Opportunities and Challenges in Aquifer Storage and Recovery

White Paper Prepared by the Texas Groundwater Protection Committee (TGPC)

Groundwater Issues (GWI) Subcommittee

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Executive Summary

Aquifer storage and recovery (ASR) is “the injection of water into a geologic formation, group of formations, or part of a formation that is capable of underground storage of water for later retrieval and beneficial use” according to the Texas Administration Code (TAC) Title 30 §331.2 (9). ASR has been of interest in Texas since the 1940s as an alternative to store water supplies, and the 2022 State Water Plan presents 192 water management strategies that include ASR. Water from sources such as surface water, groundwater, highly treated effluent, and storm water can be stored in an aquifer and later retrieved to be used for various purposes, such as drinking water, irrigation, or industrial processes. When compared to water storage in a surface reservoir, ASR has the advantage of a minimal real estate footprint without losses to evaporation. Other advantages include high recoverability rates and available stored water to meet peak demands. This white paper summarizes the current status of Texas statutes and regulations that are enforced by the Texas Commission on Environmental Quality through its oversight of the Class V Underground Injection Well program. Selected Texas ASR projects are presented to demonstrate different site conditions and operational experiences. Lessons learned in Texas and other states are presented from the professional literature. Geochemistry issues are identified, as well as operational strategies to encourage efficient injection and recovery of stored water. It is clear that ASR is a viable groundwater supply management strategy if applied correctly, and pertinent recommendations and research topics are provided to move the technologies and operations toward success.

Acronym List

AR	Aquifer Recharge
ASR	Aquifer Storage and Recovery
BSEACD	Barton Springs Edwards Aquifer Conservation District
DBP	Disinfection By-Product
HAA	Haloacetic Acid
HB	House Bill
gpm	Gallons per Minute
GCD	Groundwater Conservation District
MCL	Maximum Contaminant Level
MGD	Million Gallons per Day
ppb	Parts per Billion
RRWSC	Ruby Ranch Water Supply Company
SAWS	San Antonio Water System
TAC	Texas Administrative Code
TBWE	Texas Board of Water Engineers
TCEQ	Texas Commission on Environmental Quality
THM	Trihalomethane
TWC	Texas Water Code
TWDB	Texas Water Development Board
UIC	Underground Injection Control
USGS	United States Geologic Survey
VFD	Variable Frequency Drive
WUG	Water User Group

Introduction

Aquifer storage and recovery (ASR) is "the injection of water into a geologic formation, group of formations, or part of a formation that is capable of underground storage of water for later retrieval and beneficial use" according to the Texas Administrative Code (TAC) Title 30 §331.2 (9). ASR has been of interest in Texas since the 1940s (Webb, 2015) as an alternative to store water supplies, and the 2022 State Water Plan (TWDB, 2022) presents 192 water management strategies that include ASR. Water from sources such as surface water, groundwater, highly treated effluent, and storm water can be stored in an aquifer and later retrieved to be used for various purposes, such as drinking water, irrigation, or industrial processes. When compared to water storage in a surface reservoir, ASR has the advantage of a minimal real estate footprint without losses to evaporation. Other advantages include high recoverability rates and available stored water to meet peak demands.

According to the Texas Water Code (TWC) Section §27.151, an ASR injection well is a Class V injection well used for the injection of water into a geologic formation as part of an ASR project for recovery later, when the water is needed. The Texas Commission on Environmental Quality (TCEQ) has complete jurisdiction over the regulation and permitting of an ASR injection well (TWC §27.152). Operators of an ASR project must apply for authorization and in the application include the information under 30 TAC §331.182 and §331.186. Some required elements of the application include general facility/operator information, the ASR project area, area of review, and artificial penetrations (e.g., oil and gas wells, water wells, etc.). The well construction and closure plan along with injection well operations plan need to be included. Finally, the site-specific project geology, hydrogeology, geochemistry, and demonstration of recoverability must be included in the application (Council, 2019).

House Bill (HB) 655, enacted by the 84th Texas Legislature, amended the TWC, stating that TCEQ has jurisdiction for regulation of ASR projects. The bill included the groundwater quality standard for ASR projects in TWC §27.153(b) (4), which requires the TCEQ to evaluate issuing ASR permits and authorizations and to consider whether the introduction of water into the receiving geologic formation will alter the physical, chemical, or biological quality of the native groundwater to a degree that would

(A) render the groundwater produced from the receiving geologic formation harmful or detrimental to people, animals, vegetation, or property, or

(B) require an unreasonably higher level of treatment of the groundwater produced from the receiving geologic formation than is necessary for the native groundwater in order to render the groundwater suitable for beneficial use.

Regulations for ASR injection wells are found in Title 30 Chapter 331 of the TAC. HB 655 also changed the TWC by

- Adding siting requirements,
- Removing the requirements for a pilot test prior to obtaining authorization for an operational ASR project,
- Adding the requirement for a determination of stored water recoverability,
- Adding notice provisions for ASR projects,
- Specifying system monitoring and reporting requirements, and
- Recognizing the authority of five special purpose districts, HB 655 also required TCEQ to develop rules for ASR projects.

HB 720, enacted by the 86th Texas Legislature, modified TWC §11.157 to allow unappropriated surface water, including stormwater and floodwater, to be appropriated for use in an ASR project or for aquifer recharge (AR) as a beneficial use of appropriated state water. This white paper is focused on ASR and does not address aquifer recharge.

Enacted HB 721 from the 86th Texas Legislature authorized a study by the Texas Water Development Board (TWDB) to conduct a statewide survey of Texas' major and minor aquifers to determine their relative suitability for use in ASR projects. The TWDB published the *Statewide Survey of Aquifer Suitability for Aquifer Storage and Recovery Projects or Aquifer Recharge Projects* in December 2020 (Shaw et al., 2020). The HB 721 aquifer suitability study and resulting interactive story map provide a methodology to rate the relative suitability of aquifers in the state for ASR and AR, including favorable hydrogeological conditions, water sources, and water supply. This TWDB assessment is not restated in this white paper.

Full Issue Information and Discussion

Regulatory Terminology and Guidance

The Underground Injection Control (UIC) statutes are found in the TWC while the rules are found in the TAC. For ASR projects, specifications and requirements are found in Chapter 27 Subchapter G and Chapter 36 Subchapter N of the TWC and Chapter 331 Subchapters A, H, and K of the TAC requirements. Table 1 is a summary of key definitions, standards, or requirements of ASR regulations from each statute and corresponding rule. Planners, owners, and operators of ASR projects must be familiar with these key starting points.

ASR Authorization Application Information

When applying for authorization for an ASR project, applicants must include general site information, project area, geology, hydrogeology, geochemistry, hydrogeologic modeling data, and demonstration of recoverability. TCEQ will notify the appropriate groundwater conservation district (GCD) when reviewing an application that is in the district. It is recommended that applicants do thorough advanced planning and studies before applying, including coordination with the local GCD. The ASR authorization may have a limited timeframe and may need to be renewed or amended. Once authorization is received, operators must continue to monitor and report data to the TCEQ, and if the ASR is within a GCD area, operators must send the monitoring reports to the GCD. As shown in Table 1, TWC §27.155 (b) and §36.453 require ASR operators to report on the volume of water injected for storage, volume of water recovered for beneficial use, and average injection pressures on a monthly basis. Operators are also required to report on the water quality of injected and recovered water annually as per TWC §27.156 and §36.453 (a)(3).

