



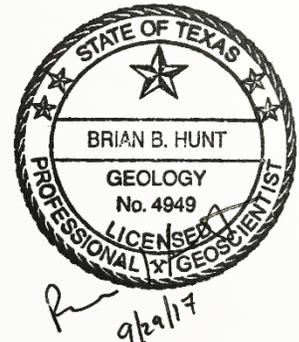
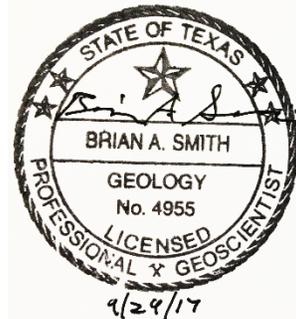
*Technical Note 2017-0930
September 2017*

Status Report for Aquifer Storage and Recovery Pilot Project: Ruby Ranch Water Supply Corporation, Hays County, Central Texas

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Summary

The Ruby Ranch Water Supply Corporation (RRWSC) and the Barton Springs/Edwards Aquifer Conservation District (District) cooperated on a project to test the Middle Trinity Aquifer as a reservoir for storage and recovery of fresh Edwards Aquifer groundwater. In March 2017, the Texas Commission on Environmental Quality (TCEQ) granted permission to conduct an ASR pilot project (Ruby Ranch’s Class V UIC authorization no. 5X2500126). The pilot project consists of multi-step tests with increasing volumes of injected water in each successive step predicated upon successful results at each step. This report serves as a status report for the project at the completion of two phases of testing and prior to an anticipated third phase.

Phase 1 occurred in April 2017 with an injection of 50,000 gallons of Edwards Aquifer groundwater into the Middle Trinity (Cow Creek Formation) Aquifer. Subsequent extraction from the Middle Trinity totaled 83,700 gallons. Phase 2 occurred in May 2017 with an injection of 280,632 gallons of Edwards Aquifer groundwater into the Middle Trinity Aquifer. Subsequent extraction from the Middle Trinity in May and June 2017 totaled 381,000 gallons. Water levels, field parameters, and lab analyses were collected during the test.

From the results of the two steps of injection and extraction, it was clear that the Middle Trinity Aquifer is capable of receiving the injected Edwards water at the planned flow rates and of storing the injected Edwards water for an indefinite period of time. The chemistry of the two mixed waters also appears to be compatible as the quality of the extracted water met primary drinking water standards of TCEQ and the U.S. Environmental Protection Agency during pilot testing. Analyses for arsenic in the extracted water show that mobilization of arsenic is minimal, given conditions under which the Phase 1 and Phase 2 recovery tests were conducted.

Phase 3 of the testing is planned to begin in October 2017 and continue through May 2018, and to increase the volume of injection and the duration of storage.

Introduction

The Ruby Ranch Water Supply Corporation (RRWSC) and the Barton Springs/Edwards Aquifer Conservation District (District) have cooperated on a project to test the Middle Trinity Aquifer as a reservoir for storage and recovery of fresh Edwards Aquifer groundwater. RRWSC must blend its Edwards and Trinity water to satisfy quality standards and could use additional permitted Edwards water. By injecting fresh Edwards water that can be permitted by the District when there is no District-declared drought, RRWSC can have a greater quantity of water available for summer-time usage by their customers.

The District has been working within its statutory authority and regulatory purview to find ways to reduce dependence on the Barton Springs segment of the Edwards Aquifer. One potential source of water is fresh Edwards groundwater pumped during non-drought conditions and stored in an aquifer storage and recovery (ASR) system using the Middle and Lower Trinity Aquifers as the receiving formations or “reservoirs”.

An analysis by the District in 2004 of available Edwards Aquifer groundwater indicated that under extreme drought conditions and high rates of pumping, flow from Barton Springs could decrease to the point that the endangered salamanders would not survive and that close to 20% of the water-supply wells in the District could go dry. It was also determined that under non-drought conditions, additional groundwater production could be permitted; however pumpage under those permits would not be available under District-declared drought. The District’s permitting structure allows continued permitting of interruptible pumpage within the all-conditions Modeled Available Groundwater (MAG) of 16 cubic feet per second (cfs) through the issuance of Conditional Production Permits. The District has four classes of conditional permits (Class, A, B, C, and D) with each class having progressively more restrictive conditions and curtailment requirements. The most restrictive class, Class D, requires 100% curtailment upon the declaration of Stage II Alarm Drought, but more importantly, it is only available for groundwater production from wells associated with ASR projects where stored water is recovered and used to supplement or substitute freshwater Edwards Aquifer supplies during District-declared drought (District Rule 3-1.24.F). However, the rule is most notable as an indicator of the District’s deliberate efforts to implement policies to accommodate such projects when it provides potential drought relief to the over-allocated freshwater Edwards Aquifer.

RRWSC applied to the Texas Commission on Environmental Quality (TCEQ) for permission to conduct an ASR test, and on March 16, 2017 they received a letter from TCEQ giving approval for the test (Ruby Ranch’s Class V UIC authorization no. 5X2500126; **Appendix A**).

Setting

The test site is located in the RRWSC service area and Ruby Ranch subdivision within the District. The supply well and source of injection water is from the RRWSC#4 well completed in the Edwards Aquifer. The injection and extraction well is the RRWSC#5 completed in the underlying Middle Trinity aquifer about 120 feet from the source water well (**Figure 1**).

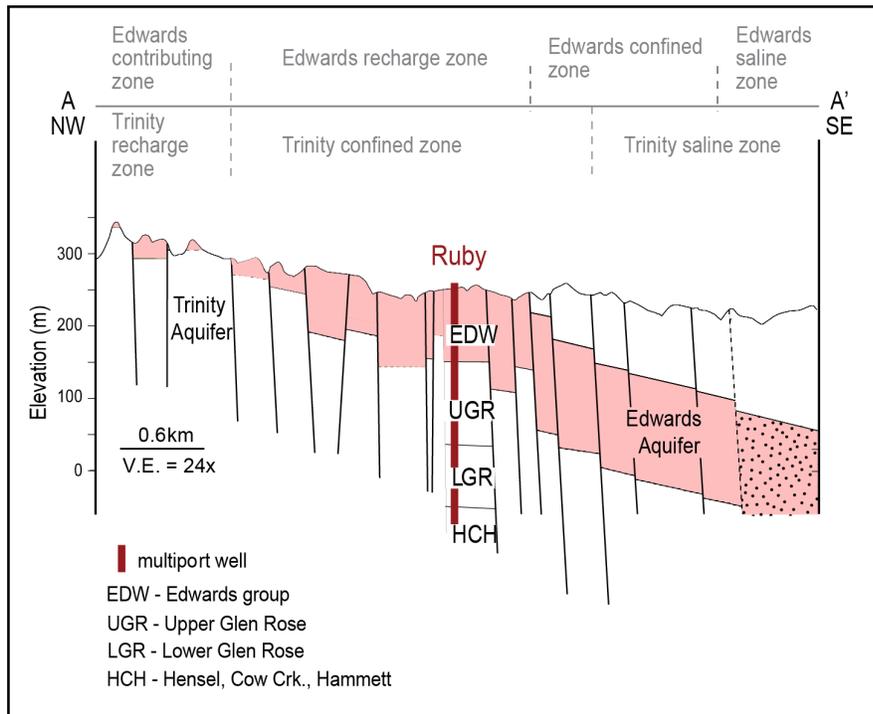
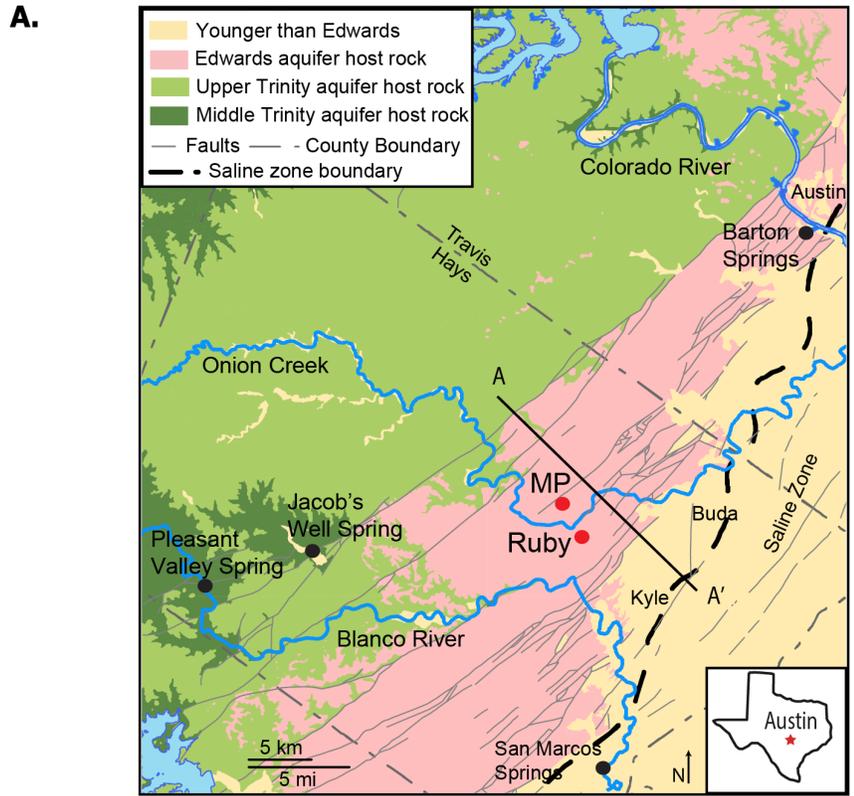


Figure 1. Regional location map (A) and cross section (B) of the Edwards and Trinity Aquifers in the study area. Ruby symbol denotes Ruby ASR test well (RRWSC#5). MP symbol represents the District's multiport monitor well. Figure modified from Wong et al., 2014.

