GEI Consultants

Consulting
Engineers and
Scientists

Technical Addendum
ASR Pilot Testing at TW-6A

March 2020

Prepared for:
Sonoma Water
404 Aviation Boulevard
Santa Rosa, CA 95403

Technical Addendum

ASR Pilot Testing at TW-6A

Prepared for:

Sonoma Water
404 Aviation Boulevard
Santa Rosa, CA 95403

Prepared by:

GEI Consultants
2868 Prospect Park Drive, Suite 400
Sacramento, CA 95670

Rodney A. Fricke, PG, CHg

PROFESSIONAL GEOLOGIST
RODNEY A FRICKE
No. 11
CERTIFIED HYDROGEOLOGIST
STATE OF CALIFORNIA

Chris Petersen, PG, CHg

PROFESSIONAL GEOLOGIST
CHRISTIAN E. PETERSEN
No. 6189
CERTIFIED HYDROGEOLOGIST
STATE OF CALIFORNIA

March 30, 2020

Table of Contents

Figures

Tables

Executive Summary

This Technical Addendum was prepared by GEI Consultants (GEI), on behalf of the Sonoma County Water Agency (Sonoma Water) and the City of Sonoma (City), to describe the results of an Aquifer Storage and Recovery (ASR) pilot test at Test Well 6A (TW-6A). The ASR pilot test involved several cycles of recharge, storage, and recovery of drinking water through a confined aquifer system of the Sonoma Volcanics in the Sonoma Valley underlying the City of Sonoma. The pilot test objective was to verify and empirically determine specific hydrogeologic and water-quality factors to support a technical and economic viability assessment of ASR techniques in the region. A Technical Report (GEI et. al., 2017) was submitted to the California Regional Water Quality Control Board – San Francisco Bay Region (RWQCB) on December 21, 2017, along with a Notice of Intent (NOI) to perform the pilot test under the State Water Resources Control Board's (SWRCB) Water Quality Order 2012-0010, *General Waste Discharge Requirements for Aquifer Storage and Recovery Projects that Inject Drinking Water into Groundwater* (ASR General Order). The RWQCB provided a Notice of Applicability (NOA) on March 1, 2018, which allowed the test to proceed according to the plan in the Technical Report. Field testing activities began on March 19, 2018 and were concluded on September 20, 2018.

The pilot test was comprised of three cycles with progressively longer periods of injection, storage, and recovery within each cycle. Over 4.10 million gallons (approximately 13 acre-feet [ac-ft]) of potable drinking water were injected into TW-6A after 44 days (total) at rates between 54 and 71 gallons per minute (gpm), including 2 days of calibration testing before the pilot test. Nearly 4.16 million gallons of groundwater were recovered from TW-6A after 36 days (total) of sustained pumping at rates between 76 and 82 gpm and during brief times of pumping to backflush or sample TW-6A during the storage periods. An additional 7,300 gallons of groundwater were pumped from nearby City Well 6 (CW-6) during several sampling events. The potable water was stored in the aquifer (fractured volcanic rock and interbedded sediments) for a total of 105 days, including an additional 44 days during the third cycle to further monitor the concentrations of disinfection by-products (DBPs), including trihalomethanes (THMs) and haloacetic acids (HAAs).

Static groundwater levels were about 70 feet below the top of the well casings (bTOC) prior to the pilot test in March 2018 and about 80 feet bTOC a week after the end of the 185-day test period in September 2018 (consistent with historical approximate 10-foot seasonal fluctuations observed at CW-6). During each injection cycle, groundwater levels rose to about 17 to 30 feet bTOC at TW-6A and to about 54 to 58 feet bTOC at CW-6. Groundwater temperatures were affected by the cooler temperatures of the potable water, especially at TW-6A and at CW-6 to a lesser degree.

A hydraulic evaluation of TW-6A indicates that TW-6A could be used to inject and store about 55 ac-ft of water during a 6-month period (November through April) at a rate of 70 gpm. This effort might raise the groundwater level during injection at TW-6A to about 20 feet bTOC and to about 55 feet bTOC at CW-6. The hydraulic evaluation also indicates that TW-6A exhibits a relatively low well efficiency of about 56% during extraction and a slightly lower efficiency of 50% during injection. The low efficiency

is likely due to its PVC mill-slot screen and limited development time. This efficiency improved with successive ASR cycles showing that a more intensive development could improve well efficiency. A new ASR well with a typical efficiency value of 70% would allow for greater injection volumes with similar rises in groundwater levels.

The quality of the potable water is excellent and appears to be ASR-compatible with the local groundwater. Both waters are relatively dilute – total dissolved solids concentrations of about 200 milligrams per liter (mg/l) but can be distinguished from each other by their cation composition (calcium, magnesium, and sodium), pH, sulfate-chloride ratio, and DBPs. THMs, primarily chloroform, were the dominant component of the DBPs and the potable drinking water contained total THM concentrations ranging from 20 to 25 micrograms per liter (ug/l) – well below the maximum contaminant level (MCL) of 80 ug/l. THMs were not detected in the groundwater prior to the pilot test. Residual chlorine in the potable water and the presence of trace organic carbon in the aquifer and groundwater produced cyclic concentrations of THMs with a maximum total of 47 ug/l at TW-6A and up to 26 ug/l at CW-6. At the end of the pilot test, the total THM concentration had declined to 14 ug/l at TW-6A and 4 ug/l at CW-6. The THM data and other water quality data indicate that residual mixing effects were present after the completion of the pilot study.

Pilot testing at TW-6A was performed following the guidelines and regulations set forth by the SWRCB ASR General Order and subsequent Notice of Applicability (NOA), including the general schedule of activities, volumes of water to be injected and recovered, and monitoring. Discharges from TW-6A and CW-6 were done in compliance with requirements of the Statewide National Pollutant Discharge Elimination System (NPDES) Permit for Drinking Water Systems Discharges to Waters of the United States.

1. Introduction

This Technical Addendum was prepared by GEI Consultants (GEI), on behalf of the Sonoma County Water Agency (Sonoma Water) and the City of Sonoma (City), to describe the results of an Aquifer Storage and Recovery (ASR) pilot test at Test Well 6A (TW-6A). A Technical Report (GEI et. al., 2017) was submitted to the California Regional Water Quality Control Board – San Francisco Bay Region (RWQCB) on December 21, 2017, along with a Notice of Intent (NOI) to perform the pilot test under the State Water Resources Control Board's (SWRCB) Water Quality Order 2012-0010, *General Waste Discharge Requirements for Aquifer Storage and Recovery Projects that Inject Drinking Water into Groundwater* (ASR General Order). The RWQCB provided a Notice of Applicability (NOA) on March 1, 2018, which allowed the test to proceed according to the plan in the Technical Report. Testing activities began on March 19, 2018 and were concluded on September 20, 2018.

The general location of the project site is shown on **Figure 1 – Site Location Map**.

ASR Pilot Project Sonoma County, California	GEI Consultants	Site Location Map	
Sonoma County Water Agency		FEBRUARY 2020	FIGURE 1

Figure 1. Site Location Map

2. Field Activities

In preparation and implementation of ASR pilot testing at Test Well 6A (TW-6A), field activities were conducted by GEI, Pueblo Water Resources Inc. (Pueblo), Sonoma Water, and the City of Sonoma (City). These activities included additional development and pumping tests at TW-6A to better understand the hydraulics of the site, modifications to TW-6A wellhead to make it ASR capable, pre-ASR test evaluation of equipment and baseline water quality sampling, and monitoring/sampling during the ASR pilot test. All samples for the duration of the pilot test were collected in laboratory supplied bottles, stored on ice, and transported to TestAmerica in West Sacramento for analysis. Pilot test field activities are described in the following sections.

