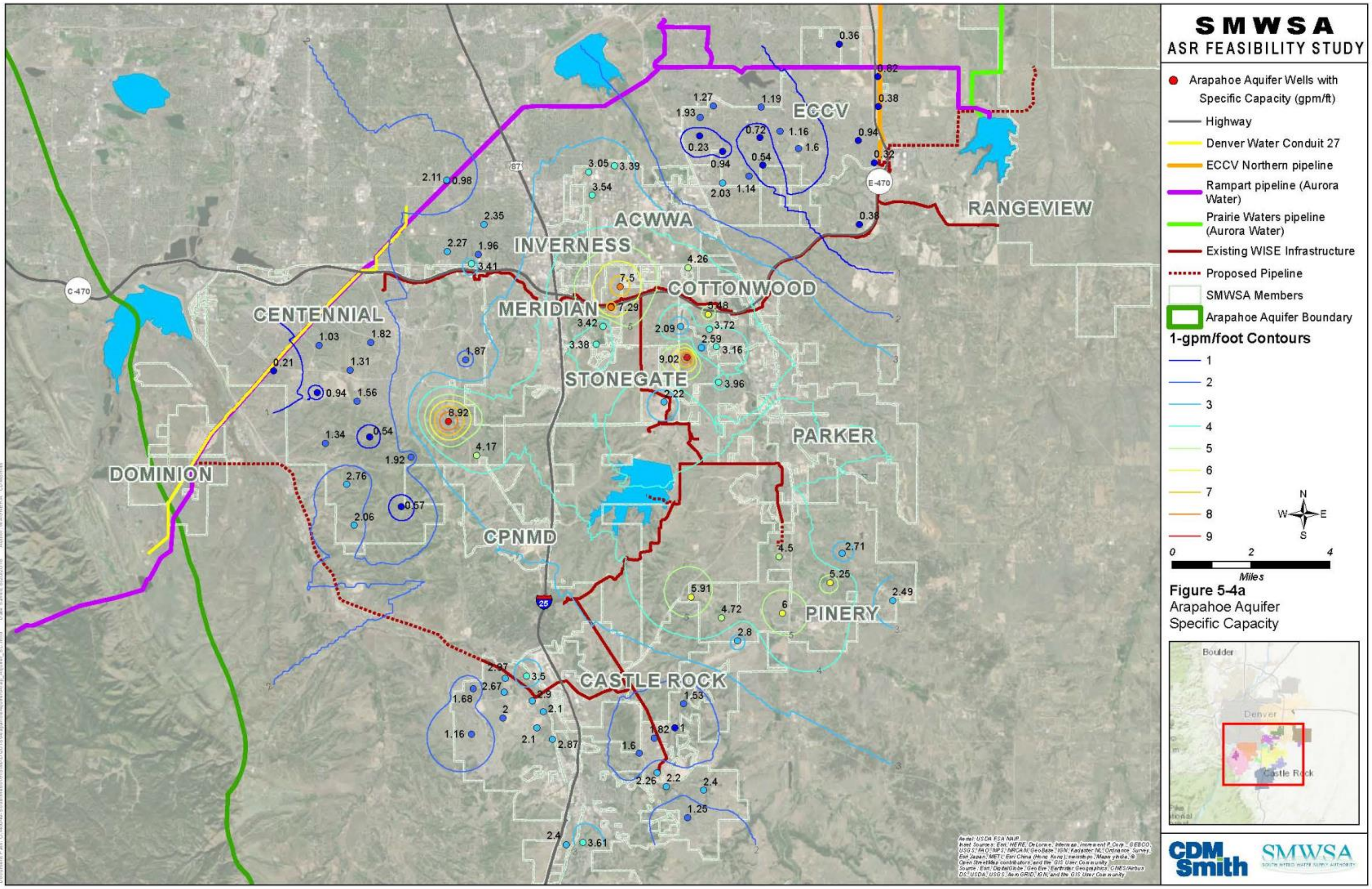


Figure 5-4a Arapahoe Aquifer Specific Capacity

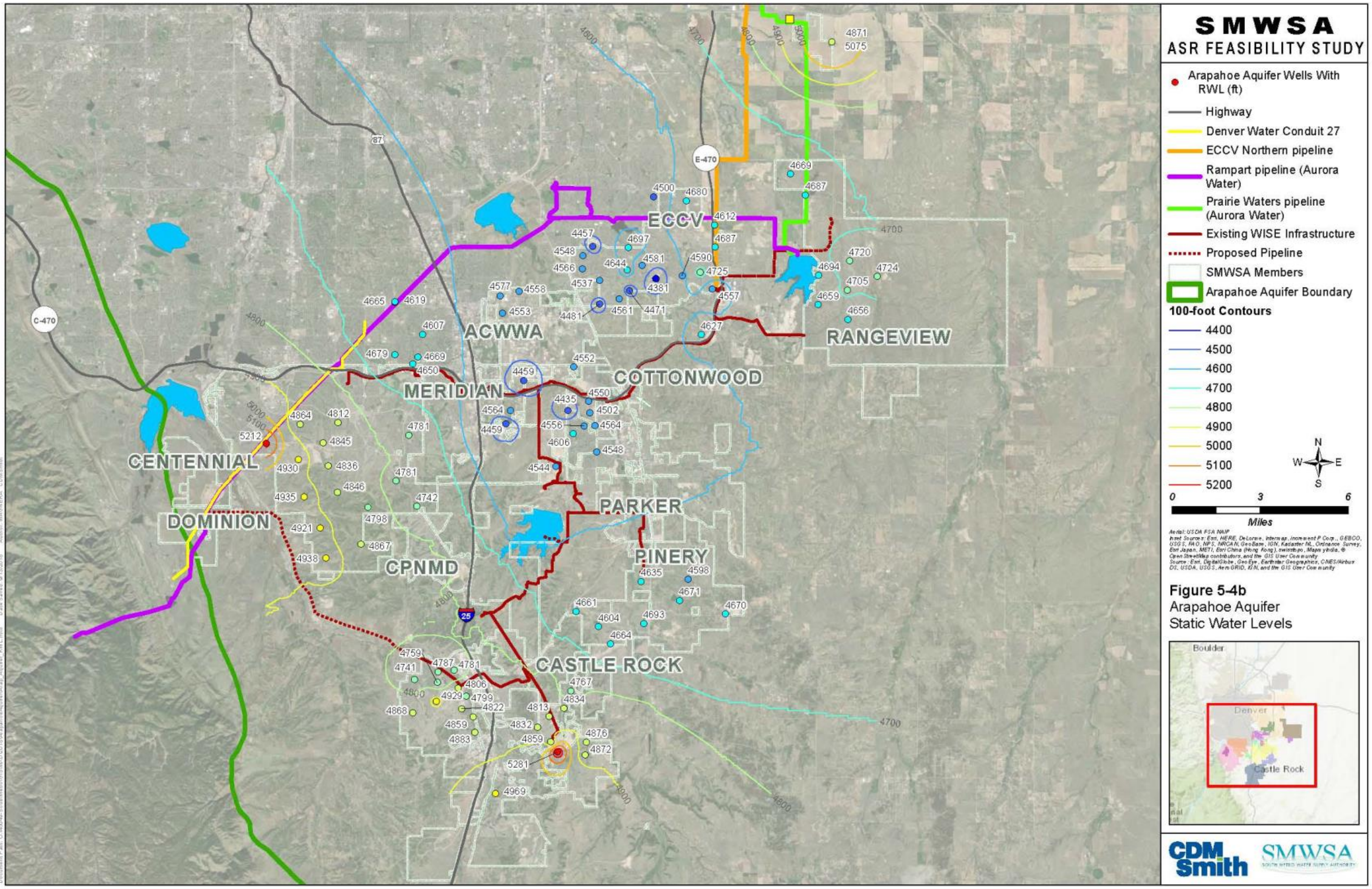


Figure 5-4b Arapahoe Aquifer Static Water Levels

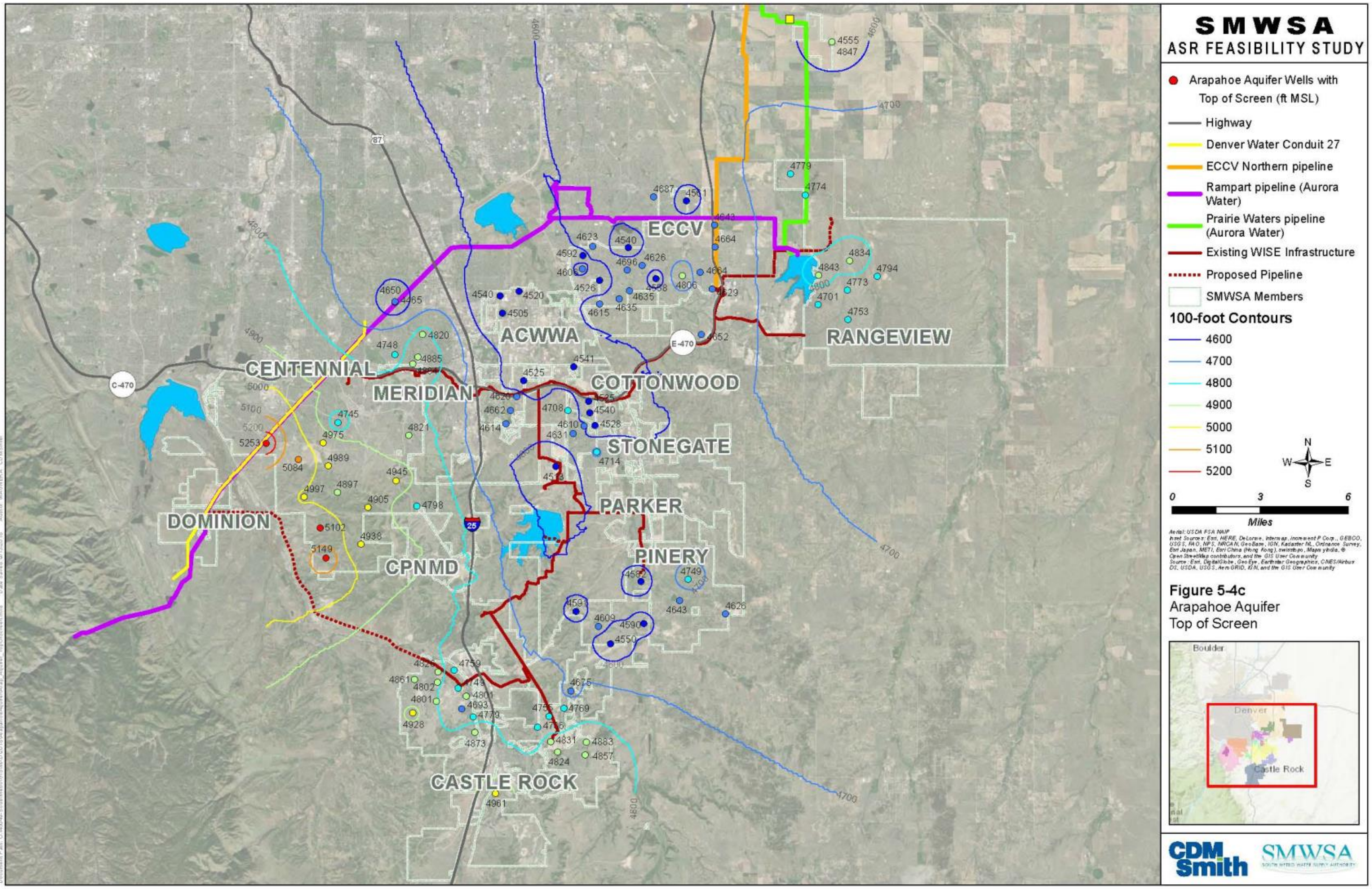


Figure 5-4c Arapahoe Aquifer Top of Screen

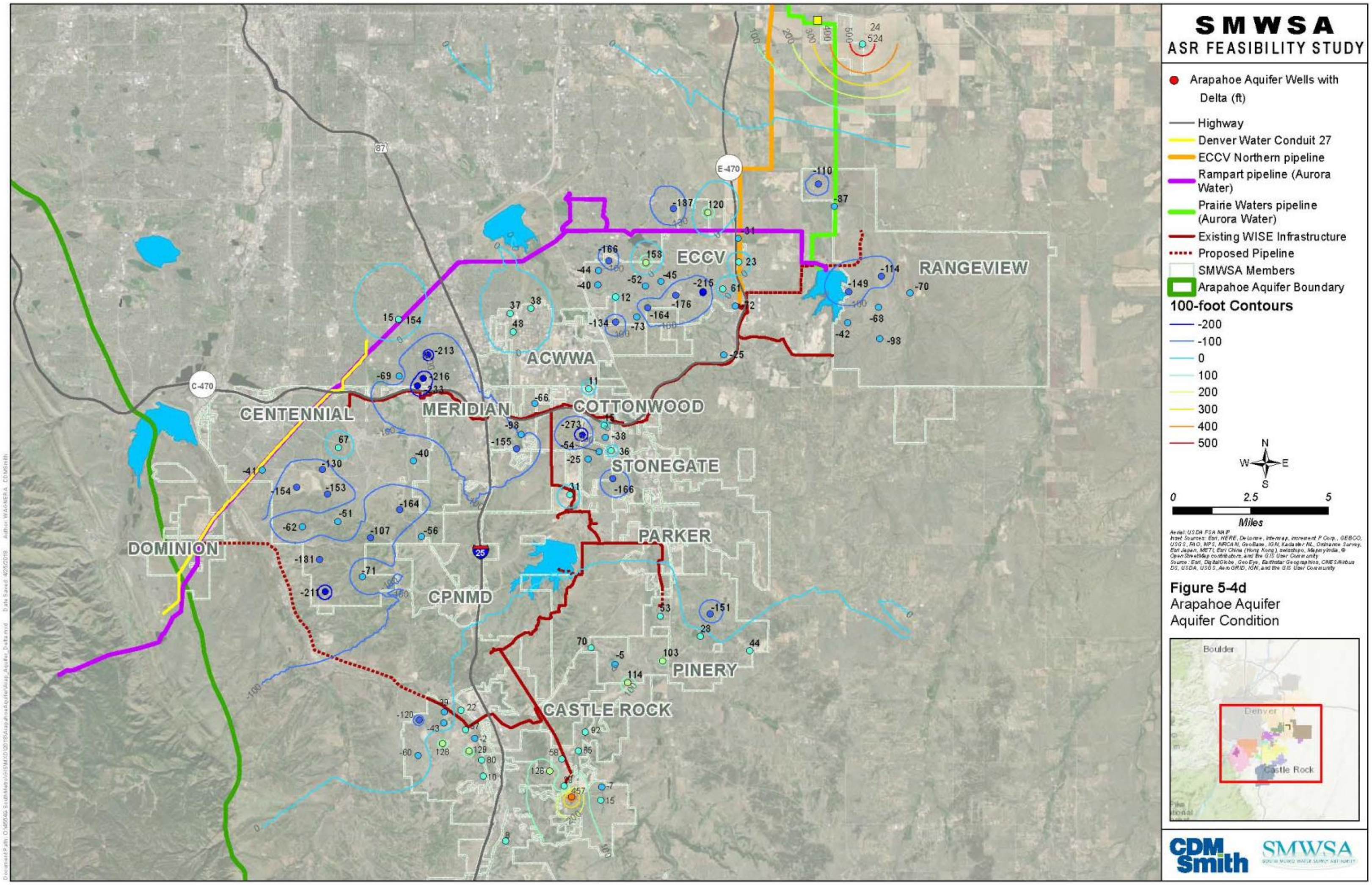


Figure 5-4d Arapahoe Aquifer, Aquifer Condition

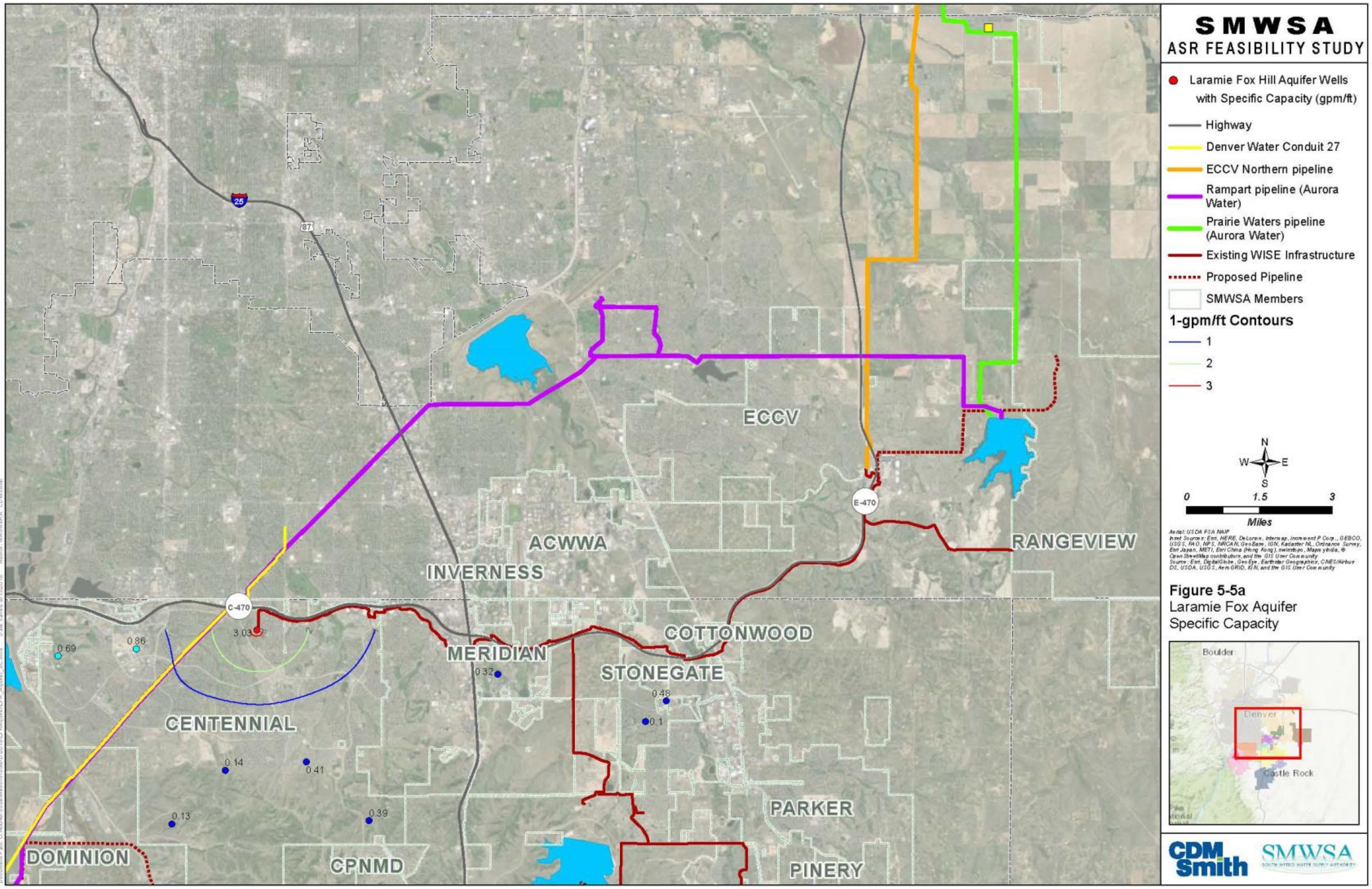


Figure 5-5a Laramie-Fox Hills Aquifer Specific Capacity

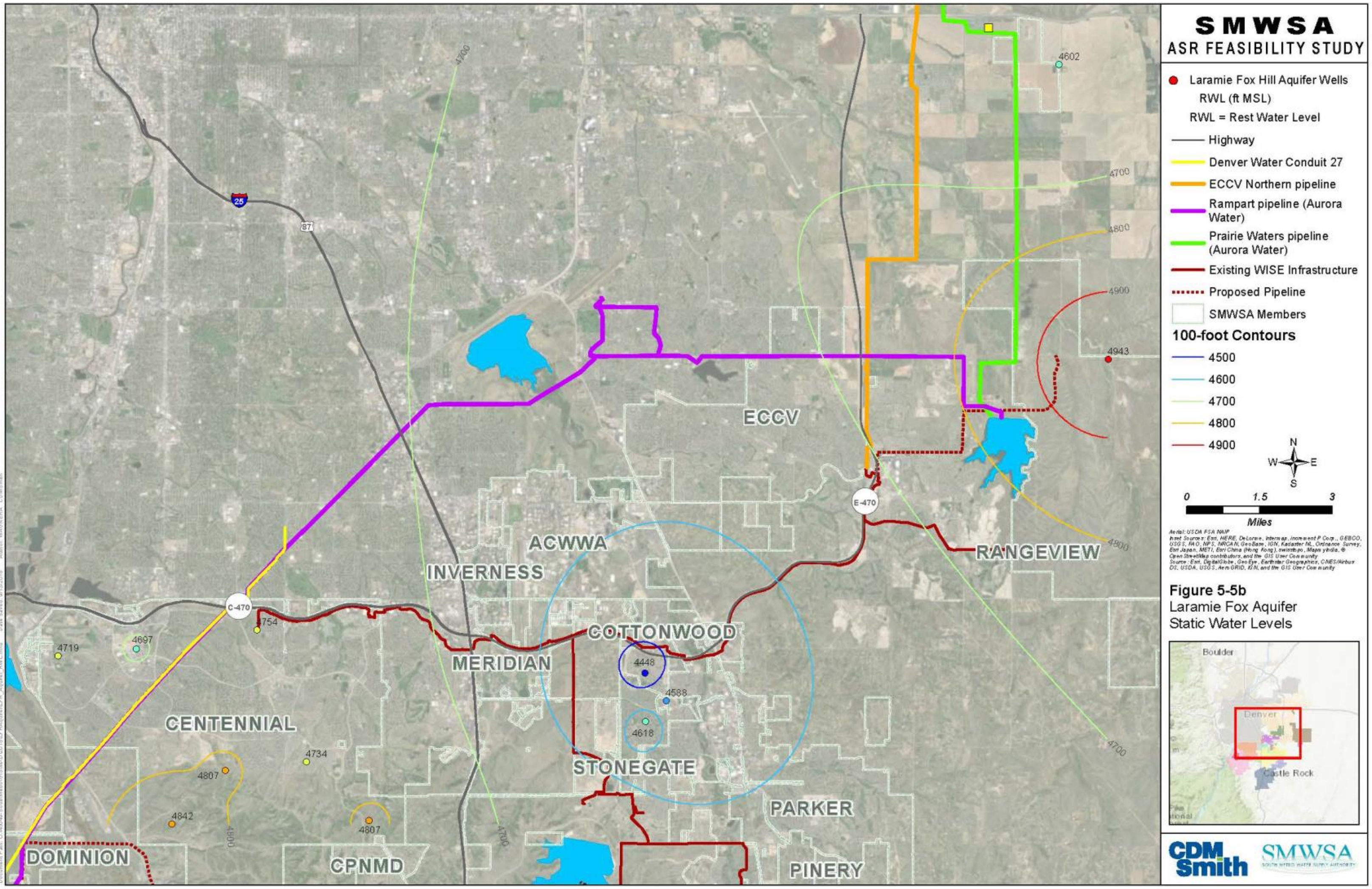


Figure 5-5b Laramie-Fox Hills Aquifer Static Water Levels

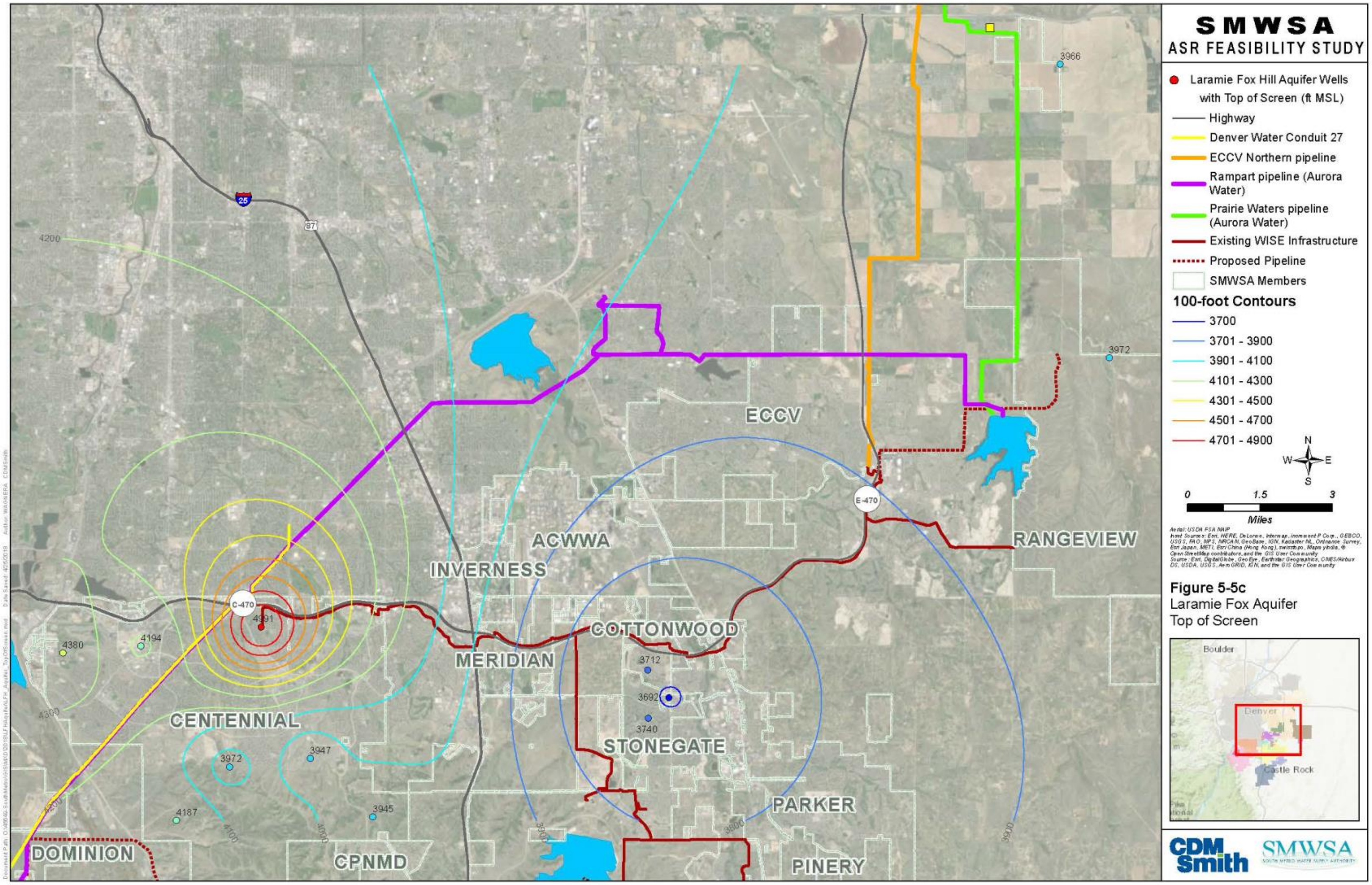


Figure 5-5c Laramie-Fox Hills Aquifer Top of Screen

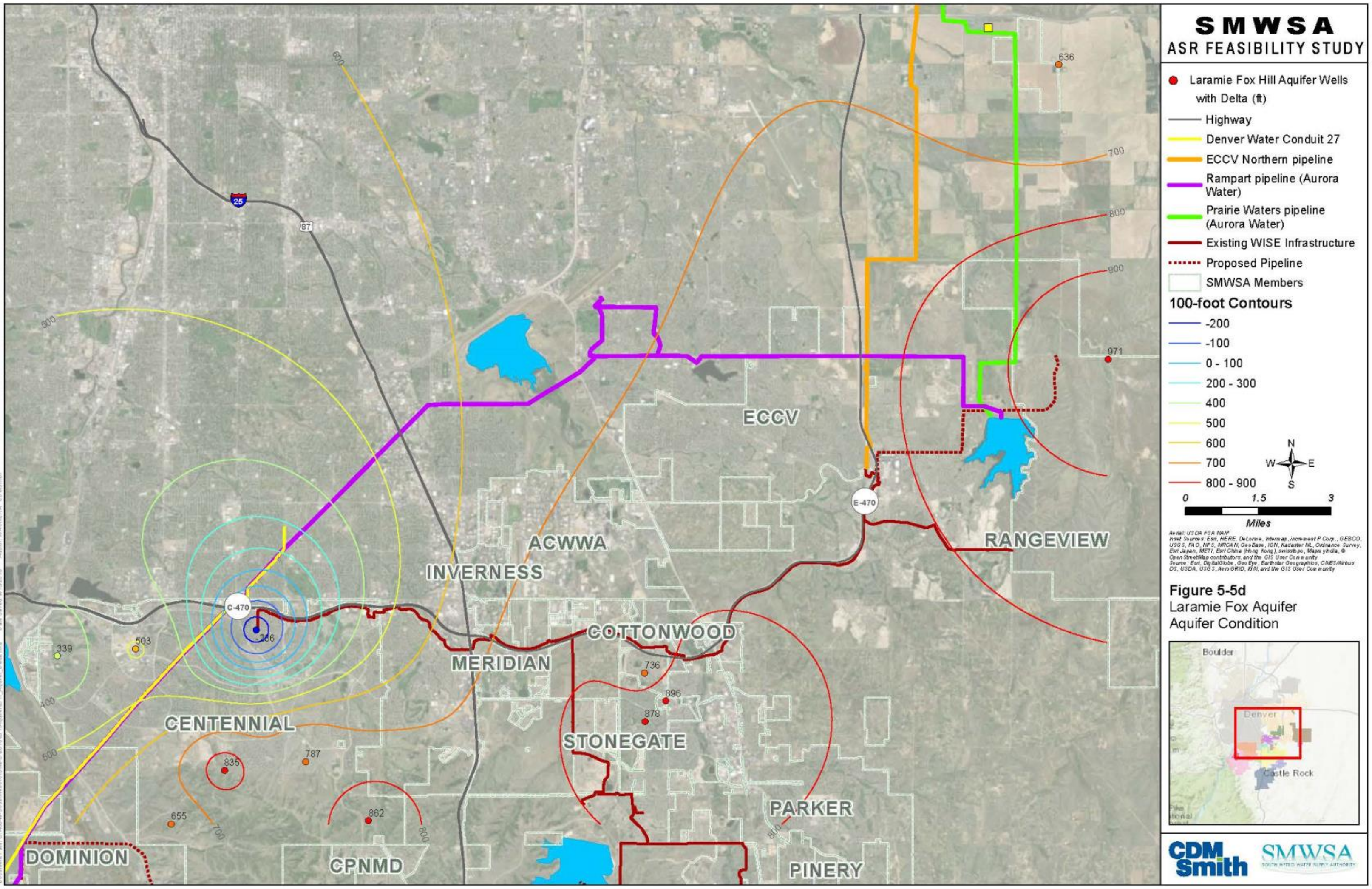


Figure 5-5d Laramie-Fox Hills Aquifer, Aquifer Condition

Table 5-1 Summary of Hydrogeologic Conditions

Aquifer	Specific Capacity	Static water levels	Top of screen	Aquifer condition
Dawson	Variations noted, generally in the range 0.5 – 2.0 gpm/ft, majority of wells less than 1.3 gpm/ft	Unable to reliably contour SWL flow directions, average head approximately 5,800 feet	Top of screens generally above 5,700 feet, although several wells locally in the southeast (Pinery W&WD) are closer to 5,500 feet	Most wells have positive heads above screens, but considering depths to SWL, aquifer levels are relatively close, less than 200 feet
Denver	Majority of wells with SC less than 0.5 gpm/ft, highest SCs in the south with many wells in the approximate range 0.8 to 2.0 gpm/ft	Highest SWLs in the northwest, influences due to pumping apparent, generally higher SWLs in the south, possibly due to higher aquifer permeabilities and/or reduced historical withdrawals	Several wells in Centennial extend into the top of the Arapahoe aquifer, most wells above 5,500 feet	Most wells have SWLs greater than 100 feet below top of screen (this is a concern), water level declines appear to be due primarily to variations in historical withdrawals