Hydrogeology

The test area is located within the recharge zone of the Edwards Aquifer. The Edwards Aquifer is a prolific karst aquifer system consisting largely of limestone and dolomite (**Figures 1 and 2**). Recent studies (Wong et al., 2014) indicate that the upper portions of the Upper Glen Rose are in hydrologic communication with the overlying Edwards Group units. For regulatory purposes, the Edwards Aquifer in the study area is composed of the Edwards Group and the upper-most 150 ft of the Upper Glen Rose. The RRWSC#4 Edwards well was drilled in 2001 to a depth of 405 feet and is completed within the Edwards Group and Upper Glen Rose (**Figure 3**).

The Trinity Aquifer is composed of the Trinity Group geologic units divided into three general hydrostratigraphic units: the Upper, Middle, and Lower Trinity Aquifers. The focus of this testing is upon the Middle Trinity Aquifer, and specifically the Cow Creek Formation of the Middle Trinity. The RRWSC#5 well is completed in the Cow Creek unit of the Middle Trinity Aquifer. The well has a total depth of 1,140 ft (**Figure 3**) with open-hole completion to only the Cow Creek Formation. Below is a brief description of the units that make up the Trinity Aquifer units. The reader is referred Wierman et al., 2010 for more information.

The Middle Trinity Aquifer within the study area is hydrologically isolated from the overlying Edwards Aquifer due to the presence of aquitard units within the lower Upper Glen Rose and also with upper Lower Glen Rose (Smith et al., 2013; Wong et al., 2014; Hunt et al., 2016). The Middle Trinity Aquifer consists of the lowermost Lower Glen Rose, Hensel, and Cow Creek formations (**Figure 3**).

The Lower Glen Rose is generally composed of reef and skeletal grain limestones and generally supplies fresh water to wells in the Hill Country. Biostromes and reef facies of the Lower Glen Rose are important water-bearing units locally, with variable water quantity and quality. The Hensel formation in the study area is about 40 ft thick and is dominantly silty shale and dolomite deposited in a marine environment. The Hensel is not an aquifer and instead acts as a semi-confining layer over the Cow Creek in the study area (Wierman et al., 2010).

The Cow Creek Formation is the target hydrogeologic unit of the ASR testing in this study. The Cow Creek is composed of a grain-skeletal limestone, over a fine-grained oyster wackestone to dolomite. The Cow Creek is very porous and permeable and is the primary water-bearing unit within the Middle Trinity Aquifer. The formation was subaerially exposed and subjected to meteoric water infiltration during early Hensel time (Loucks, 1977). Consequently, early diagenesis of the limestone created vuggy porosity. The underlying fine crystalline dolomite has well-developed porosity and both carbonates produce water in the Hill Country.

The Hammett Shale underlies the Cow Creek and is a highly plastic shale. The Hammett Shale is the regional confining unit separating the Middle Trinity Aquifer from the Lower Trinity Aquifer.

Structure

The study area is within the Balcones Fault Zone (BFZ), a zone of en-echelon normal faulting with throws generally down to the southeast. Although faults occur in the study area, no major faults (>100 ft throw) are known in the vicinity of the test area (**Figure 2**). The structural gradient in the study area is about 120 ft/mi. The thickness of the Cow Creek in the study area averages about 75 ft (Wierman et al., 2010). Relay ramps are an important structural style in the BFZ and provide aquifer continuity between and across faults (Collins and Hovorka, 1997; Hunt et al., 2015).

Middle Trinity (Cow Creek) Aquifer Parameters

An aquifer test was conducted on the Ruby Ranch #5 (Cow Creek) in support of a pumping permit application to the District (Geos, 2011; **Appendix B**). Data from this report and the Ruby Ranch multiport monitor well (Hunt et al., 2016), provides the best information about the aquifer parameters of the Middle Trinity in the study area. The aquifer test results for the Cow Creek are comparable to other Middle Trinity wells (Hunt et al., 2010). Below are hydraulic parameters from the Ruby Ranch #5 well (Geos, 2011):

- Well yield about 220 gpm
- Specific capacity of 1.3 gpd/ft
- Transmissivity 4,600 gpd/ft (615 ft²/d) median
- Storativity 6.0E-5

Water Levels

In the study area, the water levels (head) of the unconfined Edwards Aquifer are higher than those in the Middle Trinity Aquifer. However, recent studies have shown the presence of aquitard units within the Upper and Lower Glen Rose formations inhibit vertical flow from the Edwards and Middle Trinity (and visa versa), despite the vertical head gradients (Smith et al., 2013; Wong et al., 2014; Hunt et al., 2016).

Depths to water of the Middle Trinity Aquifer in the study area vary according to hydrologic conditions and the location of the well. In the study area the depth to water in the Middle Trinity at the Ruby Ranch multiport well vary about 40 feet from 195 to 156 ft depth to water (620 to 660 ft-msl). Static depths to water in the RRWSC#4 Edwards Aquifer and RRWSC#5 Middle Trinity wells were about 135 and 200 ft, respectively, during the testing.

Recharge and Groundwater Flow

The Middle Trinity units are exposed at the surface about 12 miles to the west of the study area, and receive recharge from rainfall on the outcrop and losing streams (Mace et al., 2000). The direction of groundwater flow is generally down the structural dip of the geologic units to the southeast. **Figure 2** illustrates the general direction of flow from a 2009 potentiometric surface map (Hunt and Smith, 2010). The hydrologic gradients are about 40 ft/mi in the study area (Wierman et al., 2010).

A simple calculation of average linear velocity using Driscoll (1986) is described below, where:

Average linear velocity = (Hydraulic conductivity, K * hydraulic gradient, i) / porosity

K = 8.2 ft/d

i = 40 ft/mile or 0.008

Porosity = 20% or 0.2

Based on these assumptions, the velocity is estimated at about 0.3 ft/day. The low values of tritium (³H) and carbon-14 (radiocarbon or ¹⁴C) sampled in the Ruby Ranch #5 support the estimated relatively slow flow velocities. The related matter of the age of groundwater is being addressed in a separate geochemical investigation involving the interpretation of ¹⁴C and ³H isotopes from more than 100 wells (including multiport wells) and sources of surface water in central Texas. ¹⁴C and ³H are widely used in studies of groundwater age because they are naturally occurring radionuclides with very different half-lives (5730 years for ¹⁴C and 12.43 years for ³H). Interpretations are not straightforward, owing to post-recharge processes that affect the measurement of ¹⁴C and ³H in groundwater. With respect to water wells, the ¹⁴C

and ^3H data cover the Edwards Aquifer and the Upper, Middle, and Lower Trinity Aquifers. Interpretations of the data will offer greater insight into the range of groundwater ages in each aquifer. This will help to refine conceptual models of recharge throughout the area, as well as address questions related to potential interaction of surface water and groundwater as well as inter-aquifer communication.