2.1 Development and Pumping Tests

TW-6A is an 8-inch diameter PVC well, installed to a depth of 230 feet with a total of 80 feet of 40-slot mill-slot screen. The well was completed during June 2016 (GEI, 2016) in a small at-grade Christy box, but was solely used for monitoring groundwater-levels and temperature until the startup of the ASR pilot test. During January 2018, Bartley Pumping was selected via competitive bid to complete additional development of the well and to install a pump in TW-6A for the pilot test. The depth to groundwater was approximately 70 feet below ground surface (bGS) and below the top of the well casing (bTOC) during late January 2018 and early February 2018.

The development process included the application of approximately 25 pounds of the Aqua-Clear® PFD, which is a Baroid-brand polymer dispersant to facilitate the removal of mud and sediments from filter pack and the formation. The Aqua-Clear® was installed via a tremie pipe into the two screen intervals, which were agitated via swabbing for approximately two hours, and then allowed to remain in the well overnight. TW-6A was alternately bailed and swabbed for an additional four hours to remove fines from the bottom of the well and from the filter pack and formation.

TW-6A was further developed via pumping and surging[1] (45 surges) for seven hours at variable rates up to about 160 gallons per minute (gpm). The City allowed the pump from City Well 6 (CW-6) to be used in TW-6A because the existing electrical controls facilitated the pumping operations. The pump was set into the blank screen between 160 and 170 feet. About 46,500 gallons of groundwater were removed from the well (mean rate: ~110 gpm) by developmental pumping and discharged to the nearby creek channel under the City's existing permit with the National Pollutant Discharge Elimination System (NPDES) after flowing through two 6,000-gallons tanks provided by the City. The tanks allowed solids to settle before the discharge to the channel.

[1] Water is pumped to surface and then pumping is stopped which allows the water in the pump column to fall back into the screen. This sudden inflow of water redistributes the filter pack and facilitates the removal of fine-grained material, which improves the flow of groundwater into the well.

An 8-hour step-drawdown pumping test was completed with four 2-hour steps to define the optimal pumping capacity of TW-6A and a 1,456-minute constant-rate pumping test was completed to further define the hydraulic properties of the aquifer. **Table 1** summarizes the details of these pumping tests.

The specific capacity values are relatively low (about 2 gpm per foot of drawdown) and showed a steady and relatively linear decline during the step-drawdown test – about 4% to 5% between the steps. For the constant-rate pumping test, the 2-hour specific capacity was comparable to the step-drawdown values but was lower (~6%) at the end of the 24-hour period. These pumping tests provided the initial operational basis for the ASR pilot test – 60 gpm for injection and 110 gpm for backflushing.

The constant-rate pumping test provided data to estimate the hydraulic properties of the aquifer system in the vicinity of the TW-6A (pumping well) and CW-6 (observation well). CW-6 is located about 60 feet to the northwest of TW-6A. According the Pueblo memorandum, dated February 28, 2018 (Appendix D), the transmissivity is about 9,200 gallons per day per foot for the 230-foot well and the storage coefficient is 10^{-7}, which denotes a highly confined aquifer. The hydraulic conductivity was estimated to be 115 gallons per day per square foot or about 15 feet per day, which is typical for fractured volcanics, a coarse-grained silty sand, or a medium-grained clean sand (Heath, 1983).

Table 1. Details of Pumping Tests

Step (2-hour intervals)	Gallons Pumped	Pumping Rate, gpm	Final Pumping Water Level	Drawdown (Static Water Level = 69.8’)	Specific Capacity, gpm/foot
1	6,300	53	94.5’	24.7’	2.1
2	9,600	80	110.2’	40.4’	2.0
3	12,800	107	126.3’	56.5’	1.9
4	15,600	130	142.6’	72.8’	1.8
Total	**44,300**				
Constant-Rate Pumping Test (24-hour)	132,700	91	119.7	49.7 (Static Water Level = 70.0’)	1.8
At 2 hours	11,000	92	116.8	46.8	2.0

2.2 Well Modifications

Well modifications to TW-6A were completed between February 15, 2018 and February 19, 2018; following the additional pump testing and development of the wells. Down-well modifications were completed by Bartley Pumping. Written instructions for the modifications were provided by GEI, in coordination with Pueblo, and were overseen by GEI staff. A groundwater pump was installed to a depth of about 160 feet bTOC, between the upper and lower screen intervals (130-160’ and 170-220’). Five (5) schedule 40 PVC injection tubes were installed and secured to the pump column at a depth of 80 feet bTOC, or approximately 10 feet below the static water level. The bottom of each injection tube was completed with an orifice end cap of a specific size. Each orifice was created with a hole-saw drilling bit, to sizes listed below in **Table 2**, which limited the flow of water into the well and created back pressure to maintain a full tube of water during injection. Bartley Pump installed a well cap with threaded couplings for the 3-inch diameter steel discharge piping and for the 1-inch diameter, threaded PVC injection tubes. Electrical wiring was then cut and installed in a waterproof conduit for connection to the variable frequency control box.

Injection tubing was color coded (**Table 2**) with tape during installation to ensure the identification of the orifice diameter at the surface. The selection of tubes and valves allowed for the fine tuning of injection flow rates. Pre-test activities, as discussed below, identified a crack in the T-connection of Tube #4, and this tube connection was eliminated.

Table 2. Injection Tube Details

Injection Tube #	Injection Tube Color	End-Cap Perforation Diameter
1	Red	5/8" (0.63")
2	Blue	3/4" (0.75")
3	Green	3/4" (0.75")
4*	White	7/8" (0.88")
5	Brown	7/8" (0.88")

*Removed during injection testing

The City furnished and installed the injection and discharge water piping from the wellhead, two flow meters, valves, pressure gages, and other appurtenances. In addition, the City replaced the small Christy Box with a 16-square foot wooden enclosure large enough to house all infrastructure at the wellhead. The 1-inch diameter injection tubes were connected to a 2-inch diameter PVC manifold that was connected to piping to the nearby Sonoma Water potable water supply pipeline. The manifold also included a connection to a 2-inch diameter fire hose in the event the injection piping needed flushing. Pressure gages were installed at the wellhead on each injection tube and at the connection to the potable supply pipeline. Valves were installed on each injection tube upstream of the pressure gage and both upstream and downstream of the flow meter. A pressure gage and sampling port was installed on the injection piping near the connection to the potable supply pipeline. **Figure 2** and **Figure 2** show the completed wellhead modifications and the equipment at the connection to the supply pipeline, respectively.

(Pump-to-waste via flexible hose.)

Figure 2. Wellhead Modifications

Figure 3. Supply Pipeline with Sampling Port and Flow Meters

The City also installed discharge piping from the wellhead to the two (2) interconnected 6,000-gallon settling tanks with PVC piping installed from the second settling tank to the adjacent drainage channel. **Figure 4** shows the discharge piping along with the settling tanks.

Figure 4. Discharge Piping from Settling Tanks

2.3 Pre-Test Activities

Pre-test activities were conducted by GEI, Pueblo, the City, and Sonoma Water on March 19 and 20, 2018. Pre-test activities included the following:

- Sampling of CW-6 and the potable water from the supply pipeline to define pre-test base-line chemistry.
- Pumping of TW-6A (20 minutes at 110 gpm) to determine a short-term specific capacity baseline prior to injection activities.
- Brief injection tests of the tubes (10 to 20 minutes each) to determine their individual flow and back pressure limits.
- Installation of Distributed Temperature Sensing (DTS) equipment in CW-6 by Sonoma Water to better define the depth intervals affected by the injection and recovery of water at TW-6A.
- Injection test of tube combinations for 130 minutes at various rates between 10 and 75 gpm (step injections) followed by backflush pumping for 26 minutes at 116 gpm.
- Injection test of tubes at 55 gpm for 18 hours (constant injection) followed by four 10- to 15-minute periods of backflush pumping at rates between 105 and 112 gpm.

Sonoma Water had previously installed water level probes at both TW-6A and CW-6, along with City Well No. 8 (CW-8) located approximately 840 feet from TW-6A, to document the response to the injection and recovery of water at TW-6A.