Recoverability of Water Stored in an ASR Project

The concept of ASR recoverability can be expressed as the ratio of the actual recovered water volume to the injected water volume for projects in both the testing and operational phase. The State of Texas recognizes the “Rule of Capture” basis of Texas groundwater rights and the authority GCDs have to regulate withdrawal of groundwater in their districts (Council and Hannah, 2021). Table 1 highlights statutes and rules that address recoverability and GCDs. TWC statutes are normally associated with one or more TAC rules. For example, one statute

Table 1. ASR Statutes and Rules Highlights in Texas Water Code (TWC) and Texas Administrative Code (TAC)

Key Definition, Standard, or Feature of ASR Regulation	Corresponding TWC Statutory Citation	Corresponding TAC Rule Citation
Definition of ASR injection well	27.151 (2)	331.2 (10)
Definition of ASR project	27.151 (1)	331.2 (9)
Definition of native groundwater	27.151 (4)	331.2 (7)
TCEQ has jurisdiction over permitting and regulation of ASR injection wells	27.152	331.131
TCEQ may authorize Class V injection wells for an ASR project by permit, general permit, or authorization-by-rule	27.153 (a)	331.131 331.185 (b)
In issuing authorization, TCEQ shall consider: Federal Safe Drinking Water Act standards, successful recovery of injected water, effect of the ASR project on existing water wells, and whether the quality of the native groundwater will be changed physically, chemically, or biologically to a harmful degree	27.153 (b)	331.186 (a)
ASR project within a continuous perimeter	27.153 (c)	331.183 (5)
Recoverable amount of injected water for ASR projects in a GCD	27.154 (b)	331.184 (g)
Design, construction, and closure of ASR wells will prevent comingling, mixing, and infiltration	27.154 (c)	331.183
Project operator shall install a meter on each ASR well	27.155 (a)	331.184 (f)
Operator will monitor and report on ASR injection and production well monthly	27.155 (b)	331.185 (a)
Water quality of injected and recovered water tested annually	27.156	331.185 (b)
Project operator will: Register wells with appropriate GCD Report monthly on injected and recovered volumes to district Provide annual water quality reports to district	36.453 (a) (1)-(3)	331.184 (g) 331.185
Project operator will report to district the exceeded volume of recovered water	36.453 (b)	331.184 (g) (2)

is TWC §27.154(b), which applies to ASR projects in a GCD and states that the TCEQ determines the recoverable amount of stored water. The corresponding rule is TAC §331.184(g), which adds that when the volume recovered exceeds the amount TCEQ determines to be recoverable, TWC Chapter 36, Subchapter N applies. The GCD and the ASR operator will handle the reconciliation for the excess recovered water.

With the jurisdiction to determine the recoverable amount of water as shown in TWC §27.154(b), TCEQ needed a basis to determine recoverability that was technically defensible and could be used to verify and validate the estimated recoverability amounts applicants submit. Because each ASR project has different site-specific conditions and each applicant at the time of this white paper has approached the evaluation of recoverability differently, TCEQ focused on evaluating an aquifer's potential to store and transmit water based on site-specific conditions. TCEQ collaborated with Dr. Charles J. Werth and the University of Texas at Austin, Center for Water and the Environment, to develop a simple website-based analytical evaluation tool. This tool is the ASR Applet (Alcalde, 2021), based on the analytical solution of the potential flow equation for a single pumping/injection well in a regional head gradient (Bear and Jacobs, 1965) and assesses the feasibility of water injection, storage, and recovery at that well site. Figures 1 and 2 provide the conceptual diagram for the single-well ASR simulation and a schematic plan view of the injection and recovery comparison, respectively. The ASR Applet has interactive features that allow the user to change the conditions listed to meet their site-specific conditions (Council and Hannah, 2021). Not only is the Applet an important tool for the TCEQ to use, but it also is good for applicants to get an idea of recoverability before going into more modeling and evaluation and before applying for an ASR authorization. Note that this screening tool does not replace the need for more complex numerical models to evaluate recoverability in multi-well heterogeneous ASR situations and to interpret observations at the monitoring wells in an ASR project.

Texas Projects

Two early ASR field experiments occurred near El Paso and Amarillo (Webb, 2015). In 1947, an evaluation of ASR was done in El Paso by the United States Geologic Survey (USGS) and the Texas Board of Water Engineers (TBWE). El Paso was experiencing a decrease in water levels due to pumping and wanted to find a solution to alleviate the problem. The Hueco Bolson Aquifer's ability to recharge, store, and recover treated Rio Grande River source water was evaluated. After data from the study were collected, it was shown that four wells could recharge at a combined rate of six million gallons per day for an indefinite period. The success of these findings led to the conclusion that injecting Rio Grande River source water into the Hueco Bolson Aquifer, storing, and then recovering the source water would stop the decline in water levels (Webb, 2015). Similarly, the City of Amarillo conducted an evaluation of the Ogallala

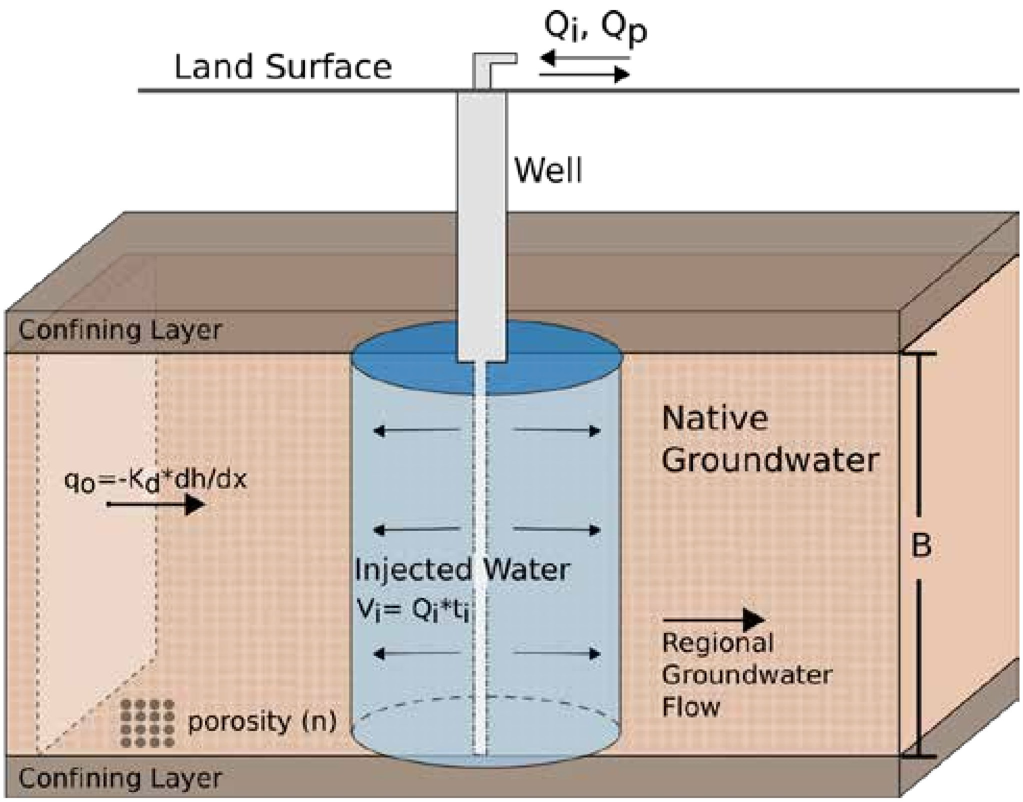

Figure 1. Conceptual Diagram of an ASR System with Homogeneous and Isotropic Properties (Alcalde, 2021)