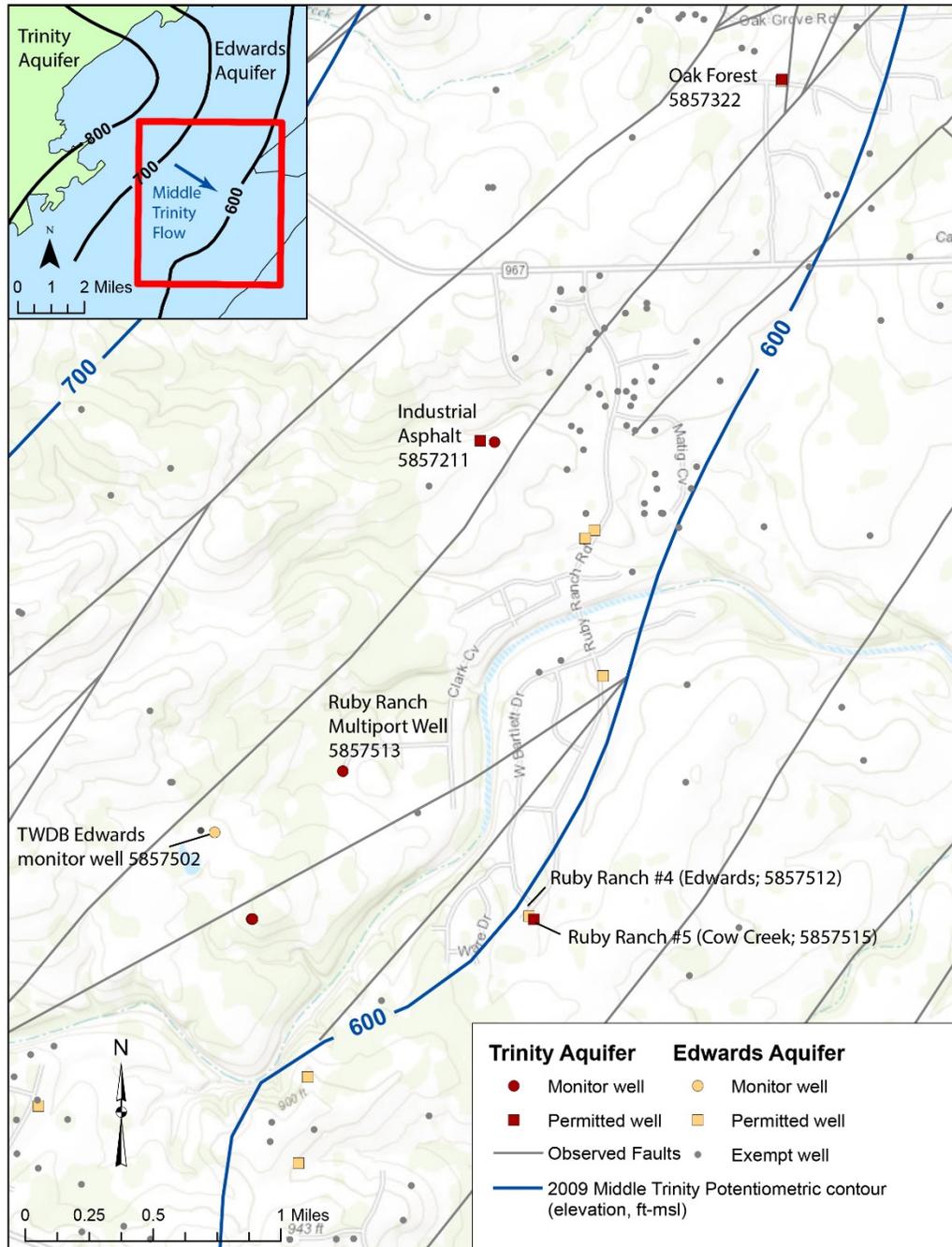


Figure 2. Location map showing wells and faults in the area. Inset map shows the aquifers and potentiometric map of the Middle Trinity indicating flow to the southeast in the study area.

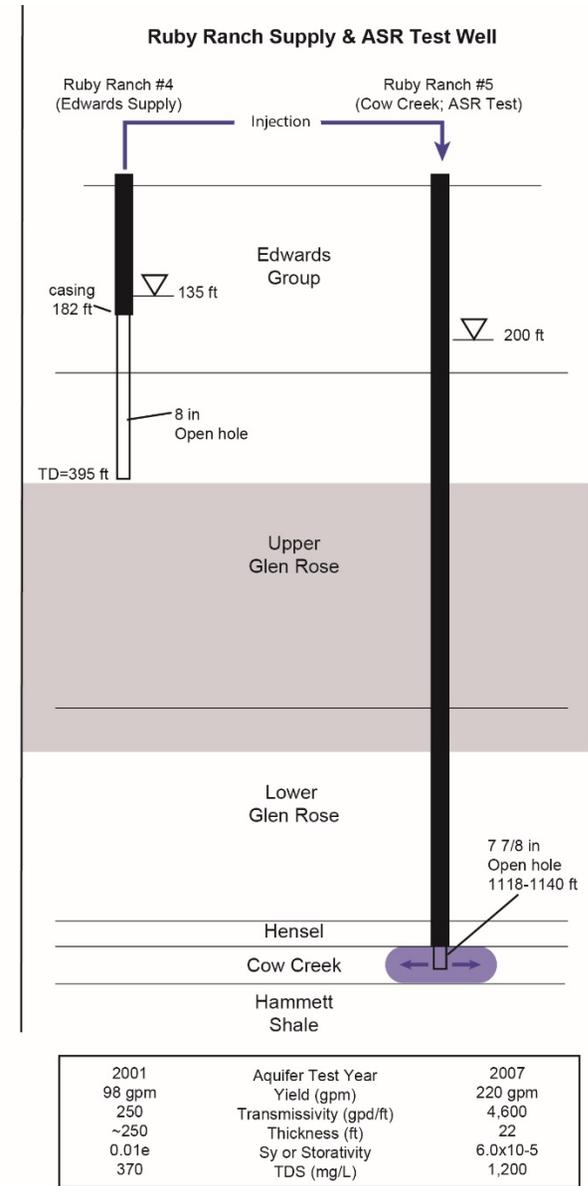
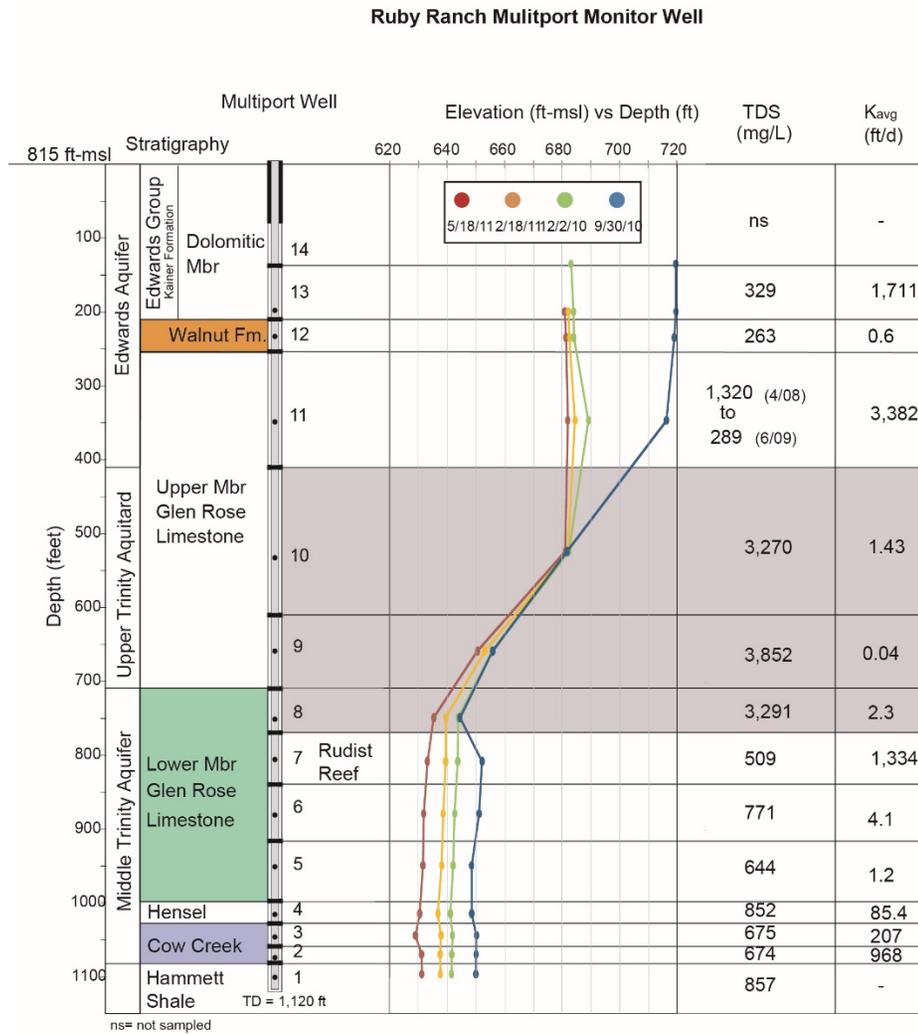


Figure 3. Detailed hydrostratigraphy, well completion, and hydrogeologic data of the study area.

ASR Pilot Test

RRWSC applied to the TCEQ for permission to conduct an ASR test, and on March 16, 2017 they received a letter from TCEQ giving approval for the test (Ruby Ranch's Class V UIC authorization no. 5X2500126; **Appendix A**). This approval was to conduct tests to determine the feasibility of storing water from the Edwards Aquifer in the Cow Creek Formation (Middle Trinity) for later recovery. The test project envisioned a multi-step process with increasing volumes of injected water in each successive step predicated upon successful results at each step. Major objectives of the project were to determine any impact to water chemistry and to the formation, and clarifying the physical parameters governing the injected water "bubble".

ASR Test Design and Methods

In preparation for the ASR tests temporary plumbing – pipes, valves, metering – was installed for manually conducting the pilot project. ASR testing was conducted between April 19 and June 29, 2017. Two phases (or cycles) of injection and extraction were conducted. Field parameters and water samples were collected during the test. Various instruments and procedures were used to collect data during the test (**Figure 4**).



Figure 4. Photograph of RRWSC#5 ASR test well. Temporary PVC pipe was used to inject stored Edwards Water. Also shown are the equipment used to measure water levels and field parameters. The storage tank in the distance holds Edwards water prior to injection.



Figure 5. Photograph of RRWSC#5 ASR test well equipped for continuous water level and field parameter measurements.

Data collected during the project include:

Chemistry

- Baseline water-quality data from samples RRWSC#4 (Edwards) and RRWSC#5 (Trinity). Data collected during extraction from Ruby #5. Analyses included major anions and cations, and were conducted by the LCRA Environmental Services Laboratory, a NELAP certified laboratory (**Appendix C**). Most data can be found at the TWDB's Water Data Interactive website at: (<http://www2.twdb.texas.gov/apps/waterdatainteractive/groundwaterdataviewer>)
- Continuous monitoring of water quality from injection and extraction using In-Situ 9500 and Horriba multparameter probes. These probes measured the following parameters: temperature, conductivity, turbidity, pH, dissolved oxygen, and oxidation/reduction potential.
- Specific sampling and analyses for dissolved arsenic and iron. Results include field and LCRA laboratory analyses (**Appendix C**). Arsenic results were expedited by the LCRA.
- XRD/XRF (x-ray) analysis of samples of Cow Creek Formation for bulk chemical/mineralogical composition (**Appendix D**). This was used to identify constituents in the reservoir that could potentially come into solution in the stored water. The sample was from a recent well drilled near Driftwood (5764613), about 6 miles west.