Arapahoe	Generally highest SCs for the Denver Basin, in the approximate range 1.0 to 9.0 gpm/ft, greatest SCs occur in the central and south areas of the SMWSA area	Generalized flow direction from the west to the east, several wells with anomalously high SWLs appear to also be intersecting the overlying Denver aquifer	Approximate north-south alignment, with lowest depths centered in the central north region (ACWWA and Stonegate); highest elevations above 5,000 feet are in the west within the CWSD supply area, although several wells also appear to be intersecting the overlying Denver aquifer	Surprisingly high percentage of wells with SWLs below top of screen (note these are SWLs for seasonal high water levels, which means during pumping and seasonal lows the decline is even higher); several of the highest declines (greater than 200 feet below top of screen) are associated with higher yielding wells that, despite greater permeabilities, are perhaps being over-pumped; SWLs in almost all wells in the west are below screen; ASR generally no longer being implemented, which means groundwater levels have fallen and would benefit from renewed recharge; least depleted groundwaters levels are in the south
Laramie-Fox Hills	Generally low SC (many wells less than 0.5 gpm/ft), which means less suited for ASR because at relatively low (several 100 gpm) recharge and recovery rates, high recharge and low recovery water levels will occur	Insufficient data for detailed analysis, SWLs generally below 4,800 feet	Top of screen generally highest in the west	Heads above top of screen (generally 500 to 800 feet) a positive attribute

5.2.5 Data Gaps