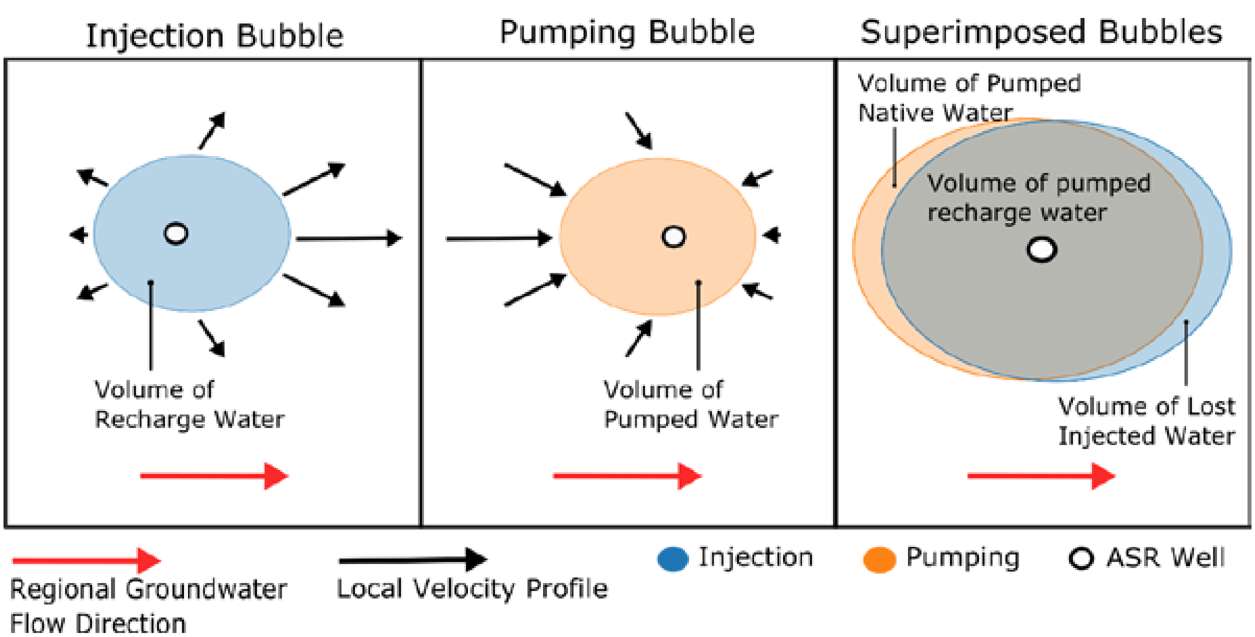

Figure 2. Schematic for Recoverability (Alcalde, 2021)

Aquifer in 1954, using water from the Ogallala Aquifer as the source water. The population of Amarillo was increasing, and the city needed to meet higher peak water demands as a result. The practicality of recharging the Ogallala Aquifer was evaluated, and flow characteristics and recovery efficiency were assessed. As in El Paso's evaluation, the City of Amarillo found no signs of well plugging, and data showed successful recovery and water levels responded as expected. In both cases however, there is no information on follow-up action taken after the evaluations were complete (Webb, 2015).

Currently there are a range of ASR projects in Texas in varying stages of development, from initial planning stages to full operation. Figure 3 below is a TWDB (2021) map of Texas showing ASR and AR projects that are in operation and the initial stages of planning in the state. Table 2 provides more legible lists of the two types of ASR sites as extracted from the smaller boxes in Figure 3. The small box labeled 'Operational ASR & AR' lists projects that are currently operational and where they fall on the map. Operational ASR projects include San Antonio Water System (SAWS), Ruby Ranch Water Supply Corporation, and the City of Kerrville. These projects are in Central and South-Central Texas, which is where there is a cluster of projects on the map. The Central/South-Central area of Texas is a suitable location for ASR projects because the geologic formations are well-suited for ASR projects, and the rapidly growing populations in this area need ever-increasing water supplies. The El Paso Water Utilities project began as an injection well-based ASR model but shifted later to spreading basins for water addition due to injection well failures. Strictly speaking, the spreading basin approach fits with AR rather than ASR, but some refer to the project as 'hybrid' because of past and possible future use of injection wells. The box labeled 'ASR & AR projects' lists projects in their initial or planning stages. ASR projects in this category include the cities of Bryan, Buda, New Braunfels, and Victoria. A discussion of six individual projects, both in the initial and operational stages, is provided in this section. The TCEQ ASR project files that were reviewed for this white paper were for the City of Bryan, City of Buda, City of Kerrville, City of Victoria, Ruby Ranch WSC, and SAWS.

The City of Kerrville ASR project has been fully operational since 1999 and is the longest-operating ASR project in Texas. Located in Kerr County, the project injects treated surface water from the Guadalupe River into the Hosston-Sligo Formation of the Lower Trinity Aquifer for storage. The Hosston-Sligo Formation is confined by the Pine Island Shale above