Water Levels

- Pressure transducer within the injection well (RRWSC#5) to record water-level data at one-minute intervals. Monitoring water levels in the closest Middle Trinity Aquifer well (5857513, Ruby Ranch multiport well).

Flow Rates and Volume

- Monitoring of injection and extraction flow rates from the RRWSC#5.

Test Results

A summary of the sequence of events for the two phases are shown in **Table 1**.

Table 1. Summary of Phase 1 and 2 activities

	<i>Date</i>	<i>Activity</i>	<i>Detail</i>
Background	3/3/2017 8:30	RRWSC#5 Background chemistry	Field parameters, major and minor ions
	4/19/2017 16:18	RRWSC#5 Background chemistry	Field parameters, major and minor ions
Phase 1	4/20/2017 8:00	Phase 1 injection begins	90-100 gpm; pressure transducer logging
	4/20/2017 16:30	Phase 1 injection ends	50,000 gallons total injected
	4/24/2017 9:00	Phase 1 extraction begins	90-100 gpm; continuous field parameters; pressure transducer logging
	4/24/2017 12:30	extraction	20,000 gallons
	4/24/2017 15:56	extraction	40,000 gallons; major & minor ions
	4/24/2017 20:30	Phase 1, official extraction ends	65,705 gallons
	4/25/2017 11:30	Phase 1 continued extraction	83,700 gallons total pumped
Phase 2	5/1/2017 14:00	Phase 2 injection begins	40 gpm; Continuous field parameters; pressure transducer logging
	5/1/2017 20:00	Phase 2 injection	12,700 gallons
	5/6/2017 11:15	Phase 2 injection ends (118 hrs)	280,632 gallons total injected
	5/16/2017 8:55	Phase 2 extraction begins after 10 day hiatus	Continuous field parameters (added ORP); pressure transducer logging; HACH arsenic kit test readings
	5/16/2017 16:40	Phase 2 extraction ~7 hrs	44,000 gallons; LCRA lab samples: major and minor ions
	5/23/2017	Phase 2 extraction begins again after 6 day hiatus and lab results returned	Continuous field parameters (added ORP); pressure transducer logging; HACH arsenic kit test readings
	6/19/2017	Phase 2 extraction ends	Assorted Fe and As analyses; Total pumped volume 381,000 gallons

Phase 1

Phase 1 started on April 20, 2017 with 50,000 gallons of Edwards Aquifer water from RRWSC#4 well injected into RRWSC#5. Beginning on April 24, approximately 84,000 gallons of water were pumped out of RRWSC#5. A summary of water-quality data from Phase 1 is shown in **Table 2**. **Figure 6** shows Phase 2 water levels in the Trinity well during injection and extraction combined with conductivity of the extracted water.

Phase 2

The injection portion of Phase 2 occurred between May 1, 2017 and May 6, 2017 with 280,000 gallons of Edwards Aquifer water injected into RRWSC#5. The extraction phase began on May 16, 2017 when 44,000 gallons of water were pumped out of Ruby well #5. Samples were collected and analyses were reviewed before pumping was started again on May 23, 2017. Between May 23, 2017 and June 19, 2017, 381,000 gallons were pumped from RRWSC#5. A summary of water-quality data from Phase 2 are shown in **Table 3**. **Figure 7** shows Phase 2 water levels in the Trinity well during injection and extraction combined with conductivity of the extracted water.

Water levels and Injection Bubble

During Phases 1 and 2, Edwards Aquifer water was injected into the Trinity well at a rate of about 90 and 40 gallons per minute (gpm), respectively. The water level in the well rose about 12 ft during Phase 1 and 6 ft during Phase 2. Once injection stopped, the water level in the well quickly returned to pre-injection levels. **Figure 8** shows the modeled rise in head due to injection, which closely agrees with measured values in **Figures 6 and 7**. As the injected water was pumped from the well during the extraction period, water levels dropped about 7 ft (**Figures 6 and 7**).

No water level response could be attributed to Phases 1 and 2 in the nearest Middle Trinity monitor well (5764613). This well is a multiport monitor well located about 1.5 miles to the west of the Ruby Ranch subdivision (**Figure 2**).

Table 5 shows the estimated radial distance of the injected Edwards Aquifer water within the Cow Creek for various assumed Cow Creek effective porosities. The estimate assumes complete displacement (no mixing) and injection of 280,000 gallons. The estimates indicate that the “bubble” of fresh Edwards Aquifer water is relatively small and is likely contained within the property of the RRWSC.

Table 2. Summary of water-quality data from historic, background, and extraction sampling during Phase 1. Laboratory results provided in **Appendix C**.

Well	Background				Phase 1 Extraction		
	RR#4 Edwards	RR#5 Middle Trinity	RR#5 Middle Trinity	RR#5 Middle Trinity	RR#5 Middle Trinity	RR#5 Middle Trinity	RR#5 Middle Trinity
Volume	n/a	n/a	n/a	n/a	20,000 gal pumped	40,000 gal pumped	65,700 gal pumped
Date	6/28/2006	6/23/2010	3/3/2017 8:30	4/19/2017 16:18	4/24/2017 12:30	4/24/2017 15:56	4/24/2017 20:30
Lab/ Data Source	ELS	ELS	ELS (Drinking water)	ELS	ELS	ELS	ELS
Conductivity (uS/cm)	590	1572	1560	1640	1351.54	1514.07	1617.92
pH	7.18	7.0	7.62	6.95	7.28	7.29	
DO (mg/L)						2.45	
Temp @	21.62	27.93		27.12	26.8	26.7	
ORP (mV)	nd	nd	nd	nd	nd	nd	nd
Calcium (mg/L)	68.5	170	164	153		132	
Magnesium (mg/L)	35.4	114	109	111		92.5	
Sulfate (mg/L)	37	677	726	657		536	
Chloride (mg/L)	10	16	14.8	13.6		12.9	
Bicarbonate (mg/L)	323.4	313.6	256	261		254	
Sodium (mg/L)	6.1	23.9	25.2	24.2		20.7	
Potassium (mg/L)	1.5	12.4		13.6		11.5	
Fluoride (mg/L)	.03	2.11	2.22	2.06		1.89	
Iron (ug/L)	<30	603	284	1000		658	
Arsenic lab (ug/L)	<1	<2.0	<1.00	<1.00	2.29	2.36/2.2	2.69
Arsenic HACH Kit (ug/L)	nd	nd	nd	nd	nd	nd	nd
Strontium (ug/L)	11000	17,300		17700		15200	
Sillica (mg/L)	11.3	13.8		13.2		12.3	
TDS (mg/L)	342	1201	1210	1161		987	

nd= no data

Table 3. Summary of water-quality data from background and extraction during Phase 2. Laboratory results provided in Appendix C.

Edwards Injection Water				Phase 2 Extraction		
Well	RR #4 Edwards Well	RR #4 Edwards Tank	RR #4 Edwards Tank	RR#5 Middle Trinity	RR#5 Middle Trinity	RR#5 Middle Trinity
Volume	n/a	n/a	97,400 gallons injected	Mix; Extract begins	44,000 gal pumped	
Date	5/1/2017 14:00	5/1/2017 14:00	5/3/2017 8:00	5/16/2017 14:20	5/16/2017 16:40	5/26/2017 12:45
Lab/ Data Source	BSEACD	BSEACD	BSEACD	ELS/BSEACD	ELS/BSEACD	ELS/BSEACD
Conductivity (uS/cm)	732	750	741	1,300	1,430	1,570
pH	7.84		8.24	8.55	8.53	
DO (mg/L)	6.4	7.25	7.04	0.22	0.13	0.15
Temp @	21.27		21.72	21.21	24.78	
ORP (mV)	nd	nd	nd	-67	-86	-122
Calcium (mg/L)	63.7				102	
Magnesium (mg/L)	27.3				62.9	
Sulfate (mg/L)	32.9				296	
Chloride (mg/L)	12.7				12	
Bicarbonate (mg/L)	299.0				246	
Sodium (mg/L)	7.11				15.1	
Potassium (mg/L)	1.28				7.19	
Fluoride (mg/L)	0.25				1.39	
Iron (ug/L)	<50				380	
Arsenic Lab (ug/L)	<1			1.89	1.88/2.09	3.19
Arsenic HACH Kit (ug/L)	nd	nd	nd	1 to 2	0 to 1	1 to 2
Strontium (ug/L)	6800				11600	
Sillica (mg/L)	11.4				11.9	
TDS (mg/L)	313				858e	

nd= no data; e= estimated based upon 0.6 of conductivity

Table 4. Summary of water-quality data from HACH testing kit and field parameters during Phase 2 extraction.