Prior to completing the above 'calibration' injection tests, the piping between the potable water supply pipeline and the injection manifold was flushed to the nearby drainage channel to better ensure that fine particle in the piping were not injected into TW-6A. Silt Density Index (SDI) tests was performed on the potable water along with the measurement of water quality field parameters. The SDI tests measured fines solids in the supply water that could have reduced the injection performance of TW-6A. The potable water was excellent quality and the SDI results quickly declined to less than 2. During the flushing, the potable water was discharged under the City's NPDES existing permit through a dechlorinating diffuser to the adjacent channel (**Figure 5**). In addition, backflush pumping was performed after the above injection tests (and after each injection period during the pilot test) to clear potential solids in the potable water that could accumulate on the screen and in the gravel pack.

The total volume of water used during pre-test activities was:

- Approximately 5,100 gallons were flushed through the piping between the supply pipeline and the injection manifold.
- Approximately 3,600 gallons were pumped from TW-6A during the pump installation / connection process and for the initial short-term specific capacity test.
- Approximately 68,000 gallons or 0.2 acre-feet (AF) of potable water were injected during the pre-test activities.
- Approximately 9,200 gallons were pumped from TW-6A as backflush after the pre-test injections.

Figure 5: Discharge of Water to Drainage Channel via Dechlorinating Diffuser

Baseline water quality samples were collected for CW-6 and the potable water supply pipeline. CW-6 was sampled after pumping at about 15 gpm until at least three well volumes (+750 gallons) were purged from the well. The potable water was sampled during the step injection tests. Baseline water quality data for TW-6A, CW-6, and the potable water can be found in the next section in **Table 11** through **Table 13**. Laboratory reports are present in **Appendix C**.

A 24-hour constant rate injection test was completed by Pueblo on March 20 as a final check of injection capabilities prior to the start of the pilot test. During testing, Pueblo periodically monitored flow rate, pressure at the supply piping and at each injection tube, 'draw-up' in the wells and total injected water volume. During the 24-hour test, the performance of the injection tubes was monitored to better define the optimum number of tubes and associated backpressures to obtain the desired injection rates. After completion of the 24-hour test, TW-6A was backflushed in 20-minute intervals until turbidity stabilized around 5 NTU or lower. Shortly thereafter, the ASR pilot test began.

2.4 Pilot Test

Field monitoring and pilot test operations were jointly conducted by GEI and the City. Daily monitoring of operations and infrastructure repairs were conducted by the City while routine inspection, field sampling, and oversight of the pilot test was performed by GEI. The pilot test was divided into three cycles with three periods per cycle: injection, storage, and recovery periods. During each site visit, water levels were measured at CW-6 and TW-6A, totalizer readings were recorded from the meters on the potable water supply piping and extraction piping, as well as flow rates. **Table 3** provides a schedule for each injection, storage, and recovery period per cycle.

Table 3. Schedule of ASR Cycles at TW-6A

Cycle	ASR Period & Cycle	Dates in 2018		Comments
		Start	End	
1	Injection 1	March 21 at 13:30	March 27 at 13:30	Backflush pumping after injection
	Storage 1	March 27 at 15:50	April 03 at 11:30	
	GW Recovery 1	April 03 at 11:30	April 09 at 12:05	
2	Injection 2	April 09 at 13:55	April 27 at 10:35	Backflush pumping and specific capacity test after injection
	Storage 2	April 27 at 12:40	May 21 at 12:30	
	GW Recovery 2	May 21 at 12:30	June 04 at 09:55	
3	Injection 3	June 04 at 11:55	June 22 at 08:40	Backflush pumping and specific capacity test after injection
	Storage 3	June 22 at 10:45	September 04 at 13:10	
	GW Recovery 3	September 04 at 13:10	September 20 at 08:40	

Injection

City staff performed daily monitoring during injection cycles. This monitoring included:

- Totalizer readings to determine total injected volume,
- Water level measurements at TW-6A and CW-6,
- Recording pressure values at the supply main and injection tubes and injection flow; and,
- Adjusting flow in injection tubes to maintain desired injection rate (approx. 70 gpm).
- Set-up and operation of the dechlorinating diffuser in the drainage channel.

GEI staff conducted start-up, intermittent monitoring, and shut-down of injection cycles, including:

- Initial set-up of injection tubes and flow,
- SDI testing to monitor for sediments,
- Sampling of injection water and testing for field parameters; and,
- Backflushing of TW-6A following each injection period.

Once injection to the well was established at the desired rate and pressure, SDI testing was performed to ensure that potable water did not pose a risk of plugging the well. If repeated SDI results had exceeded the threshold of 2, injection to the well would have stopped and the piping flushed to the drainage channel. This condition did not occur during the pilot test as SDI values (Pueblo, 2019) varied between 0.30 and 2.15 (unitless) during the three injection cycles (median: 0.55). In addition, GEI collected three samples of the potable water over the course of the pilot study to identify any changes in water chemistry or properties that may adversely affect well performance.

TW-6A was backflushed at 100 to 110 gpm following each injection period. Backflushing occurred in 15-minute intervals until turbidity was consistently at or below 5 NTU. Totalizer meter readings were recorded for both injection and backflushing to monitor total injected and extracted water volumes.

Storage

During the storage periods, monitoring was reduced to intermittent sampling of the well by GEI and City staff to monitor for changes in water quality and well operations that may result as the injected supply water interacts with native groundwater.

Sample procedures were as follows:

- TW-6A was pumped at 80 to 90 gpm,
- CW-6 was pumped at about 15 gpm while purging at least three (3) well volumes,
- Field water quality parameters were measured periodically and recorded prior to sample collection, and
- Specific capacity was recorded over the first 10 minutes of extraction.

Groundwater extracted from TW-6A was discharged to a pair of tanks to allow any fines to settle prior to the discharge to the adjacent drainage channel. Extracted groundwater from CW-6 was discharged directly to the creek under the City's existing NPDES permit. Both discharges from TW-6A and CW-6 were de-chlorinated via a diffuser (**Figure 5**) to eliminate residual chlorine that may be present due to the chlorinated potable water.

Groundwater Recovery

During the recovery periods, TW-6A was operated continuously at approximately 85 gpm to the settling tanks and then discharged through the de-chlorination diffuser into the adjacent drainage channel. City staff performed daily monitoring of recovery operations which included:

- Recording TW-6A extraction rates, totalizer values and total extracted volumes,
- Water level measurements, and
- Ensuring adequate de-chlorination tablets were in the diffuser.

CW-6 was purged of three well volumes prior to sampling. (Purging of TW-6A was not required as extraction was continuous.)

Field water quality parameters were measured during throughout the pilot test for TW-6A, CW-6, and the potable water. These parameters provide an initial assessment of water quality. Field water quality results are shown in the following tables.

Table 4. Field Parameters SCWA Supply Water

`

SCWA Supply Pipeline:		Injection 1 Injection Water	Injection 1 Injection Water	Injection 2 Injection Water	Injection 2 Injection Water	Injection 2 Injection Water	Injection 3 Injection Water	Injection 3 Injection Water
Date:	Units	20-Mar-18	27-Mar-18	09-Apr-18	18-Apr-18	27-Apr-18	04-Jun-18	22-Jun-18
Temperature	°C	13.54	14.06	16.21	15.02	13.84	18.29	19.36
pH		8.20	8.30	7.86	7.91	8.10	8.10	7.99
Specific Conductance	µS/cm	287	224	282	278	284	314	278
Dissolved Oxygen	mg/L	7.11	6.74	7.85	7.56	11.31	6.23	6.74
	%	68.5	65.5	79.6	75.0	109.4	66.3	73.2
ORP	mV	574	565	584	580	627	537	558
Turbidity	NTU	0.26	0.54	0.22	0.25	0.50	1.91	0.13
Chlorine	mg/L	0.70	0.70	0.59	0.66	0.67	0.85	0.78
Hydrogen Sulfide	mg/L	ND	ND	ND	ND	ND	ND	ND