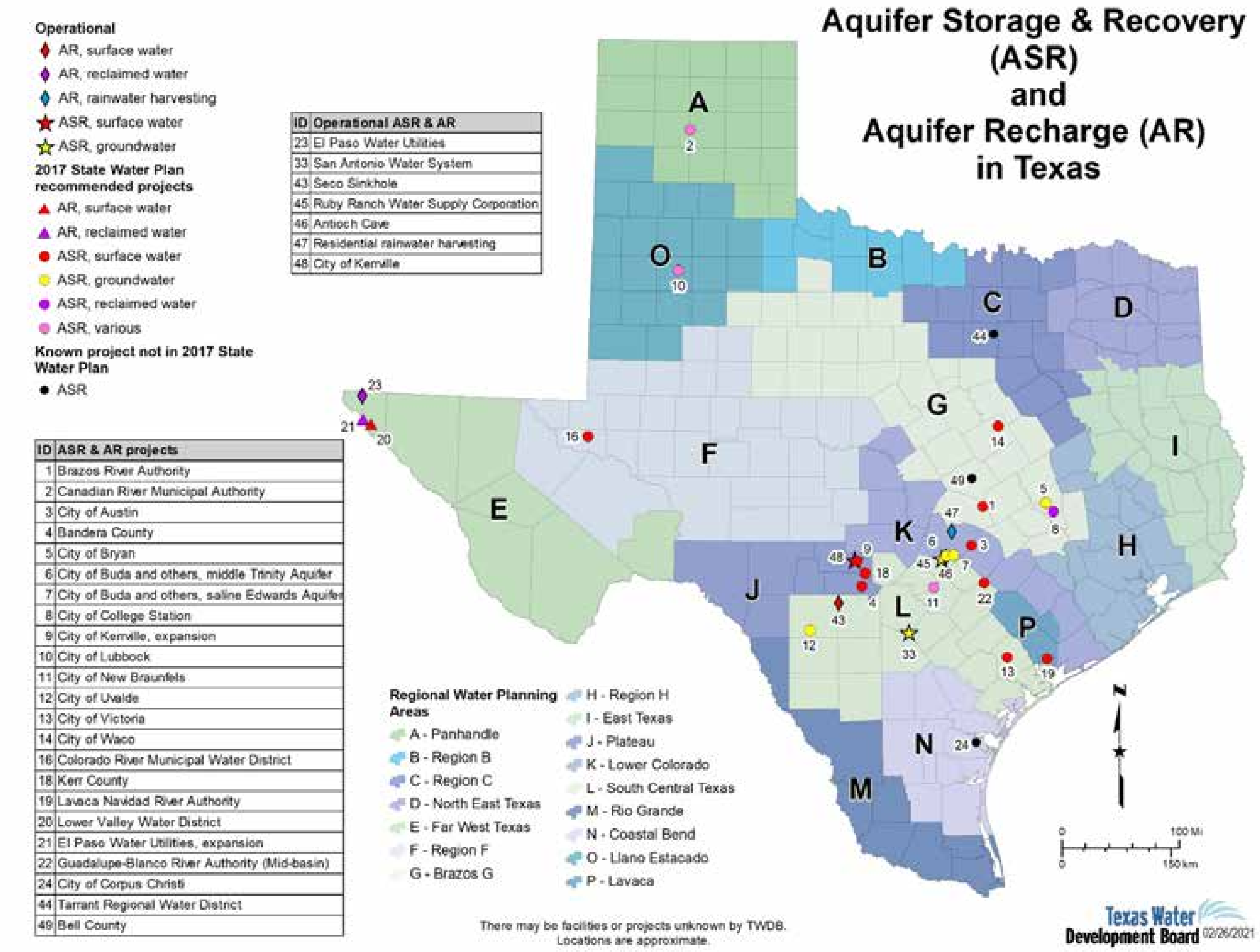

Figure 3. ASR and AR Texas Project Map (TWDB. 2021)

Table 2. ASR Projects Extracted from Figure 3 List

Type	ID	Site
Operational	33	San Antonio Water System
	45	Ruby Ranch Water Supply Corporation
	48	City of Kerrville
	23	El Paso Water Utilities (hybrid)
Proposed	1	Brazos River Authority
	2	Canadian River Municipal Water Authority
	3	City of Austin
	4	Bandera County
	5	City of Bryan
	6	City of Buda and others, middle Trinity Aquifer
	7	City of Buda and others, saline Edwards Aquifer
	8	City of College Station
	9	City of Kerrville, expansion
	10	City of Lubbock
	11	City of New Braunfels
	12	City of Uvalde
	13	City of Victoria
	14	City of Waco
	16	Colorado River Municipal Water District
	18	Kerr County
	19	Lavaca Navidad River Authority
	22	Guadalupe-Blanco River Authority (Mid-basin)
	24	City of Corpus Christi
	44	Tarrant Regional Water District
	49	Bell County
	na	Barton Springs Edwards Aquifer Conservation District
	na	Laredo
	na	Brownsville Public Utility Board
	na	El Paso Water Utilities (hybrid)

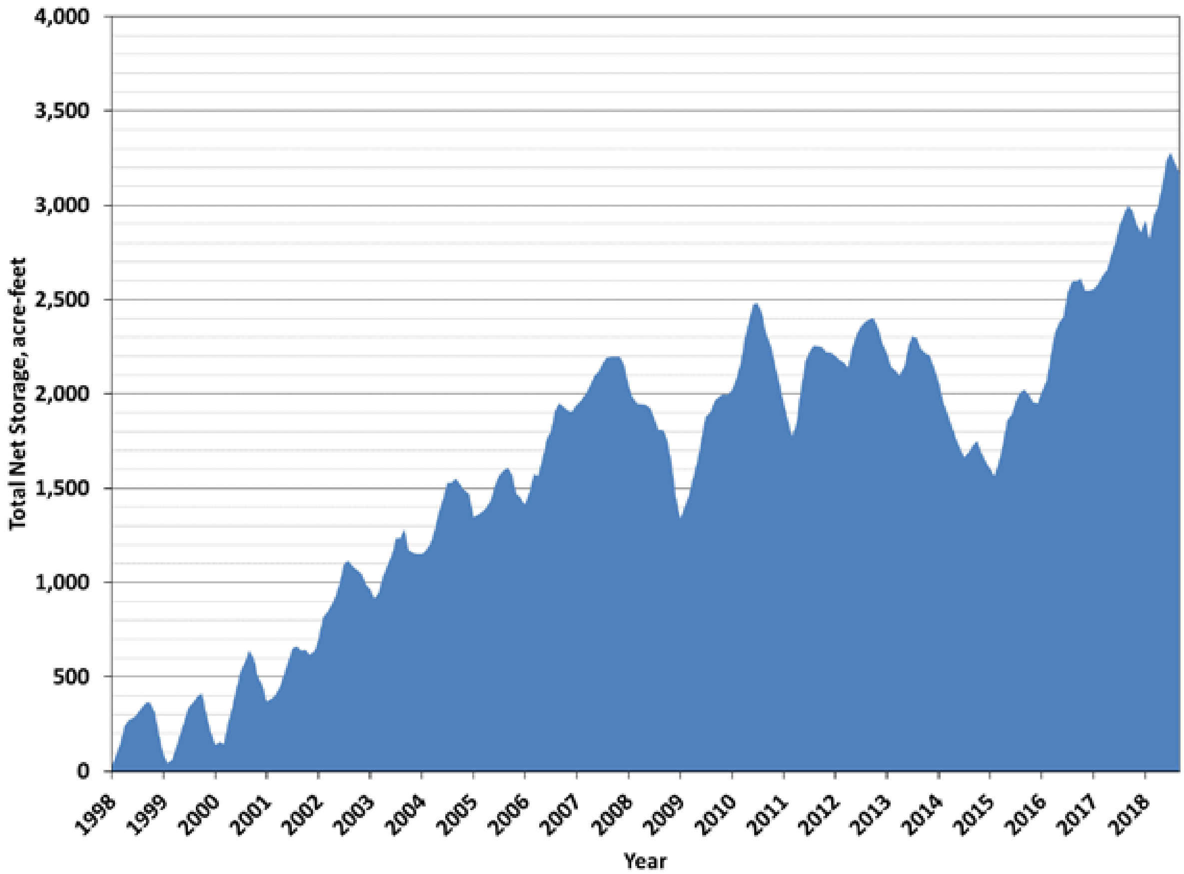

Figure 4. City of Kerrville Volume in Storage

and pre-Cretaceous rock formations below. The City of Kerrville has four authorized ASR wells that are all in use and inject 1.08 million gallons per day (MGD) on average into storage. The recovered water is used to meet peak water demands in the city. Figure 4 is an ASR volume curve that shows the amount of volume in storage from 1998-2020.