If ASR is implemented at a local scale (i.e., each SMWSA member utility implements their own ASR program), then the need to investigate regional variations in aquifer parameters becomes less critical. Instead the focus turns to implementation using existing retrofitted wells or the construction of new wells. If the recharge objective is to solely store WISE water so that it can be later retrieved, then from an economics perspective, locations with the most favorable hydraulics (aquifer permeability), and drawdowns that are not as deep (to reduce energy costs) should be targeted. One of the primary tasks is to ensure the performance of existing wells is fully understood with careful re-examination of historical pumping water level and pumping data, and implementation of controlled aquifer tests, if not already completed. Using the hydrogeologic conceptual model, essentially detailed geologic mapping using geophysical logs and geologic descriptions, local areas where ASR is being considered can be mapped so that decisions can be made if additional purpose drilled ASR wells are constructed.

If ASR is implemented at a regional scale (i.e., focus areas are identified for joint SMWSA member utility participation), then continued coordinated investigation is required. The concept of regional implementation, as outlined in Section 5.3.3, Regional ASR Development, is targeting recharge in hot spot locations that both assist in replenishing declining aquifer levels and target zones with higher permeabilities. The use of the hydrogeologic conceptual model to better define the aquifer extent is key, along with a more thorough evaluation of aquifer declines over time to be sure the right locations are targeted. Using groundwater models, such as those developed by CSU, will also be key to predicting the potential aquifer response to recharge and recovery and will identify if ASR wells need to be focused in clusters to ensure recharge mounds coalesce to ensure the aquifer is more successfully replenished.