Notes:
ND = Non-detect
NA = No analysis

Table 5. Field Parameters CW-6

Well:		Before ASR CW-6	Storage 1 CW-6	Recovery 1 CW-6	Injection 2 CW-6	Storage 2 CW-6	Recovery 2 CW-6	Injection 3 CW-6	Recovery 3 CW-6
Date:	Units	19-Mar-18	29-Mar-18	09-Apr-18	27-Apr-18	21-May-18	04-Jun-18	22-Jun-18	20-Sep-18
Temperature	°C	22.67	21.15	24.41	16.59	20.36	23.75	19.98	21.33
pH		7.14	6.86	6.76	6.95	7.51	6.82	6.85	6.98
Specific Conductance	µS/cm	185	201	195	239	246	214	245	205
Dissolved Oxygen	mg/L	4.25	5.07	4.74	10.01	5.39	4.76	6.13	6.31
	%	NA	57.1	NA	103.4	59.6	56.1	67.5	71.2
ORP	mV	NA	NA	5	693	120	36	591	53
Turbidity	NTU	3.26	1.11	0.67	0.21	0.28	0.24	0.22	0.33
Chlorine	mg/L	ND	ND	ND	0.13	ND	ND	0.22	ND
Hydrogen Sulfide	mg/L	ND	ND	ND	ND	ND	ND	ND	ND

Notes:
ND = Non-detect
NA = No analysis

Table 6. Field Parameters TW-6A

		Storage 1	Storage 1	Recovery 1	Recovery 1	Storage 2	Storage 2	Storage 2	Storage 2	Recovery 2	Recovery 2	Storage 3	Storage 3	Storage 3	Storage 3	Storage 3	Storage 3	Storage 3	Storage 3	Recovery 3	Recovery 3	Recovery 3
Well:		TW-6A	TW-6A	TW-6A	TW-6A	TW-6A	TW-6A	TW-6A	TW-6A	TW-6A	TW-6A	TW-6A	TW-6A	TW-6A	TW-6A	TW-6A	TW-6A	TW-6A	TW-6A	TW-6A	TW-6A	TW-6A
Date:		29-Mar-18	03-Apr-18	05-Apr-18	09-Apr-18	01-May-18	10-May-18	17-May-18	21-May-18	29-May-18	04-Jun-18	28-Jun-18	05-Jul-18	12-Jul-18	23-Jul-18	01-Aug-18	09-Aug-18	15-Aug-18	28-Aug-18	04-Sep-18	06-Sep-18	20-Sep-18
	Units																					
Temperature	°C	14.75	15.02	18.75	22.03	14.49	16.02	16.37	16.48	18.56	21.68	15.57	15.58	19.48	19.89	18.13	19.57	18.08	20.09	15.83	17.46	19.87
pH		8.00	7.76	7.04	6.89	7.87	7.74	7.92	8.30	6.80	7.01	8.14	8.01	7.28	7.68	7.52	7.81	7.77	7.57	7.58	6.96	7.38
Specific Conductance	µS/cm	278	226	254	211	280	275	283	296	234	237	323	314	314	340	313	312	313	299	287	301	221
Dissolved Oxygen	mg/L	6.08	6.88	6.61	5.78	11.31	8.72	6.74	7.11	7.65	6.42	7.07	6.87	6.99	8.40	5.72	5.92	6.21	6.06	5.99	6.83	8.43
	%	59.9	68.3	70.9	66.1	111.0	88.3	68.8	72.9	NA	73.3	70.9	69.0	76.1	92.3	60.6	64.6	65.8	66.8	60.7	71.4	92.9
ORP	mV	164	550	448	-26	588	250	137	296	65	53	557	164	48	46	-4	-32	121	91	-71	130	107
Turbidity	NTU	0.86	0.40	0.19	0.11	0.59	0.60	0.36	0.48	0.23	0.12	0.87	0.46	0.25	1.08	1.12	0.67	0.60	0.69	3.52	2.39	0.54
Chlorine	mg/L	0.18	0.13	ND	0.02	0.15	ND	ND	ND	ND	ND	0.15	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Hydrogen Sulfide	mg/L	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Specific Capacity	gpm/ft	2.20*	2.11	NA	NA	1.95*	2.06*	2.07*	NA	NA	NA	NA	2.21	NA	2.23	2.23	2.25	2.30	2.22	NA	NA	NA

Notes:
ND = Non-detect
NA = No analysis
* Specific capacity calculated using drawdown at 10-minutes and a rate of 80 gpm, 85 gpm where denoted by an asterisk

Minimal change in the water quality of the potable water was observed during the pilot test, except for the temperature increase between March and June. Comparison of native groundwater prior to injection activities to the potable water shows that the potable water is somewhat more alkaline with significantly higher oxidation-reduction potential (ORP) values and lower temperatures than native groundwater. Chlorine was also present in the potable water but not in the native groundwater. The pH, ORP, temperature, and chlorine are distinctive characteristics of the potable water. Dissolved oxygen and specific conductance were monitored as well.

During and after injection of the potable water, the pH of the groundwater will rise as the more alkaline potable water mixes with the native groundwater. A slight rise in chlorine concentrations occurs immediately following the injection of the potable water, but these concentrations quickly subside to or below the detection limit (0.01 mg/L) as the injected water is diluted by the native groundwater. ORP also spikes up significantly during injection and slowly falls back towards 100 mV during storage and recovery cycles.

Throughout the duration of the pilot test, specific capacity and turbidity were recorded to monitor any changes in well performance. Specific capacity is a measure of the production of a well per unit of drawdown and is reported as gpm/ft. For consistency, the 10-minute specific capacity was measured at TW-6A during sampling. Specific capacity throughout the pilot test remained relatively steady at about 2.0 to 2.2 gpm/ft for extraction rates of 80 to 85 gpm, indicating little reduction in well performance during the pilot test.

3. Pilot Test Operations

Pilot test operations occurred at TW-6 between from March 21, 2018 to September 20, 2018, and included three cycles of injection, storage, and recovery (three periods per cycle). Groundwater levels were monitored throughout the pilot test at TW-6A, CW-6, and CW-8 to better define the hydraulic character of the aquifer system. Water samples were collected periodically during the test from TW-6A, CW-6, and the potable supply piping for laboratory analysis of the water chemistry which was used for geochemical modeling.

3.1 ASR Cycles

According to the Technical Report (GEI, et al, 2017) – i.e. work plan, the pilot test was intended to last 132 days (4.3 months) and operate at 100 gpm for injection and 150 gpm for recovery. The actual test operated for 185 days (6.0 months) and the flow rates were notably less due to hydraulic limitation of TW-6A. **Table 7** summarizes the characteristics of each ASR cycle. Except for the third storage period, the other period durations were comparable to the plan durations (-1 to +3 days) and were varied to accommodate weekend and other schedule limitations. The third storage period was extended by 44 days to better define the concentrations of trihalomethanes (THMs).

Table 7. Details of ASR Cycles at TW-6A

Period & Cycle	Duration, days		Water Volume, total gallons				Mean Flow Rate, gpm
	Actual	Plan	Injection	Backflushing	Sampling	Recovery	
Pre-ASR Test	2		68,000	-9,220			54 -114
Injection 1	6	6	482,950				56
Storage 1	7	7		-6,650	-1,640		-105 / -82
GW Recovery 1	6	4				-712,320	-82
Injection 2	18	19	1,735,970				67
Storage 2	24	21		-5,970	-11,110		-107 / -82
GW Recovery 2	14	13				-1,644,890	-82
Injection 3	18	19	1,817,770				71
Storage 3	74	30		-6,170	-21,080		-104 / -81
GW Recovery 3	16	13				-1,736,020	-76
ASR Pilot Test Total	**185**	**132**	**4,036,680**	**-18,790**	**-33,830**	**-4,093,230**	Planned Injection rate: 100 gpm Planned recovery rate: 150 gpm
				-4,145,850			
Overall Total			**4,104,680**	**-4,155,070**			

The overall injection rates increased from 56 to 71 gpm, 30% to 40% less than the planned rate, and the recovery rates decreased from 82 to 76 gpm, nearly 50% less than the planned rate. The total recovery volume for the three ASR cycles was about 4.15-million gallons (12.7 AF) versus the planned volume of 6.3-million gallons (19.3 AF). Overall, the recovery volume exceeded the injection volume by about 50,400 gallons (excluding the pumping volumes prior to any injection).