Kerrville is in the Headwaters GCD, and this district does not have rules on ASR or plans to establish rules. For that reason, the city and GCD have an informal agreement that the city reports the cumulative net stored water to the District. Any recovered water above the authorized amount is counted against Kerrville's existing groundwater production permits. This example shows a city and GCD working together for the success of an ASR project and for the benefit of the community.

The SAWS fully operational ASR project is in Wilson County and was authorized on October 9, 2001, making it one of the longest currently operating projects in Texas. The SAWS H2Oaks Facility injects excess groundwater from its water rights in the Edwards Aquifer into the

Carrizo Aquifer for storage. The Carrizo Aquifer is confined by the Reklaw Formation above and the Midway Group below. The recovered water is used to meet peak seasonal demands and reduces the demand on the Edwards Aquifer. SAWS has installed 29 ASR wells and is authorized to inject 60 MGD while recovering up to 228 million gallons per month.

Figure 5 shows the volume of water in storage for the SAWS ASR project for the years 2004 to May 2022. The volume of stored water has continued to increase over time, currently over 198,000 acre-feet. For comparison, the annual volume of water used by the City of San Antonio is approximately 180,000 acre-feet or 59 billion gallons.

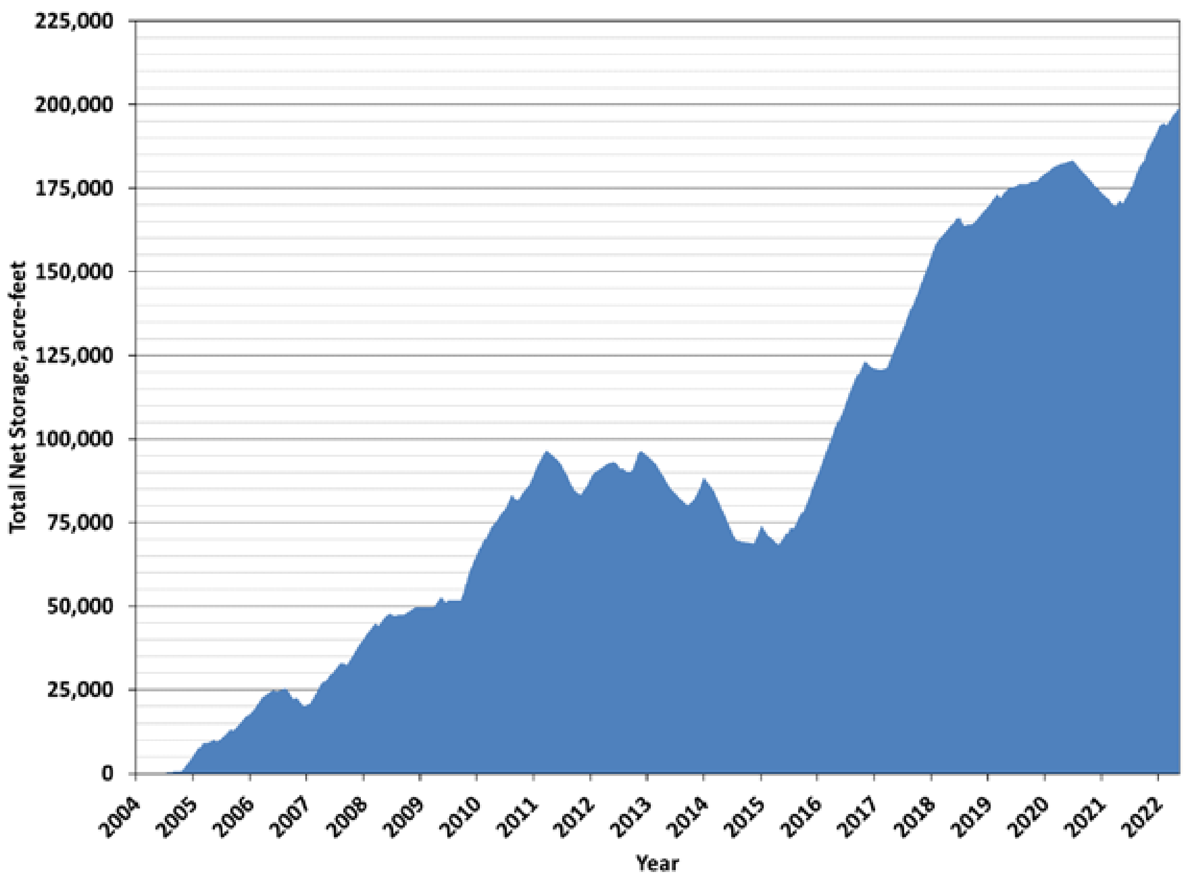

Figure 5. SAWS Volume in Storage

The City of Victoria's experimental ASR project is unique as one of the first projects to convert an existing groundwater production well to an ASR well. The Victoria demonstration project should provide useful information to other operators who want to convert a production well into an ASR well. For example, when the City staff selected Well No. 19 to retrofit, they were unaware of the deteriorated condition of the well. The well had been planned for normal maintenance, including pump and motor replacement. Despite this issue, the retrofit was successful. The City of Victoria project shows the importance of investigating and gathering sufficient information before selecting a well to retrofit. Treated water from the City of Victoria's distribution system is injected into the Gulf Coast Aquifer until the recovery phase of this demonstration project (Arcadis & ASR Systems, 2019). At the time of this white paper, the City of Victoria is running cycle tests and has received authorization to run the cycle tests through June 2023.

The City of Bryan in Brazos County was authorized in 2019 to also retrofit an existing production well into an ASR well. In 2021, the city was concluding the cycle testing phase of the project, which included injecting groundwater from one location in the Simsboro Aquifer into a different portion of the Simsboro. The cumulative volume of injected water was about 345 million gallons. By the end of the last cycle test it was estimated that 50 percent of the cumulative injected water would be recovered. The recovered injected water will be used for municipal water supply. As of the date of this white paper, the City of Bryan is moving forward with the next stages of the ASR project.

The City of Buda, located in Hays County, was authorized in 2019 for an ASR project, which was in the initial stages at the time this white paper was prepared. One authorized ASR well injects groundwater from the city's Edwards Aquifer water rights into the underlying Trinity/Cow Creek Formation. The Cow Creek Formation is confined by the Hensell Formation above and by the Hammett Shale below. As part of the initial phase of ASR operation, water will be injected at a rate of 260 gallons per minute (gpm) and stored for five years. Water will then be recovered at a rate of 340 gpm, and the total recoverable amount is estimated to be 90 percent of the total injected volume. Recovered water will be used to meet high water demands of the city during times of drought.