Date/Time	Ferrous Iron (mg/L)	Total Iron (mg/L)	Arsenic (ug/L)	Conductivity (uS/cm)	ORP (mV)	Notes
5/16/2017 9:20	0.71	0.9		1090	-30	
5/16/2017 10:25	Nd	Nd	0	1160	-50	
5/16/2017 10:36	0.52	0.57		1170	-58	
5/16/2017 12:30	0.44	0.47	0	1300	-67	
5/16/2017 13:20	0.5	0.49	3 to 4	1340	-67	RRWSC#4 (Edwards) Ferrous Iron: 0.01; Total Iron: 0.00
5/16/2017 14:00	Nd	Nd	1 to 2	1330		
5/16/2017 14:20	Nd	Nd	1 to 2	1360		As sample (LCRA)
5/16/2017 14:30	0.47	0.49		1370	-80	
5/16/2017 15:30	Nd	Nd	0			RRWSC#4 (Edwards) Arsenic: 0
5/16/2017 15:50	0.42	0.41		1430		
5/16/2017 16:30	Nd	Nd	1	1430	-89	As sample (LCRA) & TWDB suite
5/25/2017 11:00	0.94	0.88	0-1	1530	-90	3.4k gals pumped when sampled
5/26/2017 12:30	0.87	0.79	0-1	1590	-89	1.1 k gals pumped when sampled (Submitted sample to LCRA)
6/1/17 9:30	0.99	0.89	0-1	1800	-32	
6/16/2017	0.72	0.77	0-1	2060	-78	
6/29/2017	0.86	0.99	0-2	2150		BSEACD intern Django Doster took measurements

Table 5. Table of the radial distance (feet) of the injection bubble for various porosity values. Assume laterally contained within the Cow Creek (75 ft thick), no mixing, and an injection volume of 280,000 gal (37,515 cubic feet).

	Effective Porosity					
	0.05	0.1	0.15	0.2	0.25	0.3
Radial Distance (ft)	56	40	33	28	25	23

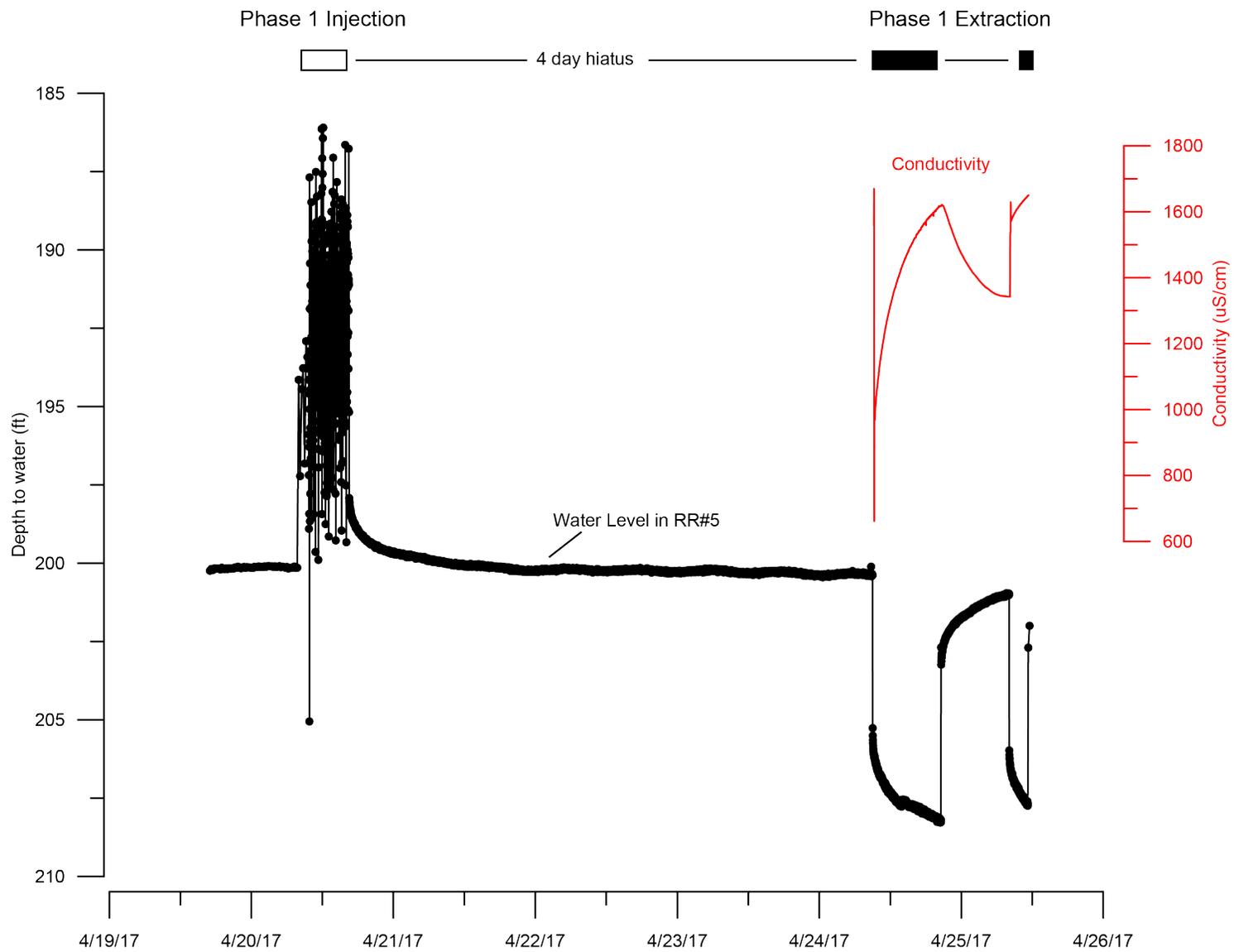


Figure 6. Hydrograph of the water level and conductivity data during Phase 1 testing of the RRWSC#5.

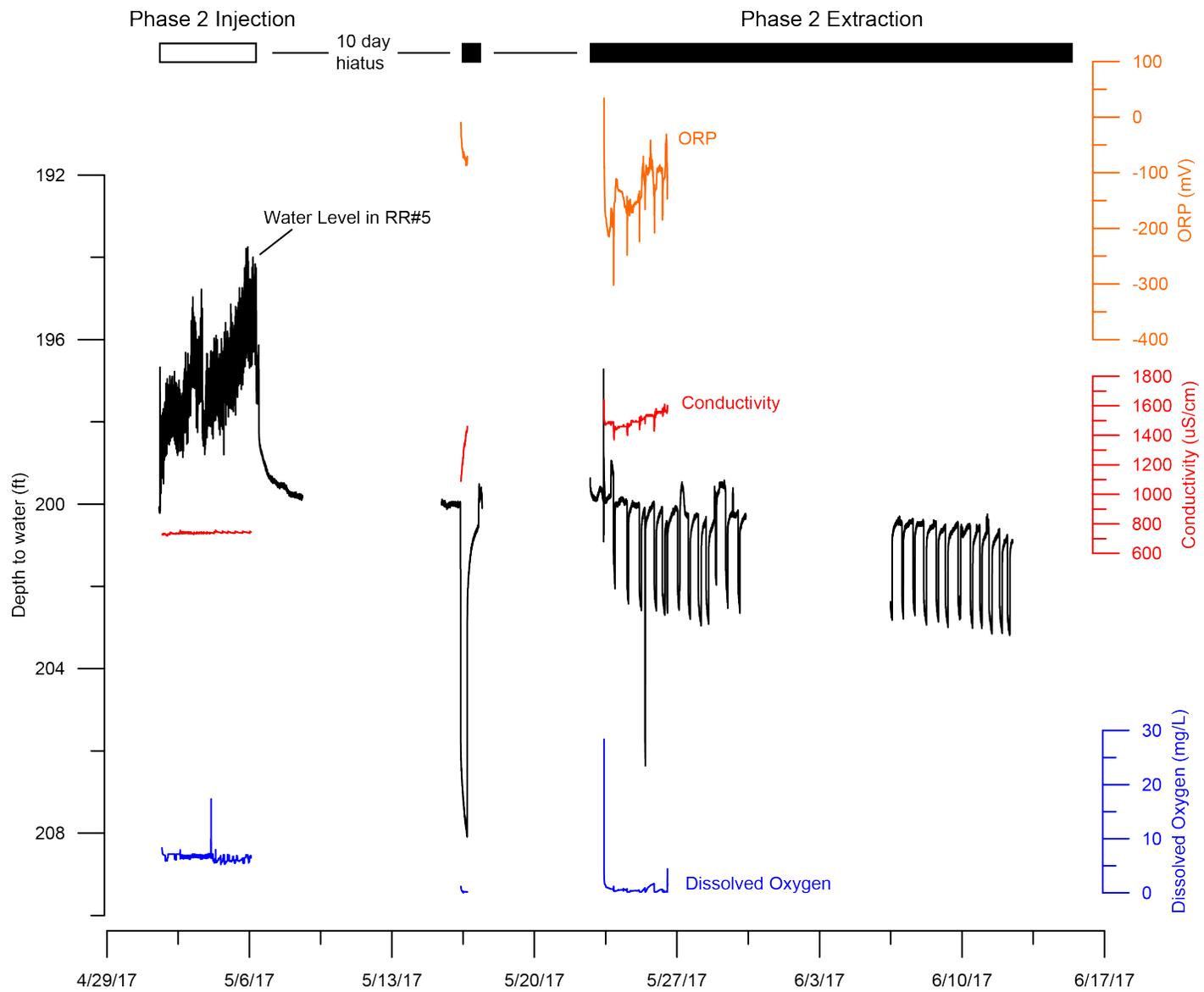


Figure 7. Hydrograph of the water level, conductivity, ORP, and DO data during Phase 2.