5.3 WISE Authority Program

5.3.1 Program Overview

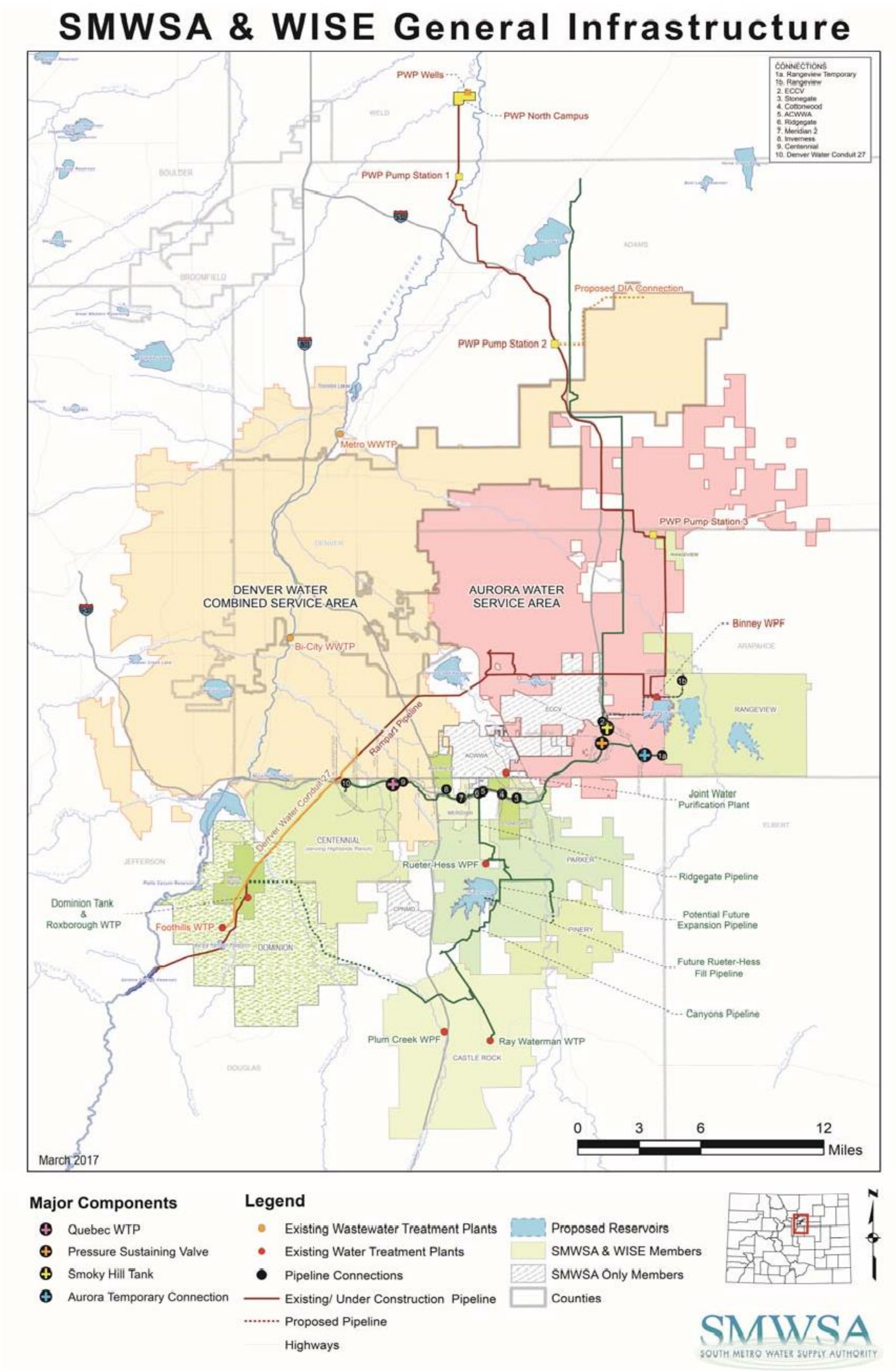
In February 2008, Aurora Water and Denver Water entered into an Intergovernmental Agreement (IGA) to investigate cooperative water supply opportunities (i.e., the sharing of water and/or infrastructure that could be mutually beneficial). In November 2008, SMWSA joined the investigation through a Memorandum of Understanding. It was the expectation of the parties that the engineering investigations would lead to the development of a joint water supply project, using available supplies and capacities in the parties' existing and planned water systems. The relationship between the three parties was solidified with an IGA executed in May 2009. Several years of engineering study identified opportunities to achieve efficiencies within the three systems of the partnership through sharing and cooperative uses of infrastructure and supplies. A regional water supply project concept was developed, and the necessary agreements were put in place. The Water Delivery Agreement (WDA) defining the terms of deliveries was executed in December 2013. The collective group of water suppliers are now referred to as the "WISE Partnership."

SMWSA is comprised of thirteen water providers in Douglas and Arapahoe counties. SMWSA has historically relied heavily on nonrenewable groundwater and, since its formation in 2004, has focused on developing renewable surface water supplies. Ten of the thirteen SMWSA members have contracted to receive water under the WISE Partnership. The ten members formed the new

South Metro WISE Authority (WISE Authority) and are a signatory to the WDA. WISE Authority includes CWSD, Cottonwood W&SD, Dominion W&SD, Inverness W&SD, Meridian MD, Parker W&SD, Pinery W&WD, Rangeview, Stonegate Village MD, and the Town of Castle Rock.

WISE combines available but highly variable excess infrastructure capacity and available water supplies to create a new reliable water supply. WISE will deliver water to WISE Authority in most years. Denver Water can also use WISE to access its supplies when needed. The backbone of WISE is Aurora's Prairie Waters (PW) project. PW, shown in the accompanying map, pumps reusable water from the lower South Platte River back to Aurora, where it is treated at the Peter D. Binney Water Purification Facility. There are times when Aurora has available reusable supplies in the lower South Platte, capacity in PW, and unused treatment capacity at the Binney facility.

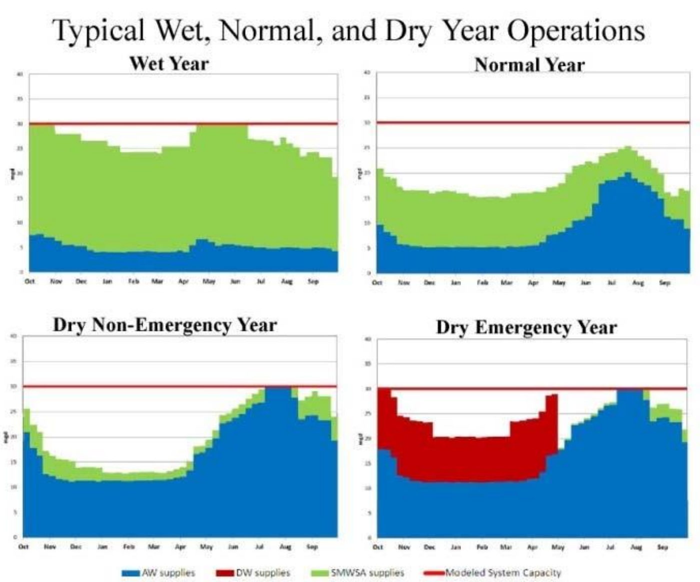
Denver Water has an extensive water delivery system, including water it diverts from the Colorado River basin to the South Platte through the Roberts Tunnel. After Denver makes use of that water, the unused portions of these flows return to the lower South Platte near PW. These return flows are fully reusable and are sometimes excess to Denver's needs. A key component of WISE is that it creates a new supply through efficient use of existing supplies—no additional water is diverted from the Colorado River Basin to supply WISE.


SMWSA & WISE General Infrastructure
CONNECTIONS
1a. Rangeview Temporary
1b. Rangeview
2. ECCV
3. Stonegate
4. Cottonwood
5. ACWWA
6. Ridgegate
7. Meridian 2
8. Inverness
9. Centennial
10. Denver Water Conduit 27
PWP Wells
PWP North Campus
PWP Pump Station 1
Proposed DIA Connection
PWP Pump Station 2
Metro WWTP
PWP Pump Station 3
DENVER WATER
COMBINED SERVICE AREA
AURORA WATER
SERVICE AREA
Bi-City WWTP
Binney WPF
Rampart Pipeline
Denver Water Conduit 27
Joint Water
Purification Plant
Rueter-Hess WPF
Ridgegate Pipeline
Potential Future
Expansion Pipeline
Future Rueter-Hess
Fill Pipeline
Canyons Pipeline
Dominion Tank
&
Roxborough WTP
Foothills WTP
Plum Creek WPF
Ray Waterman WTP
0 3 6 12
Miles
March 2017
Major Components
Quebec WTP
Pressure Sustaining Valve
Smoky Hill Tank
Aurora Temporary Connection
Legend
Existing Wastewater Treatment Plants
Existing Water Treatment Plants
Pipeline Connections
Existing/ Under Construction Pipeline
Proposed Pipeline
Highways
Proposed Reservoirs
SMWSA & WISE Members
SMWSA Only Members
Counties
SMWSA
SOUTH METRO WATER SUPPLY AUTHORITY

5.3.2 Water Quantity

Sharing available excess infrastructure capacity and available excess water supplies provides significant benefits to all three partners, the WISE Authority, Denver Water and Aurora Water. Aurora Water and Denver Water offered to make available 100,000 ac-ft every 10 years. Of this, the WISE Authority subscribed to 72,250 ac-ft every 10 years with an average delivery of 7,225 AFY. Under an option agreement with Douglas County, the project can grow to the full 100,000 ac-ft per 10 years. Deliveries noted in this summary are based on the current WDA; if additional options are exercised, delivery volumes and flow rates will be adjusted accordingly. Long-term WISE delivery commitments are shared equally by Aurora Water and Denver Water, although daily deliveries from each entity may vary based upon availability.

WISE water deliveries can vary significantly from year to year and are interruptible. Annual deliveries can range from 0 up to a maximum of 18,063 ac-ft. The WISE Authority can manage the variability of WISE supplies because they have other supplies available to them during years of minimal WISE availability. Some Wise Authority water providers may store WISE water in Parker Water's Rueter-Hess Reservoir or in ASR facilities, further firming the yield of the project.



The initial engineering studies for WISE showed that the components of the project, excess PW capacity and available supplies from Aurora and Denver Water, fit together remarkably well. WISE water deliveries are possible due to the manner in which the partners' water supplies and infrastructure can be utilized both seasonally and under varying hydrologic conditions. The chart to the left shows examples of how WISE could operate under a modeled wet, normal, and dry year, and in a year when Denver Water needs to use its supplies. The blue area represents Aurora's planned use, the red area is Denver's, and the green area represents water available to the WISE Authority. The chart shows Denver Water using its supplies during a dry year for illustration. The red line represents the capacity of the PW system.

- Wet Year – Aurora Water and Denver Water would have adequate mountain supplies and Aurora Water would not need to fully utilize PW. A large amount of water and system capacity will often be available to the WISE Authority in wet years.
- Normal Year (average; not wet or dry) – Aurora Water's use of PW will increase, but significant supplies would still be available to the WISE Authority.

- Dry Year – Aurora will rely heavily on PW, likely using the full system capacity during the summer months. If Denver Water also needs to use its backup supply, there would be limited capacity and supply available for the WISE Authority. However, Denver Water has many other sources to rely on, and may not always choose to take WISE water in dry years; some limited supplies and capacity may still be available to the WISE Authority during such years.

The WISE Authority has invested in significant connecting infrastructure to implement WISE. The WISE Authority and Denver Water purchased ECCV's western pipeline, connecting their systems to Aurora's PW project. Modifications necessary to make that pipeline successfully integrate the WISE project were constructed in 2015-2017. WISE deliveries began in summer 2017. Initially, 5,000 AFY are offered each delivery year under a phase-in period through 2021. Deliveries exceeding 5,000 AFY may be offered on an as-available basis. During the phase-in period, additional infrastructure is being constructed by the WISE Partnership to enable full WISE deliveries beginning in 2021.

5.3.3 Water Quality

The South Metro Region relies primarily on Denver Basin groundwater for their water supplies. SMWSA members have significant amounts of infrastructure related to extracting groundwater and delivering it to their customers. CWSD is a SMWSA and WISE Authority member that is located near the South Platte River and has developed surface water supplies to meet their demands. CWSD has been successfully implementing ASR for the past 22 years.

Many other WISE Authority members do not yet have access to renewable water supplies, thus the WISE project represents a significant water supply from the South Platte River downstream of Denver. Water supplies from WISE will have different water quality than the source water quality used by CWSD for their ASR operations. In particular, the WISE supplies are expected to have higher TDS but will meet all SDWA drinking water requirements. The differing water quality is one of the reasons for piloting ASR since the quality of the water is so important.

Aurora Water has agreed to make WISE water supplies available to the WISE Authority for this ASR pilot study. This partnership is a large step forward since it will allow the evaluation of using source water that will be available to WISE Authority members in the future and will allow the testing of the geochemical interactions between the source water and the aquifer(s) for which it is being injected.

5.3.4 Geochemical Analysis

A key part of determining the success of ASR is the understanding of the potential geochemical reactions that may result from the injection of water into the aquifer, storing the water, and recovering the groundwater over time. During this time the water quality of the source water will equilibrate with the groundwater and minerals in the aquifer.