The Ruby Ranch Water Supply Company (RRWSC) has an operational ASR project also located in Hays County. The source is Edwards Aquifer groundwater, and 15 million gallons were injected into the Cow Creek Formation, with 12.3 million gallons later recovered over the period of one year. The RRWSC is within the Barton Springs Edwards Aquifer Conservation District (BSEACD), and should an excess of water be recovered, RRWSC must report that volume to the BSEACD as the TWC chapter 36 subchapter N requires (Table 1). Initially, RRWSC had an experimental well authorization to do cycle testing, later obtained an ASR authorization to operate on February 18, 2020, and continues to operate today.

Lessons Learned from Existing Projects

Bloetscher et al. (2014) compiled extensive survey and analyses of available information from 204 active and inactive ASR sites across the United States. The data included construction and operational details. These researchers chose to emphasize the lessons learned that led to the eventual termination of the 53 inactive sites. Figure 6 shows the distribution of inactive sites by state. The following conditions typically led to the unsatisfactory performance of the ASR systems.

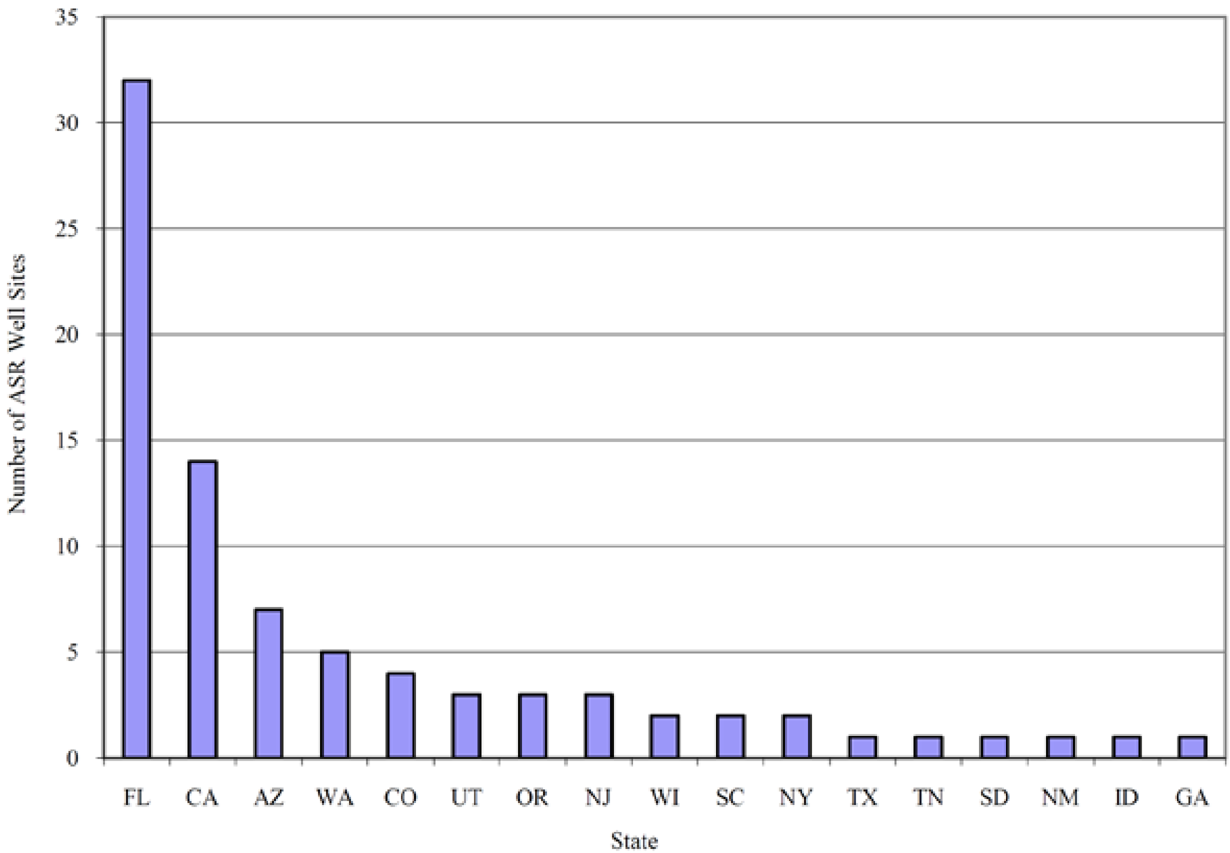

Figure 6. Inactive ASR Sites by State (Bloetscher et al. 2014)

Well clogging was noted at 29 of the inactive sites, and as the primary reason for well failure at 11 sites. Common factors were steel casings and surface source water that encourages particulate clogging and biofouling. Even with low total suspended solids concentrations, high injection rates can disturb silt and clay colloids in alluvial receiving formations as well as cause air entrainment. Chemical clogging is caused by interactions between the injected water constituents and the groundwater and minerals within the receiving aquifer. High sodium waters can hydrate and swell clays in alluvial formations. Microbiological fouling can incrust or corrode well casings and screen, as well as submersible pumps and motors. Mitigation strategies included periodic redevelopment, acidizing, and maintaining a chlorine residual in the injected water.

Presence of chlorine residual in the injected water in the presence of organics can cause formation of disinfection by-products (DBPs) such as haloacetic acids (HAAs) and trihalomethanes (THMs). The DBPs can be seen as introduced contaminants, and this issue led to termination of ASR projects in California and Washington. As of Bloetscher et al. (2014), some researchers had noted attenuation of the DBPs in the injected aquifer due to microbial activity, and minimal formation of DBPs was noted in the aquifers.

Seventeen of the inactive sites experienced water quality deterioration. Constituents of concern included radon, iron, mercury, arsenic, nickel, copper, cobalt, zinc, manganese, and other natural chemicals. When injected, oxygen-rich surface water can shift oxidation-reduction processes that mobilize trace metals from their solid mineral matrices. Overcoming these problems requires careful analyses of the aquifer sediments as well as laboratory and modeling experiments to predict potential interactions.

Inability to recover sufficient volumes of injected water was noted as a reason for abandonment at 20 sites. It is unclear how the acceptable amount of recoverable water was established, and how that recoverable amount was determined within the range of injection and production flow rates tested at the sites. Some clients may have expected the ASR systems to be quickly operational at high capacity and were disappointed by delays. Limitations in actual available storage volume capacity can be caused by presence or absence of upper confining beds to control the migration of the injected water. Operators are also challenged when injecting fresh water into a brackish aquifer, as density differences can cause a “bubble” of fresh water with a mixing zone around the interface with the brackish water. Finally, as seen in the Bryan and Victoria projects in Texas, conversion of existing groundwater production wells into ASR wells may save some capital costs, but the older wells may have lower injection or production capacities when put into ASR operation.