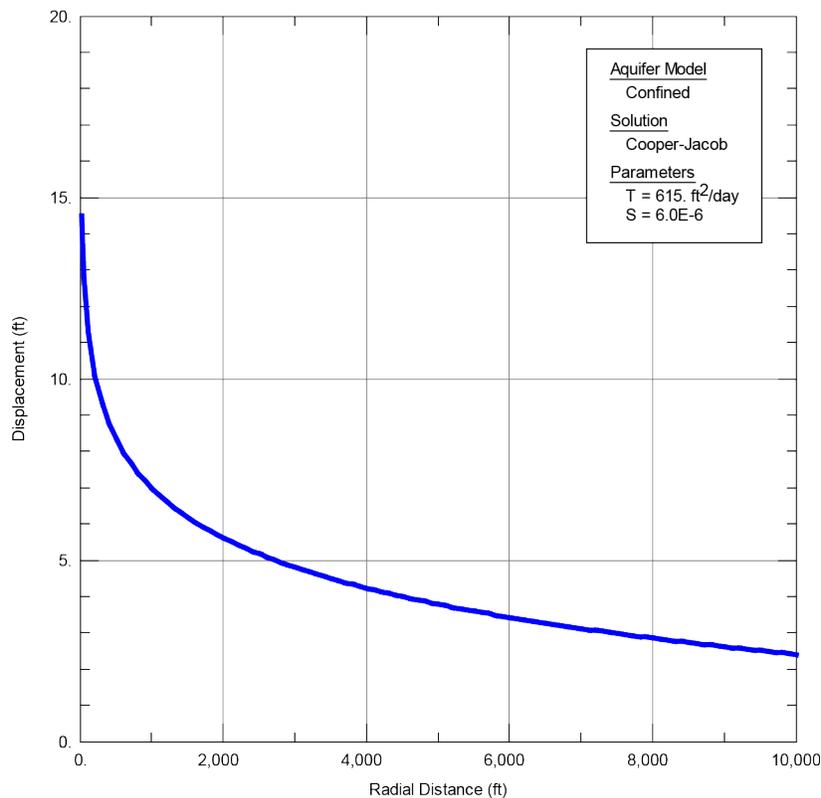


Figure 8 Modeled potentiometric results of injection into the RRWSC#5 (Cow Creek) at 40 gpm after 7,000 minutes (~116 hrs) similar to the Phase 2 injection.

Geochemistry

The Ruby Ranch multiport well has 14 discrete zones (**Figure 3**) completed in the Edwards and Trinity Aquifers and provides detailed geochemical data for source and receiving water characterization. **Figure 9**, a Durov diagram, illustrates the chemical composition of groundwater samples from the Ruby Ranch multiport well (5857513 of **Figure 2**). This appears to be typical of the range of hydrochemical facies of aquifers in the study area. Groundwater from the 14 zones varies in chemical composition from calcium-magnesium-bicarbonate (Ca-Mg-HCO₃) and calcium-carbonate (Ca-HCO₃) in Edwards aquifer Zones 11–13, to magnesium-calcium-sulfate (Mg-Ca-SO₄) in Middle and Upper Trinity aquifer Zones 8–10, and magnesium-calcium-sulfate-bicarbonate (Mg-Ca-SO₄-HCO₃) in Middle Trinity aquifer zones 1–7. Total dissolved solids range from ~350 mg/L or less in the Edwards Aquifer to between 450 and 850 mg/L in Middle Trinity zones 1–7, and from 2,800 to 3,800 mg/L in the sulfate-dominant groundwater of Upper Trinity zones 8–10.

All geochemical sampling results from the pilot testing are provided in **Appendix C** and summarized in **Tables 2 and 3**. The Durov diagram shown in **Figure 10** illustrates the hydrochemical compositions of the RRWSC#4 Edwards injection water (Ca-HCO₃ facies) and the RRWSC#5 Cow Creek native receiving waters (Mg-Ca-SO₄ facies). Also shown is the chemistry of the produced water for Phases 1 and 2 after 40,000 and 44,000 gallons of water were produced after injection, respectively.

Mixing models developed with Geochemist’s Workbench® v. 11 (GWB) reveal that Phase 1 produced water consisting of a mixture of 20 percent Edwards groundwater and 80 percent Cow Creek groundwater after 40,000 gallons were pumped from the well. Phase 2 produced water is 35 percent Edwards and 65

percent Cow Creek after 44,000 gallons were pumped from the well. **Figure 11** adds the modeled mixtures (M1 and M2) to **Figure 10**. **Table 6** lists the concentrations of major metals and nonmetals for the Edwards, Cow Creek, P1 and P2 samples, along with the modeled concentrations for M1 and M2. The table also includes saturation indices (calcite, dolomite, fluorite, gypsum, and halite) calculated by GWB, based on the WATEQ4F thermodynamic data base (Ball and Nordstrom, 1991, rev. 2001). The models assumed simple mixing according to the specified ratios and did not attempt to force equilibration with dolomite or calcite, or other reactions such as adsorption or desorption. The data to address such matters are lacking at this time, but more detailed models should be developed in forthcoming stages of the project. Nonetheless, the very close match between the modeled and actual compositions indicates that the modeled results, as specified above, are representative of the groundwater mixtures that make up the P1 and P2 samples. Points representing M1 and M2 overlie P1 and P2 in the metals and nonmetals trilinear fields, in the square cross plot representing metals and nonmetals, and in the TDS field (**Figure 11**).

The saturation indices referred to above and listed in **Table 6** indicate that the Edwards source and Cow Creek receiving waters are undersaturated with respect to fluorite (CaF_2), gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), and halite (NaCl). Edwards source water is saturated with respect to calcite (CaCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$), and Cow Creek is undersaturated with respect to both minerals. The Phase 1 and Phase 2 samples are saturated with respect to calcite and dolomite and undersaturated with regard to fluorite, gypsum, and halite. Iron concentrations and iron minerals are addressed in the following section (Arsenic Geochemistry) of this report.

Saturation indices are interpreted as indicators of the *potential* for dissolution (negative values) or precipitation (positive values), but they should not be used to infer that either process *will* occur, or that either process will occur at a known rate. It is also important to note that saturation indices might change from positive to negative (or vice versa) as a function of minor variations in the composition of water over time or in response to variations in analytical accuracy and precision.

Table 6. Saturation indices within various groundwaters with respect to mineral phases.

Sample ID	Unit	Edwards	Cow Creek	Phase 1	Phase 2	20:80 Mix	35:65 Mix
pH	SU	7.82	6.95	7.29	8.53	7.051	7.14
Temperature	C	21.27	27.12	26.7	24.78	25.95	25.07
Ca ⁺⁺	mg/l	63.7	153	132	102	135.2	121.8
Mg ⁺⁺	mg/l	27.3	111	92.5	62.9	94.29	81.76
Sr ⁺⁺	mg/l	6.8	17.7	15.2	11.6	15.52	13.89
Na ⁺	mg/l	7.11	24.2	20.7	15.1	20.79	18.23
K ⁺	mg/l	1.28	13.6	11.5	7.19	11.14	9.297
HCO ₃ ⁻	mg/l	304	265.4	258.3	250.1	318.2	315.4
SO ₄ ⁻⁻	mg/l	32.9	657	536	296	532.5	439
Cl ⁻	mg/l	12.7	13.6	12.9	12	13.42	13.28
F ⁻	mg/l	0.25	2.06	1.89	1.39	1.699	1.428
SiO ₂ (aq)	mg/l	11.4	13.2	12.3	11.9	12.84	12.57
TDS	mg/l	313	1161	987	858	991.9	864.9
Saturation Indices							
Calcite	log Q/K	0.5426	-0.1119	0.1568	1.322	-0.07738	0.02545
Sat/Unsat		Saturated	Unsat	Saturated	Saturated	Unsat	Saturated
Dolomite	log Q/K	1.021	-0.00719	0.5128	2.781	0.04074	0.217
Sat/Unsat		Saturated	Unsat	Saturated	Saturated	Saturated	Saturated
Fluorite	log Q/K	-2.255	-0.408	-0.4974	-0.7757	-0.5969	-0.7242
Sat/Unsat		Unsat	Unsat	Unsat	Unsat	Unsat	Unsat
Gypsum	log Q/K	-2.146	-0.8025	-0.9053	-1.185	-0.9002	-0.9904
Sat/Unsat		Unsat	Unsat	Unsat	Unsat	Unsat	Unsat
Halite	log Q/K	-8.626	-8.129	-8.211	-8.359	-8.214	-8.245
Sat/Unsat		Unsat	Unsat	Unsat	Unsat	Unsat	Unsat