3.1.1 Water Level and Temperature Data

Groundwater levels were recorded at various time intervals during the pilot test at TW-6A, CW-6, and CW-8 using a pressure transducer to measure changes in groundwater levels. These probes were also equipped with a temperature sensor. Significant amounts of data were recorded for each well and these data were culled to produce values at relatively uniform 15-minute time intervals. **Figure 6** is a hydrograph for TW-6A, CW-6, and CW-8. **Table 8** provides summary information about the groundwater level data for each period and cycle.

Groundwater Levels

Figure 6 appears to be complicated illustration but is really a repetition of three sets of conditions that can be described as follows. Each ASR cycle is composed of an injection period (blue shading), a storage period (orange shading) and a recovery period (green shading). Groundwater level (WL) depths are shown by a black line for TW-6A and by a red line for CW-6.

Sampling events can affect the WL depths, so sampling events are shown by a black triangle for TW-6A and by a red dot for CW-6 at the bottom of the hydrograph. (Sampling of the potable water is shown by a blue cross at the top of the hydrograph.) WLs were not recorded for two periods at TW-6A due to probe malfunction (Injection 2, Storage 3), and at CW-8 (Storage 1 and Recovery 1).

TW-6A WL depths were about 67 feet below top of casing (bTOC) during mid-March, prior to the pilot test and were about 76 feet bTOC after the test during late September, notwithstanding the effects from pumping at nearby CW-8. Similarly, CW-6 WL depths were about 70 and 79 feet bTOC, respectively, and CW-8 WL depths were 61 and 70 feet bTOC. These WL differences are not significant and are due to respective differences in the TOC location (below-grade versus above-grade), topography (lower versus higher), and the 60-foot distance between TW-6A and CW-6 and the 840-foot distance between TW6A and CW-8. The overall 9-foot WL declines in these wells over the 6-month test period is consistent with historical fluctuations recorded at CW-6, but considerably less than the mean 40-foot seasonal decline in WL depths during 2014 to 2016 at a nearby 245-foot deep CASGEM well (1.2 miles southeast).

The overall WL trends of TW-6A were matched to a lesser degree by the WLs of CW-6, as would be expected from an observation well at a distance of 60 feet, and by CW-8 to a much lesser degree due to its much greater distance. The WLs were most variable during the injection period, especially at TW-6A, due to the relatively turbulent nature of injecting water into the aquifer plus variations in the water supply flow, pressure, and temperature. WL trends were much smoother during the storage and groundwater recovery periods.

Table 8. Summary of Depth to Groundwater Data – Median Value[1]

Period & Cycle	TW-6A Depth to Water	TW-6A WL Change[2] since previous	TW-6A WL Storage Change[3]	CW-6 Depth to Water	CW-6 WL Change[2] since previous	CW-6 WL Storage Change[3]	Comments on TW-6A and CW-6	CW-8 Depth to Water	CW-8 WL Change[2] since previous	CW-8 WL Storage Change[3]
Before Pilot Test	67.1’			70.1’			Difference in WL depths due to respective below-grade and above-grade reference points, topography, and the 60-foot distance between wells	61.4’		
Injection 1	30.1’	37.0’		58.1’	11.9’			60.1’	1.3’	
Storage 1	66.0’	-35.9’	1.1’	69.1.	-11.0’	0.9’		No data	No data	No data
GW Recovery 1	114.6’	-48.7’		86.3	-17.2’		Excludes CW-6 sampling (1.5 hours) at end of Recovery 1	60.7’	No data	
Injection 2	16.9’	97.7’		53.5’	32.8’			58.4’	2.3’	
Storage 2	65.2’	-48.3’	0.8’	68.4’	-14.9’	0.7’		59.5’	-1.1’	No data
GW Recovery 2	115.5’	-50.3’		86.8’	-18.4’			61.3’	-1.8’	
Injection 3	20.3’	95.2’		53.9’	32.9’			59.1’	2.2’	
Storage 3A	70.0’	-49.7	-4.8’	72.8’	-18.9’	-4.4’	Before interference from nearby well	64.5’	-5.4’	-5.0’
Storage 3B	75.5’	-5.5’		78.7’	-5.9’		Interference from CW-8	81.8’	-17.3’	
Storage 3C	73.7’	1.8’	-8.5’	76.6’	2.1’	-8.2’	WL recovery after CW-8 interference	68.4	13.4’	-8.9
GW Recovery 3	120.2’	-46.5’		94.4’	-17.8’			70.3	-1.9’	
After Pilot Test	76.0’	44.2’		78.7’	15.7’		Before interference from CW-8	69.8	0.5’	
End of WL Data	78.6’	-2.6’		81.7’	-3.0’		Interference from CW-8	84.3	-14.5’	

1 Median value for 8-hour period prior to end of cycle

2 Positive value denotes WL rise since end of last cycle, negative value denotes WL fall

3 Positive value denotes higher WL at end of storage cycle compared to previous storage cycle, negative value denotes lower WL