To determine potential geochemical reactions from injection of supply water into the Arapahoe aquifer, a geochemical model was used. This analysis was performed for the conditions at the Rangeview Well A-20 and source water quality anticipated from Aurora Water. Modeling of the treated water and Arapahoe groundwater was performed using USGS's PHREEQC model

(Parkhurst and Appelo 1999). PHREEQC is an equilibrium speciation model that considers ionic complexing, activity effects, and the temperature and pressure conditions of the water being modeled to predict the saturation state of various minerals.

The mixing evaluation looked at potential precipitation and dissolution reactions that could affect the quality of the water or the permeability of the aquifer. The processes of potential concern, the results of the evaluation, and the possible mitigation measures are presented in **Table 5-2**.

Table 5-2 Summary of the Concerns, Results of the Evaluation, and Possible Mitigation Measures

Concern	Results	Possible Mitigation Measure
Precipitation of iron minerals	Predicted to occur, but not likely to be a problem due to low iron concentrations (0.05 mg/L or less)	na
Precipitation of manganese oxide minerals	Not predicted to occur based on modeling	na
Precipitation of carbonate minerals	Not predicted to occur unless degassing of carbon dioxide occurs	Could be mitigated by pH adjustment using an acid
Dissolution of arsenic-bearing pyrite	Based on previous ASR projects within the Arapahoe Formation (i.e., Willows Well A-6A), no increase in arsenic is observed as a result of pumping oxygenated treated water into the formation	na
Dissolution of uraninite (a uranium-rich mineral)	Not predicted to occur based on modeling results	na

Additional detail on the geochemical analysis can be found in the interim report in **Appendix A**.

5.4 Conceptual ASR Development

Many of the components for conceptual ASR development are the same for both local (individual) and regional development. For example, when retrofitting existing wells for use as ASR wells, the viability of using existing treated water mains to both convey WISE recharge water and recover the water for treatment needs to be determined. WISE water will be conveyed in potable lines. The water will be fully treated with TDS levels below 500 mg/L through 2030 and then with higher TDS levels after that (probably as high as 750 to 800 mg/L at times), though still fully treated to meet drinking water standards.

5.4.1 Pre-Treatment

As outlined in Section 2.6, ASR wells in Colorado are permitted under the Underground Injection Control (UIC) program of EPA Region 8. The primary focus of the UIC program is to protect underground sources of drinking water from contamination. ASR wells are usually allowed to operate under authorization by rule once information has been submitted in accordance with 40 CFR 144.26. Water quality of both the recharge water and the receiving aquifer must be determined at the time of application and potential adverse geochemical interactions identified.

Water quality of the WISE water will meet drinking water standards; therefore, it is anticipated that there will be no additional pre-treatment requirements prior to recharge from a regulatory perspective. From a practical perspective, there may be merits in installing guard filters that protect the wells from turbidity spikes, which over the long term, could potentially lead to well clogging. When raw water lines are used bi-directionally there is potential that sediment and other deposits that gradually accumulate in the main are mobilized. Alternatively recharge mains should be flushed prior to commencing recharge to ensure any turbidity is diverted.

5.4.2 Individual ASR Development

Individual ASR development has significant merit, primarily because it will offset the use of unsustainable nontributary groundwater supplies. Although recharge that is more evenly distributed amongst member utilities is less likely to result in locally replenished aquifer levels, it will still offset the use of groundwater by replenishing some of the withdrawals.

Hypothetically, if the entirety of WISE water supplies (7,225 ac-ft/year or 2,354 million gallons [MG] on average) were available for recharge, then this amount would be equivalent to approximately 14 percent of the combined annual water demand (51,412 ac-ft, 2013 demand), or approximately 28 percent of the average combined withdrawal from all nontributary groundwater by member utilities (25,495 ac-ft, 2013 demand). Recharged throughout an entire year this would be equivalent to 4,479 gpm, or 13 wells converted for use as ASR, assuming each well is capable of recharge rates of approximately 350 gpm (maximum 500-foot drawup with a conservatively assumed specific injectivity of 0.7 gpm/ft). The maximum amount of WISE water supplies hypothetically available for recharge in any given year is 18,063 ac-ft (5,886 MG). This is a significantly higher percentage of the average combined annual nontributary groundwater withdrawal from all member utilities (71 percent). Recharged throughout an entire year this is equivalent to 11,200 gpm, or 32 wells converted for use as ASR, assuming each well is capable of recharge at rates of approximately 350 gpm. It is unlikely, however, that the entirety of WISE supplies will be used for ASR in any given year. It is more likely that WISE authority members will only use available supplies beyond their demands for recharge. This amount will be dependent on the hydrologic conditions in the given year and the WISE authority member. Additionally, the duration over which recharge will occur during any given year is likely to be less than a full year, for example periods of 3 to 6 months. Therefore, to recharge the proposed volumes will require the use of higher performing wells, i.e. wells with higher specific injectivities, wells with final casing diameters large enough to accept flow control valves sized to accept greater flows, and/or a larger number of wells retrofitted for use as ASR wells.

Conceptually, treated water from the WISE program will be connected to individual member utility water systems with flows transferred via existing treated water pipelines and then reversed down raw water mains to individual wells. Some of the design considerations include:

- Backflow Prevention: Adequate backflow prevention to avoid mixing water of different water qualities (i.e., between WISE water pipelines and individual utility systems).
- Turbidity Control: Sediment accumulated in pipelines may be mobilized due to flow reversals. As previously outlined, purging may be required prior to commencing a recharge cycle, or turbidity monitoring and control systems installed to prevent excessive turbidity entering a well that could lead to clogging.
- Centralized treatment versus individual well treatment: When the stored water is recovered, disinfection will be required. This can be accomplished at the wellhead with simple disinfection systems; however, in some cases, removal of metals such as manganese

may be required due to the introduction of surface water with a dissolved oxygen content that may oxidize native metals concentrations. If this occurs, centralized treatment may be more appropriate.

- Aquifer and well optimization: By prioritizing wells or locations with higher permeabilities, the number of wells required to meet the recharge objectives may be minimized. However, care must be taken not to select wells with aquifer levels that are already significantly depleted below the top of well screens, unless a carefully designed recharge program is implemented so that depleted aquifer levels are restored prior to recovery.

- Recharge and recovery rates and durations: It is anticipated that the most favorable recharge objectives for individual or local ASR systems will be for seasonal use, i.e., recharge when water is available and recovery during high demand periods when the wellfields need to be operated. Recovery during peak demand periods is often at higher pumping rates, but for shorter durations (e.g., weeks and typically less than 3 months per year). For the SMWSA utility members, the highest demand periods (almost half) typically occur during the months of June, July, and August. Recharge, which may be at lower rates, will need to be for durations that ensure these recovered volumes are offset to the maximum extent possible (e.g., for periods of 6 months). The most likely secondary recharge objective will be for drought resiliency. In order to achieve the maximum possible offset so that extended recovery can occur during drought years, the maximum recharge rates and durations should occur during wet years, maximizing the availability of WISE water. These recharge objectives need to be clearly defined so that the hydraulic capacity of the system (pipelines, pumps, treatment systems, and wells) are matched to the desired rates and durations. Infrastructure details for each member utility need to be fully assessed to determine what infrastructure enhancements are required.

5.4.3 Regional ASR Development

The hydrogeologic review has identified the Arapahoe aquifer as the primary target aquifer for ASR implementation at a regional scale. It has the highest aquifer permeabilities/well performance as measured by specific capacities, and there are several locations with significantly declined aquifer levels that would benefit from replenishment. After the Arapahoe aquifer, there may be benefits in using the overlying Denver aquifer, particularly in the Castle Rock area.

Three targeted hot spots have tentatively been identified:

I Denver aquifer, Castle Rock

II Arapahoe aquifer, Meridian

III Arapahoe aquifer, Centennial

Denver aquifer hot spots are shown on **Figure 5-6a** and Arapahoe aquifer hot spots on **Figure 5-6b**. Both figures show the overlapping areas or zones where aquifer water levels (as measured by the highest 2017 static water levels) are 100 feet or greater below the top of well screens, and where SCs are greater than 1 gpm/ft. The location of individual wells for each aquifer and existing or proposed WISE pipeline infrastructure are shown on the figures for reference. This assessment does not imply ASR could not be implemented elsewhere, it is just stating these are potentially preferred areas. For example, the figures also identify additional smaller areas where even the overlapping criteria of permeability and aquifer condition are met.

An overview of the target hot spots is briefly summarized below, while the merits of each location is briefly compared with these and other local planning options in a simple risk/benefit summary table presented in Section 5.5, Alternatives Analysis.

I Denver Aquifer, Castle Rock

A local area centered on Castle Rock is identified for the Denver aquifer. Aquifer declines are more widespread than shown and encompass a significant area of the aquifer (see **Figure 5-3d**). The key criteria that differentiated this area is aquifer permeability, as measured by SC. Large areas of the Denver aquifer have lower permeabilities, but it appears in the south they may be greater. Further evaluation is required to confirm this assumption. Also note the shaded area extends north westwards where no existing utility supply wells are located—this is a function of the data contouring, and again, further evaluation is required to refine the information.

Currently, Castle Rock does not have any ASR wells located where they take WISE deliveries but is using other supplies to implement ASR pilot studies. The ability to convey recharge water, recover it, and then distribute to other neighboring utilities will depend on the timing of permitting, well retrofitting, and the interest in Castle Rock participating in a coordinated program.

II Arapahoe Aquifer, Meridian

A hot spot centered on the Meridian area for the Arapahoe aquifer is likely the most favorable hot spot. Not only is it centered on an area with significant water level declines with higher SCs, but it is also very closely located to the WISE western pipeline, so is well positioned to receive and redistribute the stored water to other member utilities.

III Arapahoe Aquifer, Centennial

This location, also in the Arapahoe aquifer, is centered on the Centennial area. CWSD already has 33 wells equipped for ASR, with the majority in the Arapahoe aquifer. ASR has been successfully implemented, but active recharge has recently been curtailed. The utility is well versed with ASR operation and so could be a good candidate for a regional project. However, detailed analysis of SC data undertaken to date show variability in aquifer permeability with areas less conducive or favorable for ASR (hence the hot spot analysis) does not encompass all the area. Therefore, further evaluation is required and an assessment undertaken to determine if additional ASR wells are better placed where permeabilities appear to be higher.