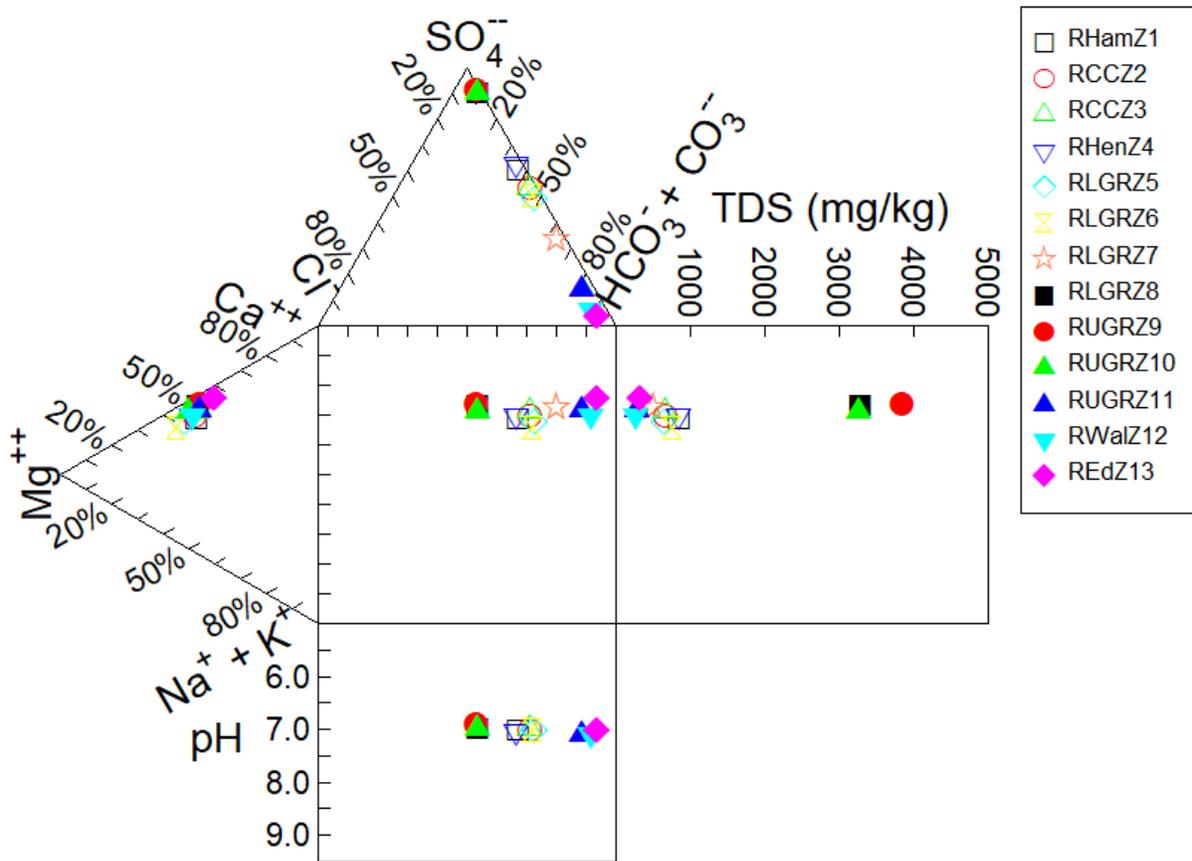


Figure 9. Durov diagram showing the hydrochemical compositions of groundwater that vary from (1) Ca-Mg-HCO₃ and Ca-HCO₃ in the (Edwards aquifer, Zones 11 - 13), to (2) Mg-Ca-SO₄ in the Middle and Upper Trinity aquifers (Zones 8 – 10). Below Zone 8, the compositions are dominantly (3) Mg-Ca-SO₄-HCO₃ in the Middle Trinity aquifer.

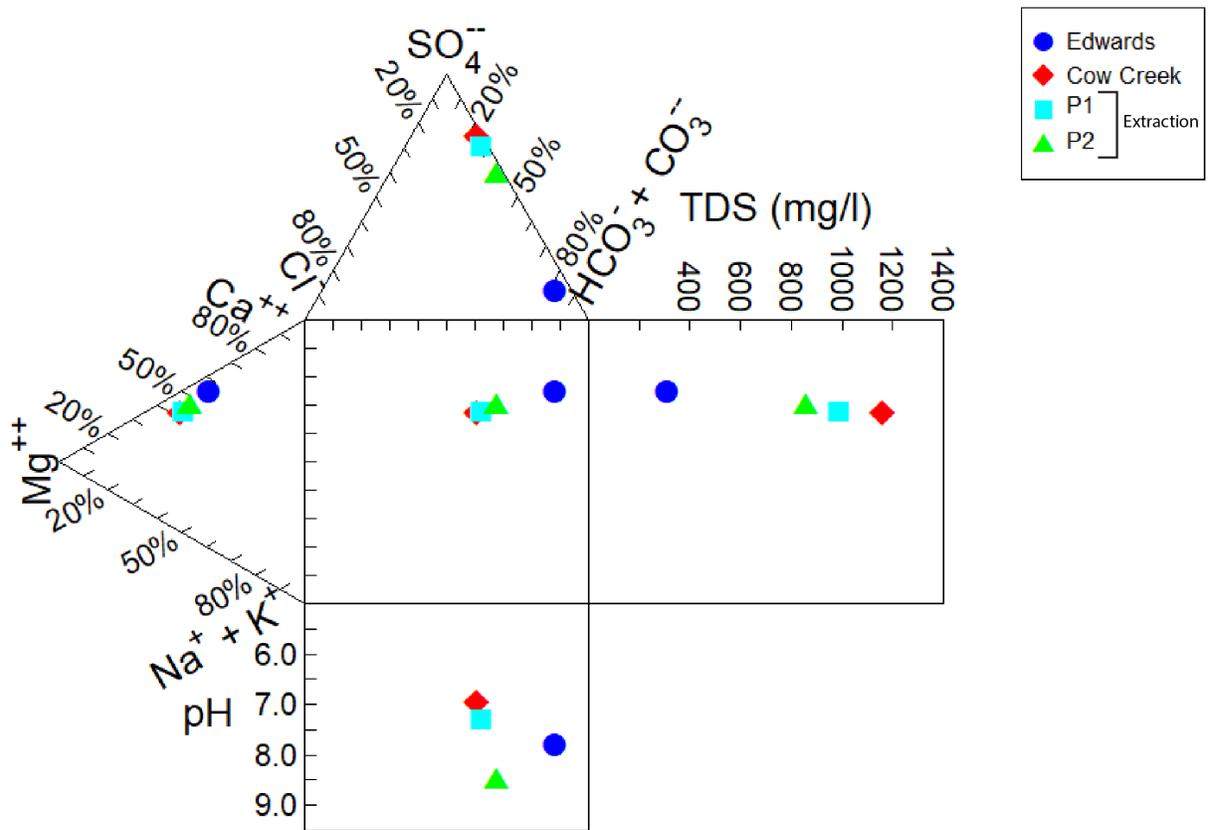


Figure 10. Durov diagram showing the hydrochemical compositions of the RRWSC#4 Edwards source or injection water (Ca-HCO₃), RRWSC#5 Cow Creek receiving waters (Mg-Ca-SO₄). Phase 1 (P1) and Phase 2 (P2) water chemistry are shown after 40,000 and 44,000 gallons were produced after injection, respectively.

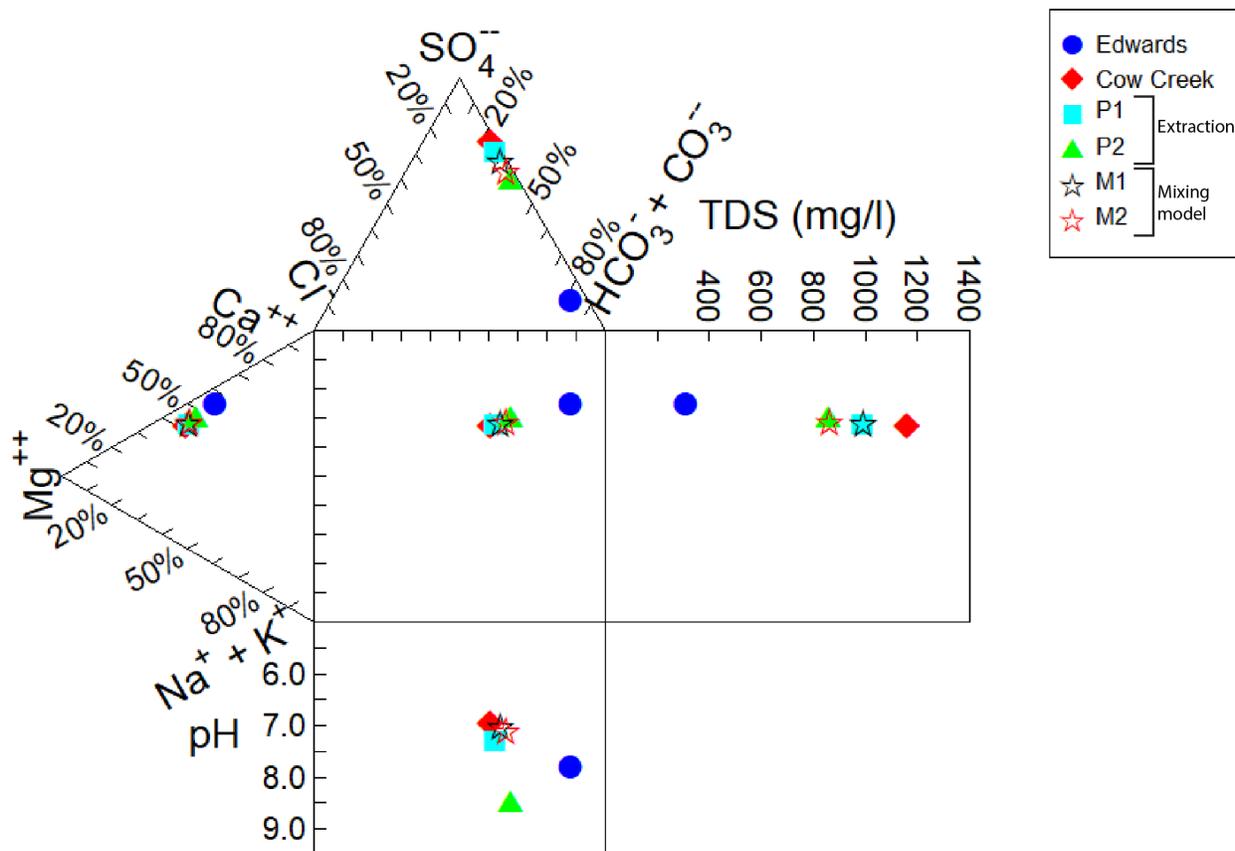


Figure 11. Durov diagram from figure 10 showing the mixing model results.