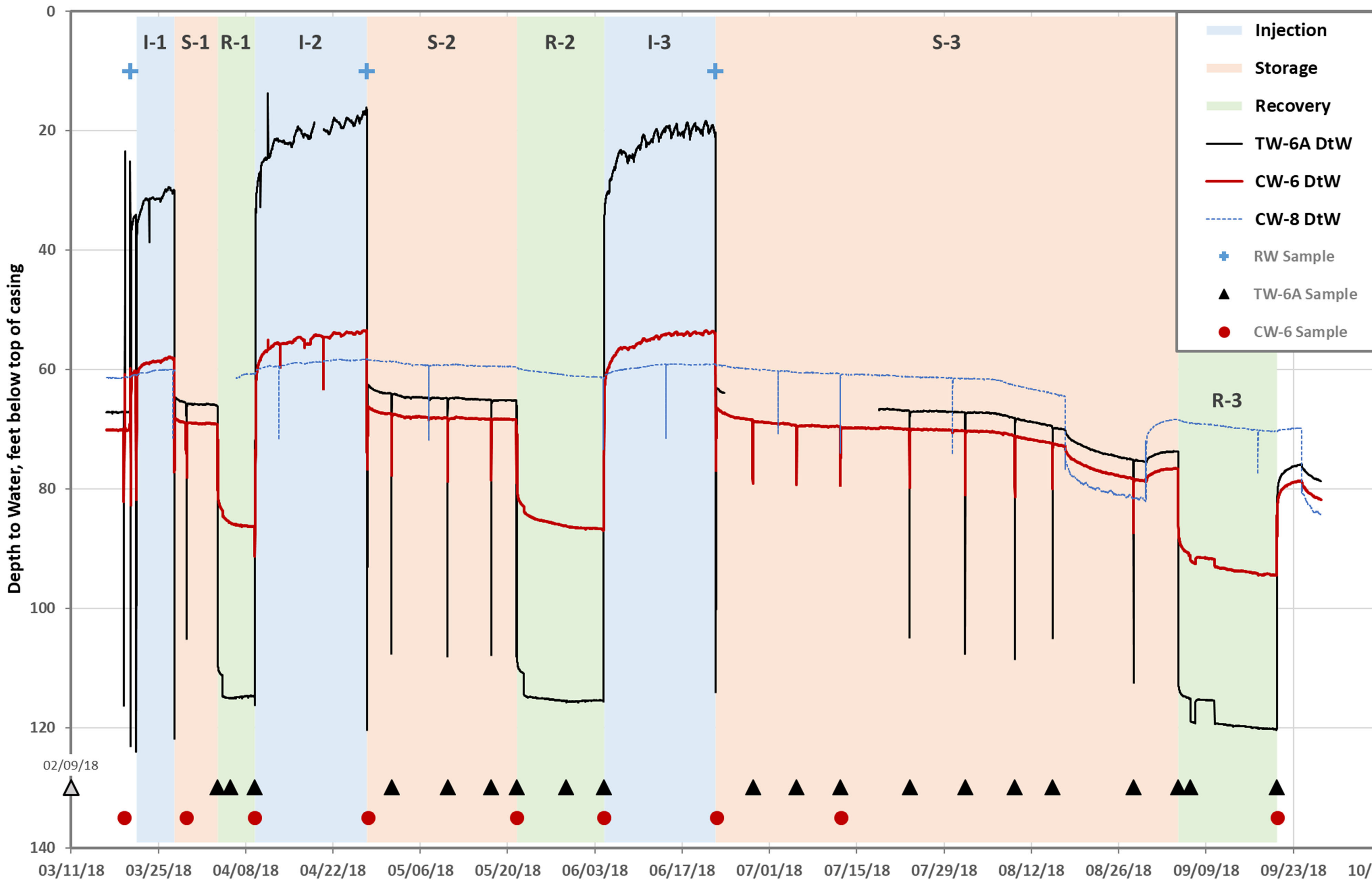


Figure 6. **Hydrograph for Wells TW-6A, CW-6, and CW-8**

The hydrograph starts on the left with three horizontal lines of static WLs and is followed by a brief period of erratic WLs at TW-6A and CW-6 during the initial calibration testing of the ASR equipment. The WLs for the first and second ASR cycles are similar even though the duration and injection volume of the second cycle are three times longer.

During the first ASR cycle, TW-6A WLs rose 37 feet to a depth of 30 feet bTOC by the end of the 6-day injection of nearly 0.5 million (M) gallons of water at an average flow rate of 56 gpm, and CW-6 WLs rose about 12 feet to a depth of 58 feet bTOC and CW-8 WLs rose about 1 foot to a depth of 60 feet bTOC. By the end of the 7-day storage period, WLs declined in both primary wells but were about one foot higher than their pre-ASR static WL. By the end of the 6-day groundwater recovery period, WLs decreased by nearly 50 feet at TW-6A and by 17 feet at CW-6 after pumping over 0.7 M-gallons. WL data were not available for CW-8 during the storage period and much of the recovery period due to a malfunction with the transducer.

During the second ASR cycle, TW-6A WLs rose to higher level – 17 feet bTOC by the end of the 18-day injection of over 1.7 M-gallons of water at an average flow rate of 67 gpm. CW-6 WLs rose to a depth of 54 feet bTOC and CW-8 WLs rose to a depth of 58 feet bTOC. By the end of the 24-day storage period, WLs declined in both wells but were nearly one foot higher (65 and 68 feet bTOC respectively) than their prior storage static WLs (66 and 69 feet respectively). By the end of the 14-day groundwater recovery period, WLs decreased by 50 feet at TW-6A, by 18 feet at CW-6, and by nearly 2 feet at CW-8 after pumping over 1.6 M-gallons.

During the third ASR cycle, TW-6A WLs rose to 20 feet bTOC by the end of the 18-day injection of over 1.8 M-gallons of water at an average flow rate of 71 gpm. CW-6 WLs rose to a depth of 54 feet bTOC and CW-8 rose to a depth of 59 feet. After 45 days of storage, WLs had declined in each well: 67 feet at TW-6A, 70 feet at CW-6, and 62 feet at CW-8 bTOC – about the same depths at the start of the pilot test, when the downward slope of the WL trends increased slightly in the three wells. The cause of this slope change is not readily apparent but could be due to pumping at a distance well.

On the 56th day of storage, WLs were about 70 feet bTOC at TW-6A and 73 feet bTOC at CW-6 – about 2 feet deeper than the projection of the original slopes, when these WLs started to decline further due to pumping at CW-8. The 13-day operation of CW-8 produced over 17 feet of drawdown at CW-8, over 5 feet of drawdown at TW-6A, and nearly 6 feet of drawdown at CW-6. The third storage period lasted another 5 days and WLs rebounded to about 74 feet bTOC at TW-6A, 77 feet bTOC at CW-6, and 68 feet bTOC at CW-8. By the end of the 16-day groundwater recovery period, WLs decreased by over 46 feet at TW-6A, by nearly 18 feet at CW-6, and by 2 feet at CW-8 after pumping over 1.7 M-gallons.

Brief WL drawdowns occurred during the transition between injection and storage periods due to backflushing and specific capacity testing of TW-6A and sampling of CW-6; and during the storage periods due to periodic sampling of TW-6A and also for the sampling of CW-6. During the backflushing, testing, and sampling, WLs varied between 50 and 122 feet bTOC at TW-6A and between 59 and 77 feet bTOC at CW-6. During storage sampling, TW-6A drawdown varied from 35 to 43 feet (median: 40 feet) for 9 of 12 events, depending on pumping rate and duration, which caused drawdown at CW-6 that varied between 6 and 11 feet (median: 10 feet) for 12 events. The CW-6 sampling drawdown was about 5 feet for two storage sampling events, which caused a 2-foot drawdown at TW-

6A. CW-6 was sampled at the end of the first groundwater recovery period and increased the drawdowns by similar values. Nearly 53,000 gallons of groundwater were pumped from TW-6A during the backflushing, testing, and sampling work and over 7,300 gallons were pumped from CW-6 prior to sampling at CW-6 during the pilot test (0.06 M-gallons total).

Note that, during each recovery period, WLs dropped suddenly at the start of each period, as expected, but then dropped again by 3 to 4 feet at TW-6A and by nearly 1 foot at CW-6 after 20 hours during the first period, after 27 hours of pumping during the second period, and after 47 hours during the third period. These deeper WLs were relatively sudden and remained throughout the duration of the first two recovery periods. During the third period, the deeper WLs rebounded after about 20 hours and then reoccurred during the sixth day of recovery and remained throughout the duration of the last recovery period. These deeper WLs are likely due to adjustments in pumping rates at TW-6A and were not observed at the more distance CW-8. (The operation of a nearby well would have produced a more gradual WL decline and should have been apparent at CW-8.)

WLs were measured for seven days after termination of the ASR pilot test. During the first four days WLs rebounded normally to about 76 feet bTOC at TW-6A, 79 feet bTOC at CW-6, and 70 feet bTOC at CW-8 – nearly 9 feet deeper than the pre-test levels. The operation of CW-8 caused the WLs to decline by about 3 feet at TW-6A and CW-6 during the last three days of the post-test period, and by 14 feet at CW-8.

Groundwater Temperature Data

Figure 7 is a time-series plot of water temperature (degrees Fahrenheit or ^{o}F) in TW-6A, CW-6, and CW-8; and **Table 9** provides summary information for temperature data for each period and cycle. This figure and table were constructed in parallel with the figure and table for groundwater levels, as discussed above.

The water temperature data are also complicated but displayed repetitious conditions during much of the three period of each ASR cycle, similar to the WL data. In general, the temperature differences between TW-6A and CW-6 were greatest at the start of the pilot test but decreased during the progression of the test – overall and for each period. This convergence was likely due to overall increase in volumes and durations of each cycle and the variable conditions of starting the test in early spring and preceding until late summer. The temperature of CW-8 was several degrees higher than CW-6 and TW-6A and showed the least variation in temperature but the temperature of the well did respond to the ASR activities occurring 840 feet away, as discussed below.

Pre-ASR test conditions start on the left with relatively steady warmer temperatures (77^{o}F) for TW-6A compared to declining, cooler temperatures (71^{o}F) at CW-6. Conversely, temperatures at CW-8 are warmer (78^{o}F) but declining prior to ASR activities. The temperature differences prior to ASR activities are notable and the reasons for these differences are not known but are likely related to location and well construction. During the pre-test calibration activities, the temperature of TW-6A was variable but dropped by nearly 20^{o}F due to the use of the colder injection water, which was subject to ambient temperature conditions. Conversely, the variable temperature of CW-6 rose about 4^{o}F, which may have been due to relatively warmer water between the two wells being pushed toward CW-6 by the injection of water at TW-6A.