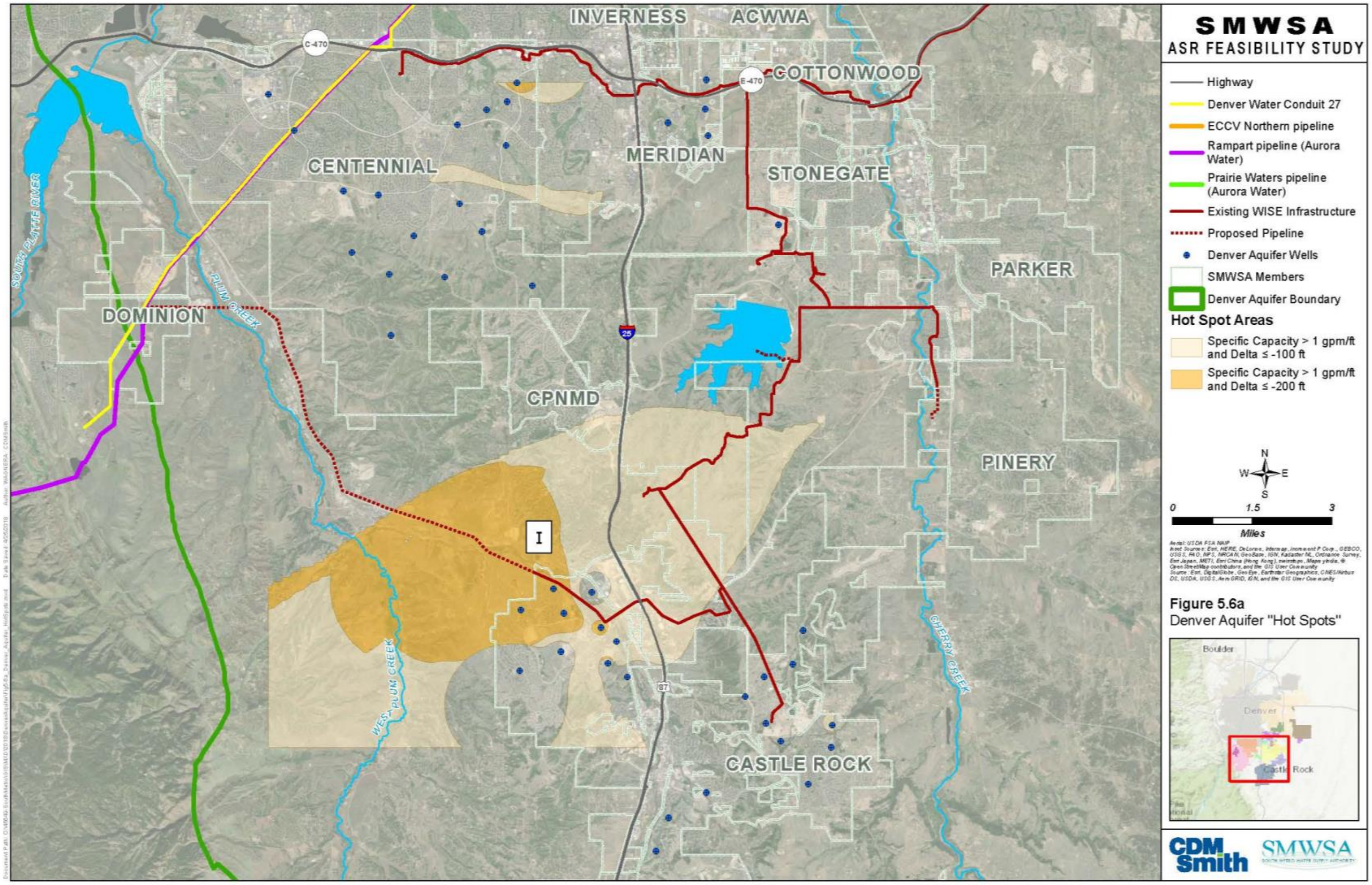


Figure 5-6a Denver Aquifer Hot Spots

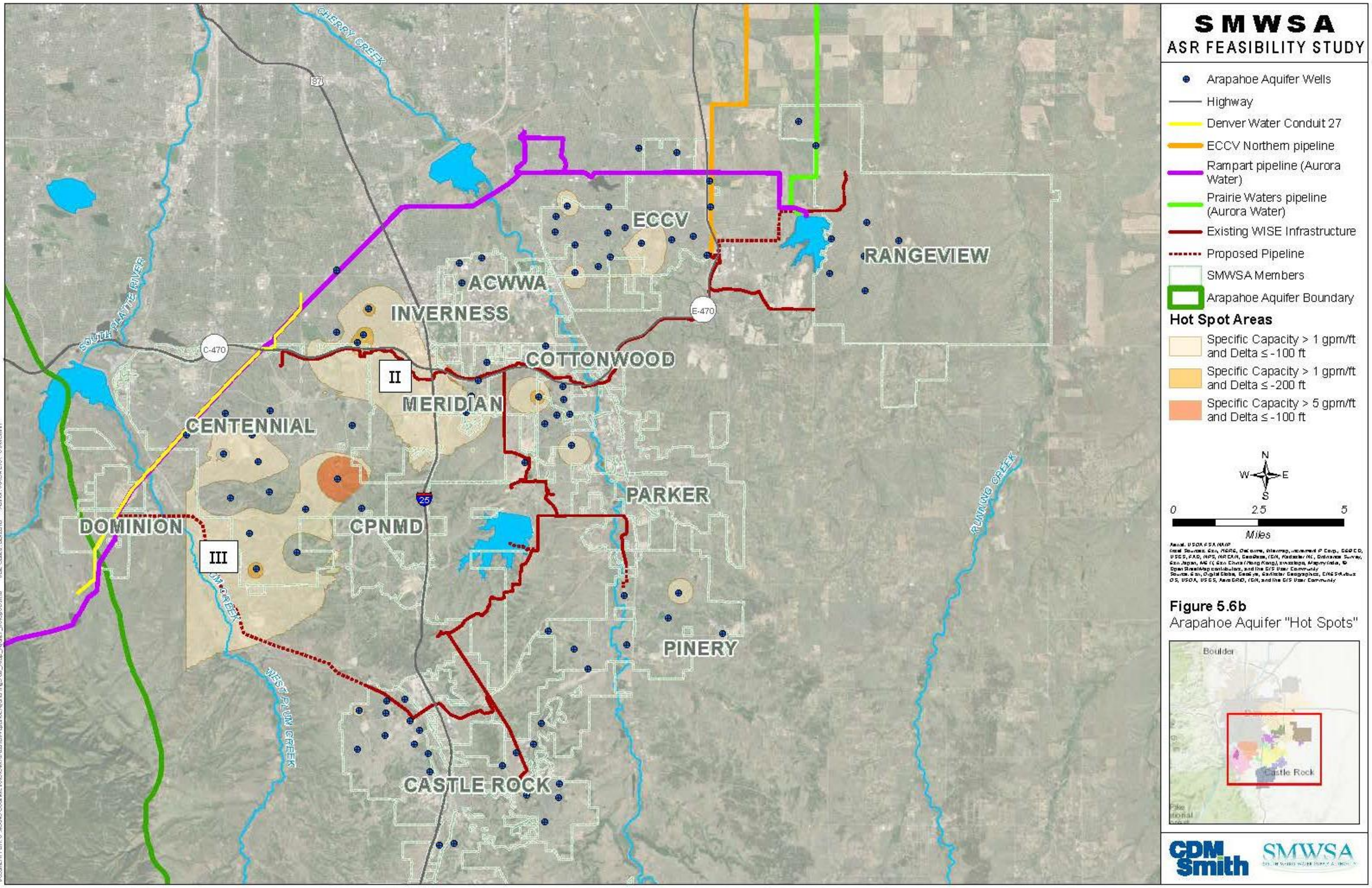


Figure 5-6b Arapahoe Aquifer Hot Spots

5.4 Economics/Costing

Concepts for both local (individual) and regional ASR development are insufficiently developed at this time to provide concept level cost estimates. There are many cost components involved in an ASR project. Some of the high-level capital costs to consider are:

- ASR well construction versus retrofitted wells
- Booster pump stations
- Conveyance pipelines
- Land acquisition
- Advanced treatment of recovered water

The most significant operating cost is power. Depending on the aquifer selected, there are significant differences in the energy cost to lift the recovered water to the surface. Many of the Denver Basin aquifers have deep water levels, and wells with lower SCs result in even greater water level drawdowns during pumping.

Section 4.3, Economic/Costing Tool, outlines a tool developed for providing planning-level costs for ASR development. The tool can be used to provide comparative costs for different ASR options. When designing an ASR system, some of the high-level questions to ask include:

Do I retrofit existing wells or install purpose-designed ASR wells?

ASR wells are approximately $1M each. Retrofitting existing wells appears an attractive alternative, with the cost of the downhole control well and wellhead costing approximately $100,000 assuming existing well pumps are reused. However, do not expect the performance of a retrofitted well to always be the same, and the asset life of a retrofitted well is obviously less.

How many wells do I need?

The recharge and recovery rates vary dependent on available drawdowns, aquifer permeability, and well efficiency. So, some aquifers/locations will be capable of higher yields, requiring fewer wells to be drilled or converted. Well number will also depend on the storage and recovery volumes planned.

What well spacing do I use?

Aquifer properties and recharge objectives dictate how closely wells should be spaced. The primary advantage of closely spaced wells is not only that water quality is potentially improved (due to coalescing recharge "bubbles") and aquifer levels recovered in low permeability aquifers creating a "recharge mound", but the cost of conveyance pipelines to recharge and recover the water is significantly reduced.

Do I need booster pump stations?

The likely answer is booster pump stations will not be required to convey WISE water to individual ASR wells. The residual pressure available should be sufficient to maintain a positive working *pressure at the ASR wellhead so that the downhole control valves remain pipe-full and no air is allowed to cascade down the well. It is also assumed that recovery pumps installed in the wells will be sufficiently sized to pump directly into supply. However, if these assumptions are incorrect, the cost of (centralized) pump stations can be significant.*

Who owns the land?

The footprint for ASR wells is typically small, and if no institutional control of the ASR bubbles is required (e.g., land surrounds the ASR wells to prevent adjacent land owners from drilling wells and "stealing" the stored water), or land is already owned by the ASR operator, then the cost of land acquisition can be reduced.

What treatment of the recovered water is required?

If the sole requirement is to redisinfect the recovered water, then water treatment costs are relatively low. However, if additional treatment is required (e.g., to remove manganese), then typically centralized treatment is provided, and the cost is much more significant.

In summary, when individual concept options have been selected, the costing tool may be used to provide comparative costs and can also be used to "value engineer" a design.

5.5 Alternatives Analysis

Several broad implementation options are considered for each of the local and regional ASR concepts outlined. The risks and benefits of each option are outlined below. The options grouped under local implementation focus primarily on the suitability of the different aquifers for different recharge objectives, while those outlined under regional implementation focus on those offering the highest potential for larger scale ASR implementation and replenishing depleted groundwater levels.

5.5.1 Implementation Options

5.5.1.1 Local Implementation

The potential opportunity for ASR development in each aquifer was briefly outlined in earlier sections. The Arapahoe aquifer generally has the highest permeability, but there are also many locations were aquifer water levels have declined significantly below the top of screens. Therefore, to avoid further potential aquifer degradation, recharge should be focused on these locations, but withdrawal or recovery of the stored water should initially be limited until aquifer levels rise.

The Denver aquifer also offers opportunity for ASR, although greatest permeabilities appear to be in the south where aquifer levels have also declined.

The Dawson aquifer has aquifer levels that are generally above well screens and appears to be less stressed. Given the relatively limited availability of WISE water, this recharge water may be best directed to aquifers and locations most under stress. The same comment applies to the Laramie-Fox Hill. This aquifer appears to be the least stressed, with aquifer levels that are generally the greatest above the well screens,and aquifer permeabilities are also generally the lowest.

The following options are outlined:

Option*	Aquifer	Recharge Objective
IL	Dawson	seasonal storage
IIL	Denver	seasonal storage, drought banking, aquifer replenishment
IIIL	Arapahoe	seasonal storage, drought banking, aquifer replenishment
IVL	Laramie-Fox Hill	seasonal storage

* "L" denotes local

5.5.1.2 Regional Implementation

Hotspots have been identified based on aquifers and areas with well yields (as measured by SCs) that are greater than 1 gpm/ft and where aquifer water levels (as measured by the highest 2017 static water levels) are 100 feet or greater below the top of well screens. The rationale for identifying these potentially preferred areas was based on the likely ability for individual wells to recharge and recover at higher rates, thereby reducing cost by limiting the number of wells required, and to identify aquifers under stress that would benefit from restored groundwater levels. Additional locations may be possible but during the preliminary screening, three options were identified:

Option*	Aquifer	Utility
IR	Denver	Castle Rock
IIR	Arapahoe	Meridian
IIIR	Arapahoe	Centennial

* "R" denotes regional

In concept, the aim is to direct WISE recharge water to one or more locations, combining the WISE water deliveries from all participating utilities that would receive water that is recovered. The WISE water pipeline would convey the recharge water to the utility within the ASR wellfield. Using existing member utility treated water and raw water pipeline infrastructure, the WISE water would then be conveyed to individual wells located within the ASR wellfield(s). Additional purpose-drilled ASR wells to supplement existing wells would likely be required, and it is possible booster pump stations may also be required to convey water from the WISE water pipeline to the ASR wellfield and back to the participating utilities.

5.5.2 Benefits and Challanges

There are generalized benefits and challanges associated with all the local and regional options outlined above, which are outlined in this section. For comparison, specific challanges and benefits associated with each option are summarized in **Table 5-3**. The different options have not been ranked, primarily because the regional ASR concept options are not yet sufficiently developed. Once they are, then a simple ranking exercise could be performed to assist with identifying preferred options.

5.5.2.1 Benefits

The overriding benefit of recharging the Denver Basin aquifers using WISE water is it helps offset the use of unsustainable nontributary groundwater. Secondary benefits include the potential to store surplus WISE water during wet years for later use drought periods, and the potential to locally recover depleted groundwater levels if sufficient water is recharged.