Arsenic Geochemistry

Because of concerns about mobilization of arsenic from host rocks, additional analyses for arsenic were made during the extraction phases of the tests. Some samples were collected for analysis by the LCRA laboratory on an expedited schedule (**Tables 2 and 3**). Other analyses were made in the field with test strips to detect low levels of arsenic (**Table 4**). Analyses of groundwater from the Edwards source well (RRWSC#4) and the Middle Trinity well (RRWSC#5) prior to the Phase 1 injection showed that arsenic concentrations were less than the detection level of 1.0 microgram per liter (ug/L). During Phase 1 extraction, the concentration of arsenic was 2.2 to 2.7 ug/L; and during Phase 2 extraction, the concentration of arsenic was 1.9 to 3.2 ug/L. The U.S. Environmental Protection Agency lists the maximum contaminant level (MCL) of arsenic as 10.0 ug/L.

It is important to note differences in dissolved oxygen (DO) concentrations in Edwards and Cow Creek groundwaters (see **Table 3**) as factors to be considered in the mobilization of arsenic in recovery water from RR#5. The mineral associations of arsenic in the Cow Creek are not well understood at this time. The XRD/XRF analyses in **Appendix D** show that arsenic is present within the predominantly dolomite matrix, but the analyses do not show the specific mineral or minerals with which arsenic occurs. Oxygenated waters injected at early ASR sites in Florida were the key factors that led to the release of arsenic in concentrations greater than the 10-ug/L MCL (Arthur, Dabous, and Cowart 2002; Price and

Pichler 2006; Jones and Pichler 2007), primarily from pyrite (FeS_2) and arsenopyrite (FeAsS). The occurrence of arsenic in groundwater at ASR sites in Florida was not observed until the early stages of cycle testing, and the mineral associations were discovered only after investigators examined cores and cuttings from the storage zone (Suwannee Limestone).

The concentration of arsenic in Phase 1 and Phase 2 recovery samples was well below the 10- $\mu\text{g/L}$ MCL. In both the source water and the receiving water, the concentration of arsenic was reported to be less than 1.0 $\mu\text{g/L}$ (**Table 2**). The higher arsenic concentrations reported for the Phase 1 and Phase 2 samples are probably related to the effect of oxidative dissolution of ferrous iron minerals disseminated within the Cow Creek. The DO concentration in the Edwards source water was 6.4 mg/L (**Table 3**). DO was not analyzed in the Cow Creek receiving water (**Table 2**), but it is unlikely that the concentration would be greater than a few tenths of a mg/L. This assumption is based on the DO measurement of 0.13 mg/L in the Phase 2 produced water (**Table 3**). The DO concentration reported for the Phase 1 recovered water was 2.45 mg/L, which is unexpectedly high for confined Cow Creek groundwater. That measurement probably reflects the mixing of oxygen-rich Edwards water with DO-deficient water of the Cow Creek.

The concentration of iron reported in receiving water is difficult to interpret, compared with concentrations in the two recovery samples. The concentrations in the recovery samples appear to be related to the dissolution of iron minerals, a geochemical process that would lead to the mobilization of associated arsenic. The higher iron concentration (1.0 mg/L) reported for the receiving water is not consistent with that model. The arsenic concentration in the receiving water was reported to be less than 1.0 $\mu\text{g/L}$ (**Table 2**). If arsenic-bearing iron minerals were undergoing dissolution to yield an iron concentration of 1.0 mg/L, one would expect the concentration of arsenic to be greater than the method detection limit. Corrosion of the casing could account for the elevated iron and the low arsenic concentrations because the source of the iron is not derived from arsenic-bearing iron minerals of the Cow Creek.

It will be necessary to monitor arsenic concentrations on a regular basis, especially with increasing storage time in the Cow Creek. Initial geochemical speciation modeling with GWB shows that the dominant species of arsenic is in the form of the monoprotonated arsenate HAsO_4^- . The dominance of this species is illustrated in the form of an Eh-pH diagram (**Figure 12**).

Eh-pH diagrams represent the stability fields of different redox-sensitive dissolved and mineral species within the stability limits of water. **Figure 12** shows the stability fields of different oxidized (arsenate, As^{5+}) and reduced (arsenite, As^{3+}) species of arsenic. Arsenate species are in stability fields 1-4 of the diagram, and arsenite species are in fields 5-7. The points in stability field 3 are based on pH measurements and ORP measurements, adjusted to Eh by adding 0.20 volts (V) to each ORP measurement recorded during recovery testing. The cluster of points indicates very little variability with respect to pH and Eh. All the points lie entirely within field 3. In addition to ORP, the mobility of different arsenate and arsenite species is highly dependent on pH (Goldberg, 2002), and the points plotted on **Figure 12** appear to lie within the upper range of pH measurements at which arsenate tends to adsorb to various iron minerals (Goldberg, 2002). If the pH of the source and receiving water remains stable, the potential for purely pH-driven mobilization should not be expected to be a significant factor in the release of arsenic. However, under the current and planned injection procedures, it is unlikely that there will be any significant change in pH. Under conditions observed in RRWSC#5, the primary factor accounting for the occurrence of arsenic in the recovery samples is oxidative dissolution. This can be managed by treatment processes that strip DO from water prior to injection, or by minimizing introduction of oxygen into the source water prior to injection.

The results of the recovery tests indicate that a small mass of arsenic was mobilized during each test. This illustrates that arsenic is available and mobile. Additional points to be addressed over time are (1) the minerals with which arsenic is associated in the Cow Creek, (2) the form of association, that is, adsorption or absorption, and (3) the factors that control the stability of the minerals with which arsenic is either adsorbed or absorbed.

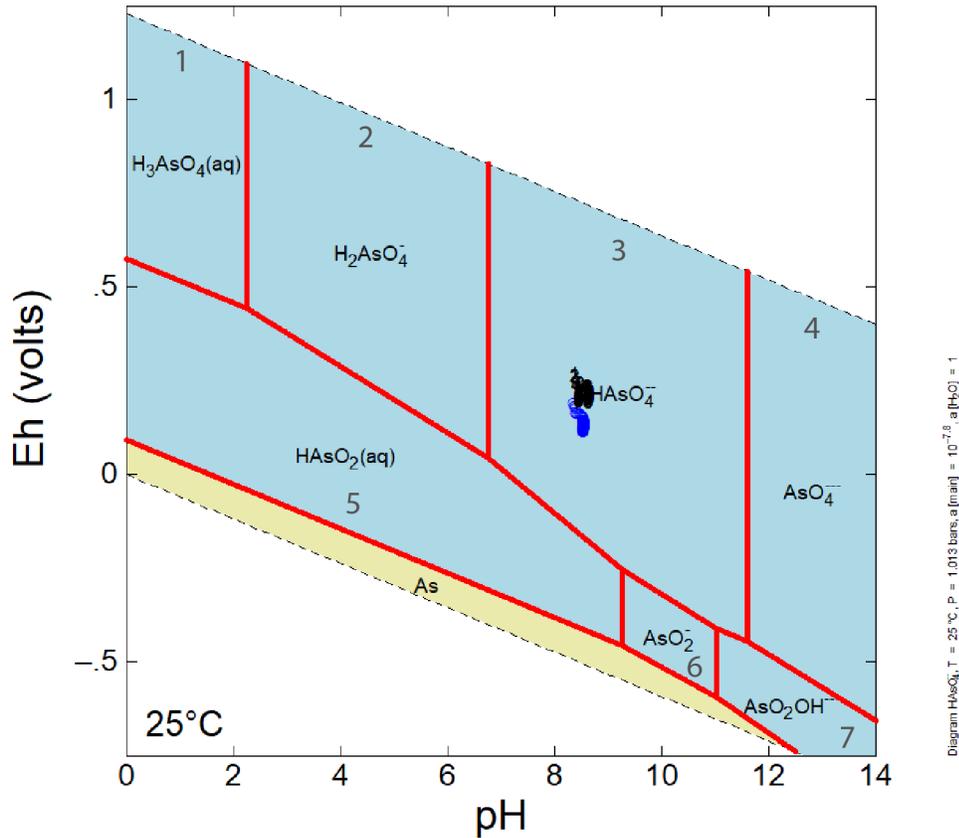


Figure 12. Eh-pH diagram for AS-O system. The points plotted with the stability field are based on ORP measurements (corrected to yield Eh) during the recovery phase.

Conclusions

From the results of the two phases of injection and extraction in the Middle Trinity Aquifer, it was clear that the aquifer is capable of receiving the water at the planned flow rates and of storing the injected Edwards water for an indefinite period of time.

The chemistry of the mixture of the two waters also appear compatible as the quality of the extracted (and highly mixed) water met all primary drinking water standards during the pilot testing. Analyses for arsenic in the extracted water show that the concentration of arsenic has not exceeded, nor approached, the 10- $\mu\text{g/L}$ MCL. Routine monitoring of arsenic concentrations will be required during extended storage periods and all phases of groundwater recovery.

Future Work

Phase 3 of the testing is planned to begin in October 2017 through May 2018 and increase the volume of injection and the duration of storage. Current plans are to inject up to 7 million gallons of Edwards water.

Acknowledgments

Thomas Doebner and Dale Olmstead of the Ruby Ranch WSC, in consultation with the District staff and Joe Vickers, implemented and operated the ASR pilot test. District staff and Joe Vickers collected data during the testing. Kendall Bell-Enders and Vanessa Escobar of BSEACD helped with initial discussion, planning, and regulatory aspects of the project. Robin Gary (BSEACD) provided editorial review of this report.

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