During each injection period, the TW-6A temperature data declined substantially from the previous period and were cyclic during the injection period as the overall temperatures were increasing, from the high 50s during March to the high 60s during June. These diurnal cycles and the overall increase were due to the ambient conditions of the supply pipeline. The daily range of temperatures varied up to 1° F during the first injection period in March, between 1.4 and 2.3° F during the second injection period in April, and between 0.7 and 1.9° F during the third injection period in June. The overall temperature at TW-6A decreased during the first injection period and during the first half of the second injection period at similar rates, whereas the overall temperature of the second half increased at twice the rate, presumably due to warmer weather in late April. The overall temperature at TW-6A continued to increase during the third injection period in June.

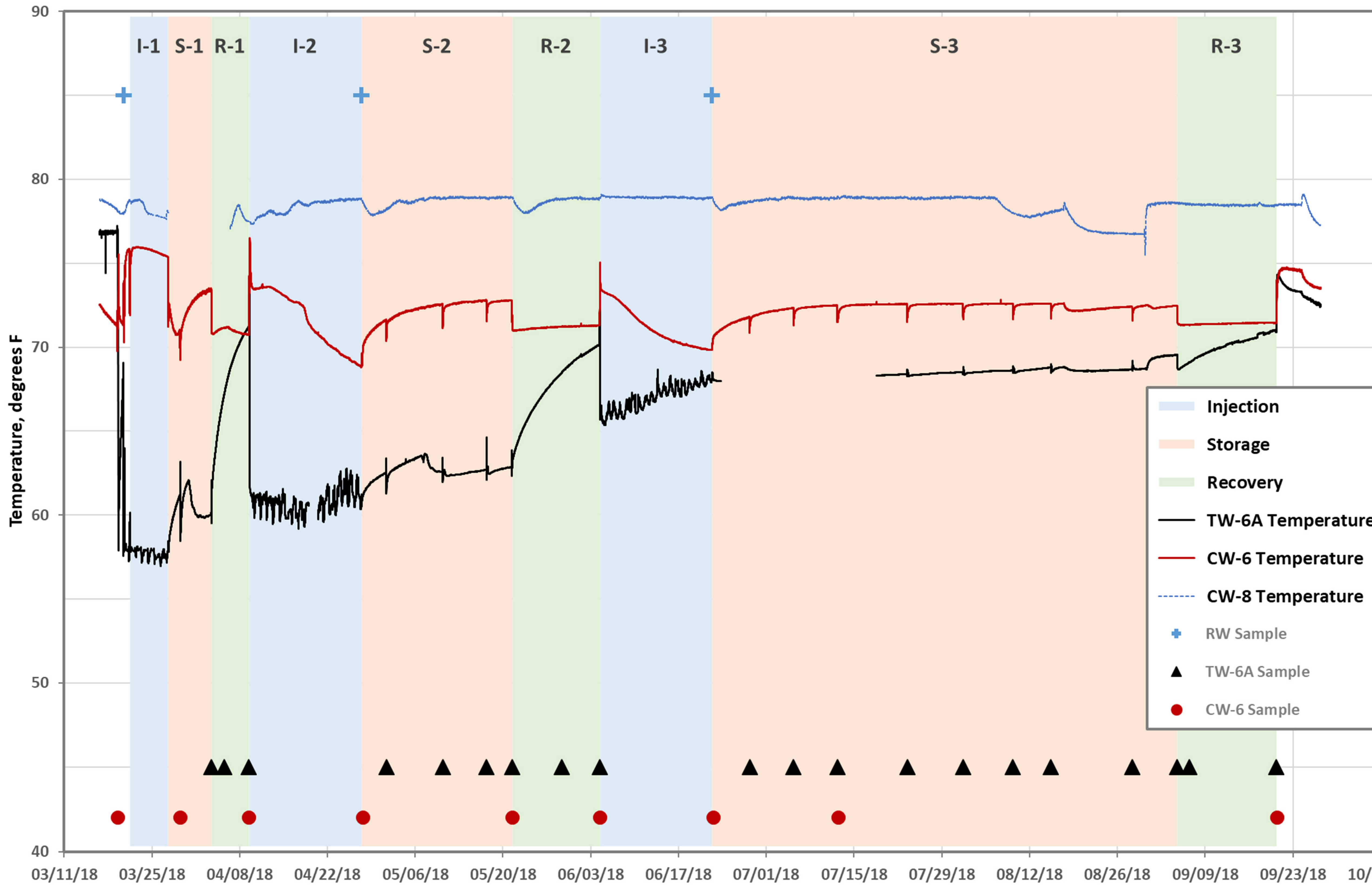


Figure 7. Groundwater Temperature at Wells TW-6A and CW-6

Table 9. Summary of Water Temperature (° F) Data – Median Value[1]

Period & Cycle	TW-6A	TW-6A Change since previous	CW-6	CW-6 Change since previous	Difference TW-6A minus CW-6	CW-8
Before Pilot Test	76.9		71.4		5.5	78.2
Injection 1	57.5	-19.3	75.4	4.0	-17.9	78.1
Storage 1	60.0	2.5	73.4	-2.0	-13.4	No Data
GW Recovery 1	71.1	11.1	70.8	-2.7	0.4	77.5
Injection 2	60.4	-10.7	68.9	-1.9	-8.4	78.9
Storage 2	62.9	2.4	72.8	3.9	-.9.	78.9
GW Recovery 2	70.1	7.3	71.3	-1.5	-1.2	78.8
Injection 3	68.0	-2.1	69.8	-1.4	-1.8	78.9
Storage 3A	68.8	0.8	72.6	2.8	-3.8	78.2
Storage 3B	68.7	-0.1	72.5	-0.1	-3.7	76.7
Storage 3C	69.5	0.8	72.5	0.0	-2.9	78.6
GW Recovery 3	71.0	1.5	71.4	-1.0	-0.4	78.5
After Pilot Test	73.3	2.3	74.5	3.1	-1.2	78.5
End of WL Data	72.5	-0.8	73.5	-1.0	-1.0	77.3

[1] Median temperature for 8-hour period prior to end of cycle

For CW-6, the temperature data were smooth (no diurnal cycles) during the injection periods and showed other, different characteristics in comparison to the data for TW-6A. The CW-6 temperature data increased at the start of each injection period over the previous period and then declined thereafter. The amount and rate of decline were minimal for the first injection period and but were greater (11X) and steeper (3X) during the second period. This difference may have been due to a minimal transfer of injected water to CW-6 during the first period, whereas, during the second period, a larger volume of injected water reached CW-6, possibly indicated by increase in slope during the middle of the period. During the third injection period, the temperature decline was somewhat less than the second period and the rate was midway between the first and second periods.

For the storage periods, the TW-6A temperatures generally increased until the middle of the first and second periods and then decreased to more stable values throughout the remainder of each period, except during sampling events. This initial increase at TW-6A was not recorded for the third storage period due to a malfunction with the temperature probe. However, TW-6A temperatures were recorded for latter portions ($^2/_3$) of the period, including a decrease in temperature during the operation of CW-8.

For CW-6, the temperature dropped abruptly (+3° F) due to backflushing and testing at TW-6A and continued to drop during the early portion of the first storage period and dropped further due to sampling at CW-6 and TW-6A. Thereafter, CW-6 temperatures rose until the first recovery period. For the second and third storage periods, CW-6 temperatures increased at the start and then leveled off for the duration of each period, except during sampling events and during the operation of CW-8.

The sampling events produced distinct spikes in the temperature data. The TW-6A spikes included abrupt changes in temperature, both increases and decreases, while the CW-6 spikes were only abrupt decreased in temperature. The largest spike amplitude (5 ^{o} F) at TW-6A occurred during the first storage period when the area was a mixture of native and injected groundwaters, and temperature differences were greatest. Thereafter, the amplitudes were progressively smaller, 1.5 to 2.5^{o} F during the second storage period and 0.6^{o} F during the third period. For CW-6, the sampling amplitudes decreased with time and varied from 1.9^{o} F during the first period to 1.5^{o} F during the second period to 1.1 and 1.3^{o} F during the third period.