Geochemistry Issues Specific to Texas

Native groundwater is defined as groundwater naturally occurring in a geologic formation (TWC §27.151 (4)). Important site-specific conditions of ASR sites include the local hydrogeology, mineralogy, and geochemistry of the target storage zone, intended site operation, and the source water quality. These factors need to be thoroughly evaluated before beginning an ASR project as they control potential geochemical reactions, such as mobilization of naturally occurring contaminants including metals like arsenic (Fakhreddine et al., 2021), iron, and manganese. According to 30 TAC §331.186, TCEQ must consider whether the injection of water into the geologic formation will change the physical, chemical, or biological quality of the native groundwater. A shift in geochemical conditions resulting in metals mobilization can degrade water quality for human and ecosystem health. Additionally, mobilization of common metals like iron or manganese can also cause operational issues including well biofouling and formation plugging. Arsenic is a particular contaminant of concern at ASR sites owing to its ubiquity in soils and sediments globally and its toxicity at trace concentrations. The drinking water maximum contaminant level (MCL) for arsenic is 10 parts per billion (ppb) (Werth et al., 2021), which is very low. ASR projects can mobilize arsenic by shifting geochemical conditions including injecting oxygen-rich water into an anoxic aquifer, which can trigger reactions with arsenic and key aquifer minerals (e.g., sulfidic minerals like pyrite) (Bloetscher et al., 2014).

To address the potential for ASR projects to experience geochemical reactions that mobilize arsenic, the TCEQ contracted with the University of Texas Center for Water and the Environment (Werth et al., 2021) and the University of Texas Bureau of Economic Geology (Fakhreddine et al., 2021) to develop guidance for ASR operators. Both guidance documents are available on the Class V Injection Wells Regulated by the TCEQ web page (https://www.tceq.texas.gov/permitting/radmat/uic_permits/UIC_Guidance_Class_5.html). A summary of their work is provided in the paragraphs below. The guidance documents provide an overview of proposed strategies to prevent or limit arsenic mobilization during ASR. It is important to note that the efficacy of arsenic mitigation strategies depends on several site-specific conditions and requires mechanistic geochemical studies. Potential strategies to prevent arsenic mobilization are summarized herein.

First, the injected water can be treated and modified to be geochemically compatible with the native groundwater prior to being pumped into the storage zone. One pretreatment strategy is deoxygenation, which removes dissolved oxygen and other oxidants (e.g., nitrate, hydrogen peroxide, residual disinfectants) from the source water to limit the geochemical shifts that occur when source water is injected into an anoxic aquifer. Another pretreatment approach is the removal of organic carbon because organic carbon can promote microbially mediated reactions that can negatively impact water quality, including potentially releasing iron, manganese, arsenic, and other metals.

Physical approaches to mitigating arsenic release involve developing and maintaining a buffer zone. When water is injected into an aquifer, geochemical reactions can occur between the stored water and the aquifer solids. Additionally, there will be some mixing between the native groundwater and injected water as the injected water pushes out the native groundwater. Where this mixing occurs is referred to as the buffer zone. The following is a methodology that ASR operators in Florida have proposed to develop an ASR buffer zone. First, a small volume of water is injected, and that amount is recovered during cycle testing. Then, the volume of water injected is increased over multiple cycles. The aquifer is thus conditioned and has lower levels of arsenic in the storage zone. As arsenic mobilization can occur in the buffer zone, maintaining the buffer zone can help prevent the recovery of contaminated water. Figure 7 below is a visual example of ASR injection and recovery (Bloetscher et al., 2014). On the left side of the figure, water is being injected into the formation and on the right side, water is being recovered from the formation. The injected water is represented by a tan color, the buffer (or mixing) zone is a dark green color, and the native groundwater is a lighter green color. Figure 7 shows that the buffer zone keeps the injected water and native groundwater separated throughout the injection and recovery phases. Guidelines for maintaining a buffer zone have been developed based on operator experience and require further geochemical studies to understand their efficacy and transferability to various ASR sites.

Other factors that can influence arsenic mobilization, in addition to geochemistry and formation mineralogy, are injection and recovery volumes, pumping rates, and the phases of the ASR project operation. For this reason, modifying the operational controls is a mitigation strategy that can be done to decrease or increase the velocity at which the water moves through the pores in the geologic formation, referred to as porewater velocities. However, these

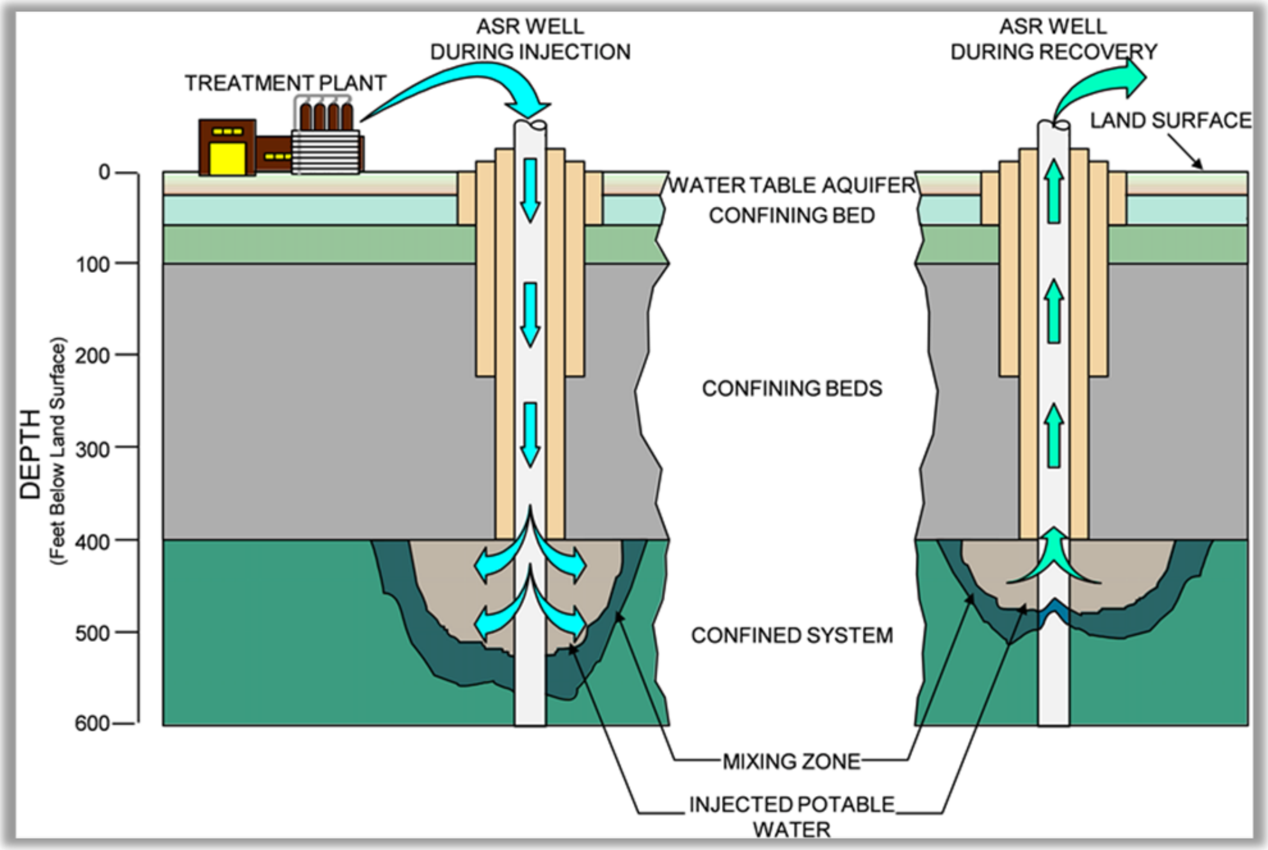

Figure 7. ASR Injection and Recovery (Bloetscher et al., 2014)