5.5.2.2 Challanges

The use of ASR as a water resource solution is already proven in the Denver Basin. Many of the technical challenges and risks have been overcome, for example the use of downhole control wells to prevent water cascading down-well and causing air binding was essentially developed in the Denver Basin. The primary risk is cost. Increased costs are associated with the potential need to provide additional centralized treatment if manganese and other metals are mobilized during recharge, the requirement to drill additional wells if closer well spacing is required to recover groundwater levels, and the cost of increased infrastructure (e.g., conveyance pipelines to transfer the recharge water to individual wells).

Table 5-3 ASR Option Risks and Benefits

Option	Aquifer	Benefits	Challenges
Local Implementation			
IL	Dawson	Seasonal storage	Lower priority for recharge
IIL	Denver	Seasonal storage, drought banking, aquifer replenishment	Well spacing required for recharge mounding in areas of depleted groundwater not understood.– Care needed in areas of declining water levels.
			Lower aquifer permeabilities except south, where permeabilities need to be confirmed. Variable permeabilities and the potential local leaching of radionuclides may be a concern
IIIL	Arapahoe	Seasonal storage, drought banking, aquifer replenishment	Well spacing required for recharge mounding in areas of depleted groundwater not understood. Care needed in areas of declining water levels.
IVL	Laramie-Fox Hills	Seasonal storage	Low aquifer permeabilities, with the exception of one well in the Highlands Ranch area, therefore generally low priority for recharge
Option	**Aquifer/Member**	**Benefits**	**Challenges**
Regional Implementation			
IR	Denver, Castle Rock	Replenish locally depleted groundwater	Need to confirm aquifer permeabilities are suitable
			Additional conveyance infrastructure likely required unless focus is with just adjacent member utilities
IIR	Arapahoe, Meridian	Replenish locally depleted groundwater	Locating sufficient well sites
		Strategically located close to WISE water infrastructure	Well spacing required for recharge mounding not understood
IIIR	Arapahoe, Centennial	Replenish locally depleted groundwater	Additional ASR wells required, leading to increased costs
		ASR proven with ASR wellfield already in place	Well spacing required for recharge mounding not understood
		Treatment plants for iron and manganese removal already in place	Ability to convey recovered water to member utilities not understood, additional expensive infrastructure may be required

Page intentionally left blank.

Section 6
Implementation Steps

Typical implementation steps for an ASR program are outlined in Section 6.1. ASR projects typically start as smaller pilot or demonstration projects; once proven, the systems are then expanded, often incrementally, as every ASR well added increases the overall system capacity.

Every ASR program is different. In the case of SMWSA utility members, there are several recharge objectives, which include local implementation, focused on recharging Denver Basin aquifers with WISE water to offset use of unsustainable nontributary groundwater, and regional implementation with additional recharge objectives that consider restoring depleted groundwater levels in the most impacted aquifer locations. The more specific implementation steps relevant to these recharge objectives are outlined in Section 6.2, SMWSA ASR Implementation.

6.1 Typical Implementation Steps

ASR projects are typically implemented in phases. A phased program reduces risks and costs by ensuring the next phase of work is only implemented if the previous phase is successful. Implementation typically includes the following broad phases:

- Preliminary desk-top based feasibility and planning studies
- Design and permitting for an ASR pilot/demonstration project
- Exploratory well program (or assessment of existing wells intended for retrofitting)
- ASR pilot/demonstration construction
- Operational testing
- ASR system expansion

Variations to this approach can occur, for instance, a program can be further divided to match the expertise of different construction contractors used. Well contractors, for example, are competent at the construction and testing of wells but often do not have all the necessarily skills for the construction of ASR wellhead appurtenances, instrumentation, and controls; electrical and other civil mechanical components associated with recharge pipelines; and control valves and recovery pumps. **Figure 6.1** is an example where the phased steps were divided to match the different contractors. A benefit of this approach is a civil construction contractor is only engaged if the results from the initial exploratory well drilling are successful. The well construction contractor is used to drill an initial exploratory well and if the outcome is promising, this well is either converted to a full-scale ASR well or used as a monitor well.

When assessing the suitability of existing wells for potential retrofitting to ASR wells, the well construction contractor can be used to assess the well condition, prepare CBLs to determine the integrity of final casing, and complete baseline testing to determine well hydraulics and native groundwater quality.

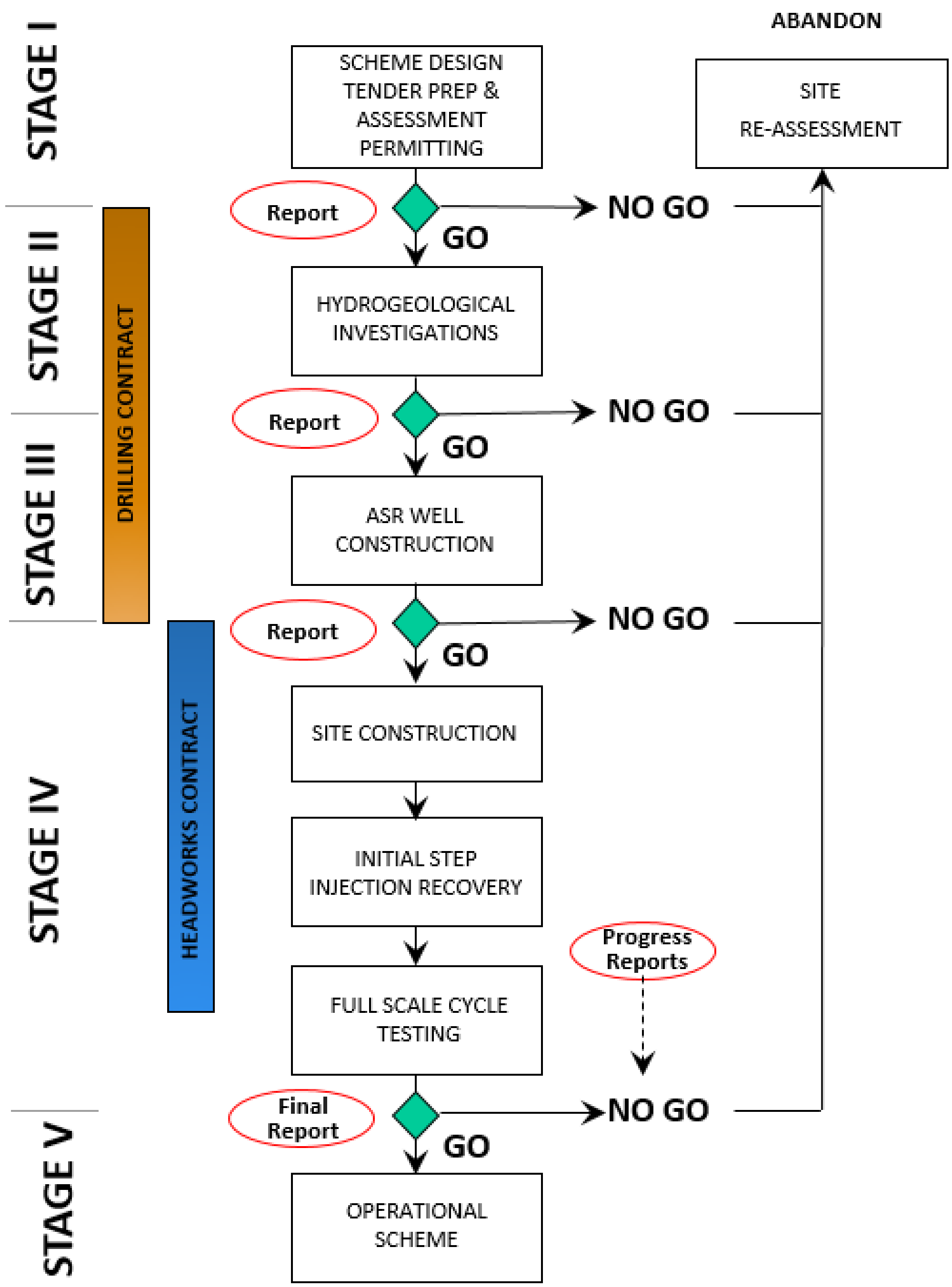


Figure 6-1 Example Customized ASR Implementation Diagram

A summary of each of the implementation phases in a typical ASR program are outlined in the following subsections.

6.1.1 Preliminary Desk-Top Based Feasibility and Planning Studies

Feasibility and planning studies serve several primary functions: they confirm the recharge objectives including assessing the availability and timing of recharge waters; they identify potential locations for pilot or demonstration projects including the suitability of target aquifers; they consider existing infrastructure so that the costs of implementing an ASR pilot may be minimized; they review available hydrogeological and environmental data to determine impacts; and they assess the economic costs.

6.1.2 Design and Permitting for an ASR Pilot/Demonstration Project

This phase focuses primarily on the design and permitting of an ASR well. Technical specifications and drawings are prepared suitable for construction. In addition to the obvious design features for the well (or retrofitted well), design of wellhead appurtenances, electrical, instrumentation and control, and recharge pipelines or connections are completed, with packages prepared suitable for bid. One consideration sometimes overlooked is the disposal of development and cycle test waters. Until it is determined that the recovered water meets required water quality standards, the water cannot be put into supply and water from preliminary cycle tests are typically discharged to waste.

6.1.3 Exploratory Well Program (Assessment of Existing Wells Intended for Retrofitting)

Depending on the availability of hydrogeological data, a pilot well may be required. During pilot drilling, the aquifer characteristics are more closely determined. Testing may include drill stem water quality sampling (assuming the drilling circulation is using formation water and not drill mud), chip sampling (drill cuttings), borehole geophysical logging, packer testing, and coring and potentially aquifer pump testing combined with water quality sampling. Aside from understanding potential geochemical compatibility issues, it is important to confirm the target recharge interval, the likely permeability of the recharge interval, and gain confidence the recharged water will remain within the recharge interval.

With a suitable design, the pilot diameter drilling may subsequently be reamed to larger diameters and production well casing installed. Alternatively, the well can be used as a storage zone monitor well.

For retrofitted wells, it is important that the well condition is clearly understood. Aside from knowing the well is in suitable condition, it is also important to know the well was constructed correctly with cement behind the final casing. A lack of cement behind this casing string may be less critical for a production well designed to capture as much groundwater as possible, but during recharge, a lack of cement may allow recharged water to move vertically behind the casing and be lost. Once the condition of the well has been determined, aquifer pump tests and water quality sampling is completed to determine baseline well hydraulics and the native groundwater quality.

6.1.4 ASR Pilot/Demonstration Construction

Assuming the results from pilot drilling or assessments of existing wells to be retrofitted are favorable, the next phase is to construct the remaining components. This includes installing monitor wells or a full-scale ASR well, depending on the design of the exploratory well program.

Careful coordination is required during the final stages of construction, particularly start-up. It is important that the construction contractor correctly installs all well components and confirms all equipment, including monitoring equipment and control valves, are working as designed. This is typically demonstrated during substantial completion inspections. However, it is important that no water is recharged into an ASR well unsupervised and without careful monitoring so that any unanticipated issues are identified early. For this reason, start-up should be carefully planned and agreed upon, often integrated during a start-up testing phase (preliminary cycle testing).

6.1.5 Operational Testing

Operational testing of a pilot/demonstration ASR well involves the recharge, storage, and recovery of water. Typically, several cycles of recharge, storage, and recovery are performed to confirm the system response. Pressure heads in the ASR well and any monitor wells, recharged and recovered water quantities and rates, and the water quality of both the recharged and recovered water are monitored. Prior to recharge, baseline native groundwater quality and well hydraulics are also measured so that any changes may be determined.

The duration of each cycle may be variable, in part, dependent on the recharge objectives. In situations where changes in the recovered water quality are anticipated, emphasis is placed on establishing a target storage volume early in the testing program (the concept is outlined in Section 2.3.3., Target Storage Volume), typically after a very short duration baseline cycle test of less than a week duration has been completed.