approaches have not been studied for their ability to limit arsenic mobilization and require further evaluation (Fakhreddine et al., 2021). An ASR project in Texas recently implemented an operational control strategy. During RRWSC's pilot study, the potential for elevated arsenic concentrations was identified. To mitigate this problem, a water-level transducer/sensor was installed on the well along with a submersible variable frequency drive (VFD) on the motor/pump from which the source water originates. This sensor alerts the operator if the water level in the well corresponds to withdrawal of water with arsenic above the MCL, and then the VFD can control the motor speed. These operational controls help ensure that the level of arsenic in the source water would not exceed the MCL.

ASR Siting

Before constructing an ASR project, extensive work should be done to establish a good geologic description of subsurface conditions. Having good baseline data is important because if an unexpected geochemical, operational, or formation issue occurs during the project, baseline data are needed to determine the magnitude of the induced impacts and help direct possible mitigation strategies. Every ASR project site is different, and specific geologic, geochemical, and operational aspects should be taken into consideration when planning and designing a project. Observed data can be combined with appropriate groundwater flow and solute transport models to determine strategies to mitigate water quality issues and keep the project moving forward.

Public Understanding

It is important that citizens and stakeholders understand exactly what an ASR project entails. The key motivations, challenges, costs, and benefits of an ASR project must be clearly presented and documented. Emphasizing the importance of ASR as a water management technique and the previous successes of projects in the United States and around the world can generate public support for local applications that will provide local benefits.

Conclusion

Aquifer storage and recovery projects have been successful around the world, including here in Texas. Each ASR project has site-specific concerns that can and must be addressed. For example, metals mobilization, well clogging, and retrofitting existing production wells into ASR injection wells are some challenges that have occurred in ASR projects in the state. However, there are strategies to mitigate these problems, allowing projects to move forward. Increasing population levels across Texas are increasing water demands. Texas also experiences drought, so wise management of water supplies to meet those demands is also needed. A major benefit of an ASR project is protection of the stored water from evaporation losses, so that during times of drought that water is available to meet the drinking, agricultural, and/or industrial demands of the area. The positive potential of ASR for present and future water storage in Texas is reflected in the large number of proposed water management strategies that include ASR in the 2022 State Water Plan (TWDB 2022) as shown in Table 3. The projects can benefit six different categories of Water User Groups (WUGs), not just municipalities.

Table 3. ASR Proposed Projects in 2022 State Water Plan

WUG Category	Number
Municipal	166
Steam-electric	7
Irrigation	5
Manufacturing	10
Mining	4
Total	192

Continuing Research Needs

With multiple ASR projects in long-term operation or currently coming on-line, we must take full advantage of their experiences to benefit other potential ASR projects. The following technical research needs should be pursued.

- Similar to Bloetscher et al. (2014), survey and compile useful data across the Texas ASR projects to correlate ASR success with site hydrogeologic and operational characteristics
- Clearly describe which Texas ASR projects and or wells have been abandoned and why
- Support and conduct research into metals mobilization and mitigation strategies during ASR operations
- Identify and collect samples from aquifer formations with smectite or montmorillonite clays that could have geochemical reactions with injected water, thus causing the clays to swell and reduce the formation porosity and permeability

Recommendations or Policy Options

The Texas Legislature and the TCEQ have made significant progress in updating the statutes and rules associated with ASR projects. These efforts can be strengthened through consideration and implementation of the following recommendations.

- Require an evaluation of the geochemical interactions between the source water and the receiving aquifer water in ASR projects, including metals mobilization studies and the compatibility of injected and recovered waters with existing water treatment regulations and distribution systems

- Require the use of monitoring wells to help evaluate the subsurface effects of ASR stored water placement on injection zone water quality and on other nearby water wells
- Review the required monitoring and reporting for existing ASR projects with the goal of using these data to help improve ASR system performance
- Require ASR projects associated with public water systems to coordinate with the TCEQ Water Supply Division during the ASR project design and permit application process

TGPC GWI Subcommittee members include, but are not limited to:

- Texas Commission of Environmental Quality (TCEQ);
- Texas Water Development Board (TWDB);
- Railroad Commission of Texas (RRC);
- Texas Department of State Health Services (DSHS);
- Texas Department of Agriculture (TDA);
- Texas State Soil and Water Conservation Board (TSSWCB);
- Texas Alliance of Groundwater Districts (TAGD);
- Texas A&M AgriLife Research (AgriLife Research);
- Bureau of Economic Geology of The University of Texas at Austin (UTBEG);
- Texas Department of Licensing and Regulation (TDLR);
- Texas Parks and Wildlife Department (TPWD);
- Texas Tech University (TTU);
- Texas A&M AgriLife Extension Service (AgriLife Extension); and,
- United States Geological Survey (USGS).

The primary goals of the TGPC GWI Subcommittee are to:

- Facilitate interagency communication for assessment programs addressing groundwater contamination;
- Coordinate and assist member agencies with monitoring programs for:
  - Ambient groundwater conditions;
  - Pesticides; and,
  - Emerging contaminants or constituents of concern;
- Support the intent of the *Texas Groundwater Protection Strategy* (https://www.tceq.texas.gov/downloads/groundwater/publications/as-188-texas-groundwater-protection-strategy.pdf) by:
  - Reviewing published data reports, and evaluating data independent of published reports, to assist in the determination of the effectiveness of existing regulatory programs and to identify potential groundwater contaminants not addressed by existing regulatory programs;
  - Developing recommendations for consideration by the TGPC to address potential groundwater contamination identified through monitoring and data review; and,
  - Developing white papers on the groundwater issues listed in their biannual *Activity Plan* which summarize the best available scientific data on a specific groundwater issue, identify areas where there is insufficient scientific data to thoroughly assess the issue, evaluate the effectiveness of existing regulatory programs to address the issue, and provide recommendations or policy options to the TGPC regarding the issue.

The above recommendations or policy options represent the opinion of the TGPC GWI Subcommittee and do not necessarily reflect the views and policies of each participating organization. The United States Geological Survey (USGS) may have contributed scientific information, only.

For more information about this white paper, please contact the TGPC (https://tgpc.texas.gov/contact-us/).

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