To improve data collection, the use of inline instruments for water quality, pressure, and flow are recommended with instruments connected to SCADA or data loggers. Following completion of each operational cycle test, the data is then evaluated. The evaluation includes an assessment of the recovery efficiency, changes in water quality during storage, the well performance (as measured by specific capacity), and any regional impacts (for example hydraulic impacts on other wells or monitor wells).

If results are favorable, then the next cycle test may be performed. If not (e.g., there is evidence of well clogging), then this data should be used to trigger any well remediation before commencing further recharge. If unchecked, potential exists for irreversible well damage. One of the significant benefits of pilot testing at a full scale is not only can there be assurance that the results may be replicated at full-scale, but once operational cycle testing is complete, the well may be used as a fully functional ASR well.

6.1.6 ASR System Expansion

Based on the outcome from the pilot/demonstration testing, scheme expansion is implemented if required. Sometimes this may involve the construction of just one or two wells. No matter what the final objective is, further feasibility study is still appropriate at this stage.

CDM Smith

Design considerations include defining any requirements to coalesce recharge bubbles, so that recovered water quality may be improved. This is particularly important when recharging into saline aquifers. To ensure recharge bubbles coalesce without adverse hydraulic interference effects (increased drawdowns or drawups can limit recharge or recovery rates due to well spacing being too close), the layout or well spacing needs to be carefully determined. Groundwater models to predict the lateral extent of recharge bubbles, hydraulic well interference, and potential environmental impacts or benefits (using aquifer parameters obtained during cycle testing), are typically used to assist with the design.

Confirming permitting requirements and performing public outreach prior to the construction of large scale ASR expansion is also recommended. Performing these tasks, in outline at least, is also appropriate during the early phases of the program so that any site chosen for pilot testing may subsequently be incorporated into an expanded ASR system.

6.2 SMWSA ASR Implementation

For the SMWSA member utilities, the feasibility and planning studies that need to be completed depend on the recharge objectives. For local implementation focused on recharging Denver Basin aquifers with WISE water to offset use of unsustainable nontributary groundwater, more traditional approaches may be followed as outlined in the previous section. Primary considerations include the selection and use of existing wells for retrofitting versus drilling purpose-built ASR wells. Using the pricing tools developed as part of this study, ASR solutions can be compared with other water resource alternatives to ensure appropriate implementation.

For regional implementation, with additional recharge objectives that consider restoring depleted groundwater levels in the most impacted aquifer locations, additional feasibility evaluations are required. A number of these technical considerations are also outlined in Section 7, Recommendations.

One of the key success criteria for regional development will be to predict the likely restoration of aquifer levels due to aquifer recharge. By restoring aquifer levels, not only will declines of unsustainable groundwater use be reversed, but increased aquifer heads will allow increased recovery rates/volumes during critical drought periods—a significant recharge benefit outlined in Section 5.5, Alternatives Analysis. However, primary constraints include lower aquifer permeabilities that result in more limited radial distances at which recharge heads increase, and volumes of recharge water available are insufficient to replenish all Denver Basin aquifers at all locations. Therefore, effort is required to focus on the optimum aquifers and locations that would benefit from recharge.

Some of the components that need to be included in a detailed feasibility evaluation include:

- Groundwater modelling using available data to predict changes in aquifer levels, identify optimum well spacing, and identify the potential need for additional ASR wells located between existing wells. Modelling different recharge scenarios and well spacings will likely determine how many ASR wells are required to recharge different volumes and ensure the stored water can be subsequently recovered without drawing water levels significant below top of well screens.

- Detailed infrastructure.
- Cost-benefit analysis of different recharge alternatives to determine the capacity of existing water mains to transfer higher flows to and from the selected ASR wellfields, including any requirement to pump flows from the WISE water main to the wellfields if there is insufficient residual pressure available in the WISE pipeline. If there are any limitations, develop concept designs for enhanced infrastructure.
- Share agreements (with volumes including 72,250 ac-ft every 10 years), so that recovered water may be redistributed to member utilities. Opportunities for additional WISE water should also be explored so that agreements can be in place before the current option agreements expire in 2021.

Section 7

Recommendations

The Denver Basin aquifers are nontributary aquifers, which means they have little to no hydraulic connection with the natural streams in the area. This allows withdrawals from the Denver Basin aquifers without impacting surface water bodies, which is a significant advantage when tasked with managing the delicate balance between groundwater and the surface water catchments. However, these deep basin aquifers receive limited natural recharge, therefore historical groundwater withdrawals have resulted in declining groundwater levels. This is a significant disadvantage.

To offset the groundwater declines, supplementing the natural recharge with artificial recharge is potentially a key water management strategy, and has already been successfully implemented in the past by CWSD. Several other SMWSA utility members including Castle Rock are actively engaged in implementing ASR programs. The potential for recharging WISE water into one or more Denver Basin aquifers is a significant opportunity, although the volumes of water proposed are still a smaller percentage of the total groundwater withdrawn by SMWSA member utilities. Therefore, careful consideration is required to maximize this opportunity.

To move these projects and opportunities forward, the following recommendations (which essentially fall into three categories) are made:

- Define recharge objectives
- Develop and improve planning tools
- Path forward

7.1 Define Recharge Objectives

Two broad recharge approaches have been identified: local ASR development and regional ASR development. Within these two broad approaches, there are specific recharge objectives that include offsetting seasonal groundwater use to meet peak water demands with WISE water, recharging and storing surplus WISE water during wet years for drought banking, and replenishing depleted groundwater levels.

Clear resolution of the appropriate recharge objectives is required. For example, do individual member utilities continue with their individual recharge objectives with the primary aim to recharge aquifers to help offset their groundwater withdrawals, or do members more fully explore the potential for collaborative development of ASR wellfields at optimum locations with multiple recharge benefits and redistribute the recovered water to member utilities?

For individual member implementation, it is recommended that, at the very least, members share lessons learned from their ASR programs, including providing updates on aquifer parameters, cycle test results, and for those wells that are retrofitted for ASR use, the performance of these wells.

7.2 Develop and Improve Planning Tools

The tools provided, developed in collaboration with CSU, provide a significant step forward in understanding and making decisions for ASR. However, benefits can be gained from the following enhancements:

- The hydrogeologic model is a synthesis of hydrogeologic data using geophysical log plots, formation strata picks, and pump test data to identify the lateral extent and suitability for ASR storage zones. The approach has been demonstrated for two case examples (CWSD and Castle Rock); however, much of the data for other member utilities has not been released. The data would be beneficial for wellfield-scale analysis.

- The water level prediction tool would benefit from user interfaces or a user manual to aid use of this tool. The water level prediction tool is an analytical model designed for application at a wellfield-scale and is calibrated by adjusting aquifer parameters to match observed water level changes. Therefore, to ensure accuracy, ongoing data collection programs that include water level monitoring and analysis of aquifer test data when it becomes available is required to ensure the tool is applied using the best available data.

- The economic costing tool is currently suitable for planning-level estimates but would benefit from several refinements. Among these would be adding functionality to account for increased lifting costs related to well performance degradation with time, and refining the head loss calculations through providing references for friction losses through pipes and appurtenances. Additionally, the costs used are not indexed so as costs escalate, there is currently no method to apply appropriate cost increases to the different cost components. For costing specific to individual design projects, the use of more detailed conventional pricing tools may be appropriate, although as ASR projects are implemented, actual costs could be updated into the economic costing tool.

7.3 Path Forward

For local ASR development, the feasibility and planning steps outlined in Section 6 are recommended, including the use of the tools offered. For member utilities still deciding on whether to proceed with ASR, the economic costing tool should be helpful for comparing ASR costs with other water supply alternatives.

For regional ASR development, increased member coordination will be required for those members wishing to participate. Some of the key coordination components to consider include:

- Confirming hot spots

- Formulating share agreements

- Completing further groundwater modelling during planning phases with model scenarios that assess aquifer responses to recharge using existing wells, recharge with additional more closely spaced ASR wells, and recharge and recovery scenarios under different climatic scenarios to assess the likely availability of WISE water and the level of drought-proofing provided. One of the key potential success measures will be if aquifer levels in more productive aquifer locations are recovered, recharge mounds created, and increased water is then made available for later recovery during drought periods.

- For existing wells and utility infrastructure, understanding in more detail any hydraulic constraints (i.e., conveyance limits on existing pipelines and well diameter constraints that may limit recharge and recovery rates due to pump and control valve sizing), and from this analysis, determining the infrastructure opportunities and constraints so that system improvements and concepts that involve directing recharge water to specific ASR wellfields using multiple WISE water member allocations and then redistributing the recovered water to members may be proposed. With planning-level pricing completed, appropriate solutions can then be agreed upon.

Given the coordination required for regional implementation, it is appropriate for SMWSA to continue in a leadership role, using ASR specialists as needed and guidance from a technical steering committee to ensure the best interests of the member utilities are met. There are significant opportunities for ASR development with WISE water deliveries as a potential source of recharge water, and existing infrastructure already in place for groundwater withdrawals from the Denver Basin. Although the volumes are notable, they do not fully offset the current groundwater withdrawals. Therefore, SMWSA should explore other potential sources that could be used for recharge. With careful planning and coordination, the benefits can be maximized, with the ultimate benefits of reducing SMWSA members' reliance on nonrenewable groundwater and providing a drought reserve when renewable supplies are unavailable.

Page intentionally left blank.

Section 8

References

American Association of Cost Engineering (AACE). 2005. Cost estimate classification system – as applied in engineering, procurement, and construction for the process industries, TCM Framework: 7.3 – Cost Estimating and Budgeting, AACE International Recommended Practice No. 18R-97: AACE.

Black and Veatch. 2004. *South Metro Water Supply Study*. Prepared for South Metro Water Supply Authority.

Cannan, C. 2016. Influence of subsurface heterogeneity on the performance of aquifer storage and recovery in the Denver Basin. Master's thesis, Colorado State University, Fort Collins, Colorado.

CDM Smith. 2014. *SMWSA Aquifer Storage and Recovery Pilot Study Interim Report*. Prepared for the South Metro Water Supply Authority.

CDM Smith. 2010. *SMWSA Regional Aquifer Assessment Final Report*. Prepared for the South Metro Water Supply Authority.

CDM Smith. 2007. *SB06-193 Underground Water Storage Study Final Report*. Prepared for the Colorado Water Conservation Board.

Centennial Water and Sanitation District (CWSD). 2016. *Water Efficiency Plan*. Highlands Ranch, Colorado. p 47: CWSD.

Hendrickson, C. 1998. *Project Management for Construction, Fundamental Concepts for Owners, Engineers, Architects, and Builders*. Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA. Version 2.2. Available online at http://pmbook.ce.cmu.edu/.

Musgrove, M., J.A. Beck, S.S. Paschke, N.J. Bauch, and S.L. Mashburn. 2014. Quality of groundwater in the Denver Basin aquifer system, Colorado, 2003–5: U.S. Geological Survey Scientific Investigations Report 2014–5051, 107 p. Available online at http://dx.doi.org/10.3133/sir20145051.

Parkhurst, D.L. and C.A.J. Appelo. 1999. User's guide to PHREEQC (Version 2) – A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations: U.S. Geological Survey Water-Resources Investigations Report 99-4259, 312 p.

Robson, S.G., G. VanSlyke, and G. Graham. 1998. Structure, outcrop, and subcrop of the bedrock aquifers along the western margin of the Denver Basin, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA–742, scale 1:50,000, 5 sheets.

Sale, T.C., A. Bailey, A. Maurer, B. Baker, and C. Hemenway. 2010. "2010 Studies supporting sustainable use of the Denver Basin aquifers in the vicinity of Castle Rock, CO." Unpublished project report for the Town of Castle Rock, Colorado.

Sale, T.C., M.J. Ronayne, A.A. Alqahtani, and C. Hemenway. 2017. "Tools supporting development of ASR Projects." Unpublished report for CDM Smith and the South Metro Water Supply Authority, Colorado State University, Fort Collins, Colorado, and Hemenway Groundwater Engineering, Colorado.

United States Department of Energy (DOE). 2011. *Cost Estimating Guide*. DOE G 413.3-21, Washington, D.C. Available online at https://www.directives.doe.gov.

Paschke, S.S., ed. 2011. Groundwater availability of the Denver Basin aquifer system, Colorado: U.S. Geological Survey Professional Paper 1770, 274 p.

s

cdmsmith.com