The operation of CW-8 reduced the groundwater temperatures at TW-6A and CW-6 by 0.3^{o} F and 0.5^{o} F, respectively, at the start of the operation. Moreover, the TW-6A temperature increased to a somewhat higher values after CW-8 stopped operations.

During groundwater recovery, TW-6A temperatures increased throughout each period and then were followed by a brief, upward spike in temperature at the end of the period, which may be due to the cooling of the submersible pump motor after shutdown. For the first recovery period, TW-6A temperatures increased substantially (11^{o} F), while CW-6 temperatures dropped 2.7^{o} F at the start of the period and showed some variability during the period. For the second recovery period, TW-6A temperatures increased by over 7^{o} F while CW-6 temperatures dropped by 1.5^{o} F and showed little variation thereafter. For the third recovery period, TW-6A dropped initially by 0.9^{o} F and then increased by 2.4^{o} F by the end of the period, converging with the CW-6 temperatures, which dropped 1 ^{o} F at the start of the period and remained relatively steady thereafter.

After the termination of the pilot test, groundwater temperatures increased in both wells, initially by more than 3^{o} F. However, the TW-6A temperature started to decrease abruptly thereafter, while CW-6 temperatures continued to rise to a somewhat higher temperature for a short time and then started a gentle decline. The subsequent operation of CW-8 increased the temperature decline at CW-6 and at TW-6A to lesser extent. By the end of the data collection period, the groundwater temperature relationship had reversed between the two wells – TW-6A was cooler (73^{o} F) than the start of the test by 4^{o} F and cooler than CW-6 by 1^{o} F while CW-6 was warmer (74^{o} F) than the start by 2^{o} F.

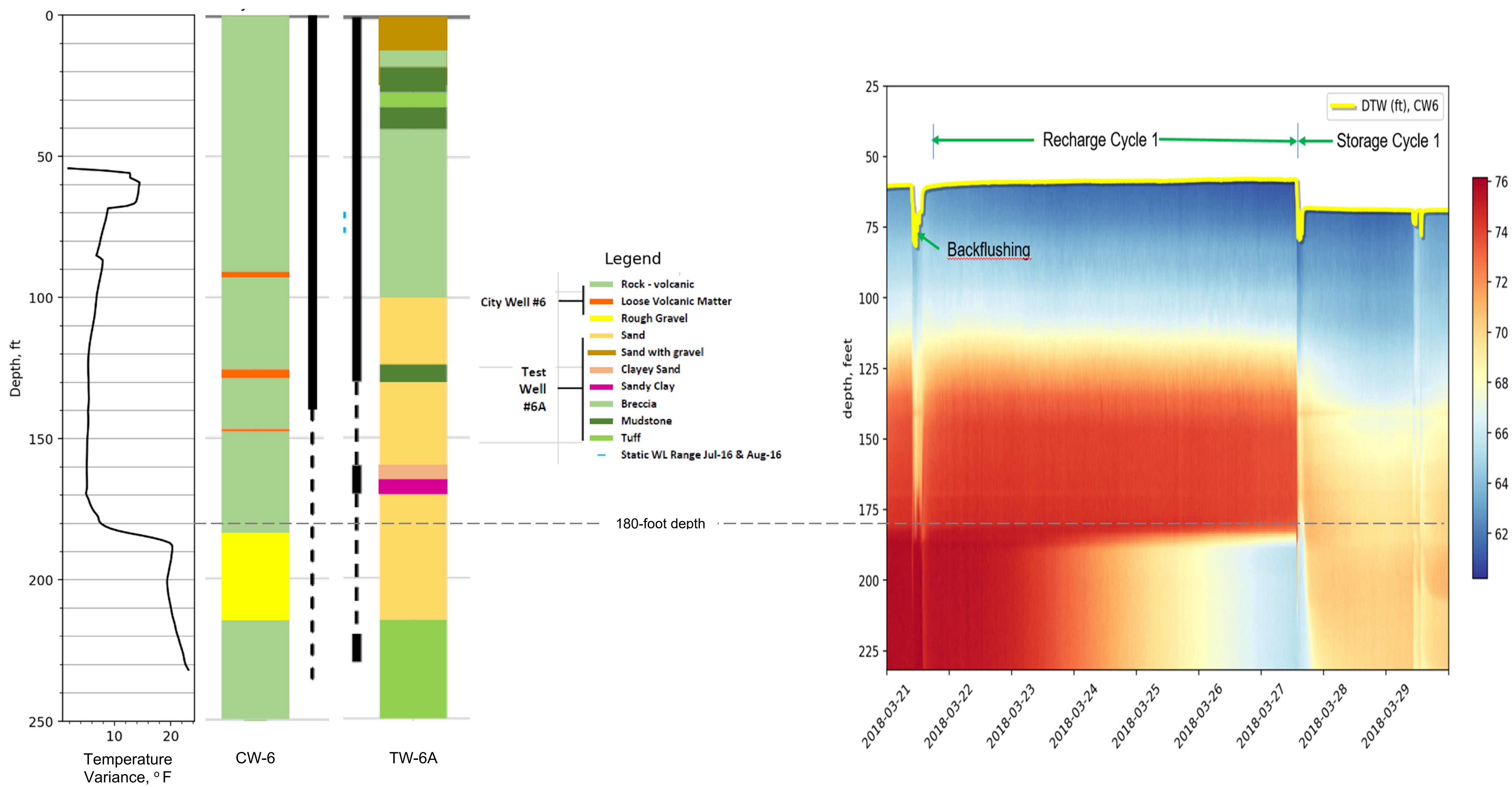
Temperatures at CW-8 were several degrees higher than CW-6 and TW-6A throughout the pilot test, as stated above. Prior to the pilot test, the temperature was decreasing, similar to the temperature at CW-6. The temperature increased at CW-8 during the pre-test set-up and remained high during the initial third of the first injection period and then decreased rapidly before a steady decline throughout the latter half of the injection period. Temperature data were not measured during the first storage period and half of the first recovery period. During the latter half of the recovery period, the temperature at CW-8 increased sharply (1.5^{o} F) and then decreased quickly (1^{o} F) by the end of the recovery period. During the second injection period, the temperature rose somewhat (1.6^{o} F), variably during the first half and then steadily thereafter. The temperature dipped quickly (1.2^{o} F) at the start of second storage period and then increased shortly thereafter and was relatively steady during the remainder of the period. This initial temperature pattern occurred during the start of the second recovery period and the third storage period. The temperature of CW-8 did not respond to the third injection or recovery periods and simply decreased slightly (less than 0.3^{o} F) throughout these periods. During the latter half of the third storage period, the temperature decreased twice by several degrees. The first decrease coincides with the subtle change in slope of WLs, likely due to the operation of a distant supply well, while the second decrease coincides with the operation of CW-8.

Distributed Temperature Sensing System

In addition to the temperature sensors paired with the pressure transducers and suspended at single specific depths in each monitored well, Sonoma Water also deployed a distributed temperature sensing (DTS) system within the casing of CW-6. The DTS consisted of small-diameter downhole fiber-optic cable suspended in a double-ended (looped) configuration from the surface to approximately 232 feet. This configuration allowed the DTS to collect temperature measurements at a vertical resolution of approximately 4 feet. At the surface, the cable was wound within a thermally insulated ice bath for calibration prior to being connected to a Silixa XT-DTS base unit, which produced high frequency laser pulses and recorded the temperature data. The DTS was installed on March 21, 2018 and operated through the beginning of the Cycle 3 storage period in early June 2018.

Figure 8A displays the relative temperature variance with depth over the entire DTS monitoring period and provides clearer evidence that the vast majority of thermal transport (and groundwater movement) occurs within the 180- to 230-foot depth horizon. This depth interval corresponds with a zone of "rough gravels" identified on the log for CW-6 and the lower interval of medium to coarse-grained sands (volcaniclastic) identified at TW-6A.

As shown in Figure 8B, the strong temperature contrast between the cooler recharge water and warmer native groundwater, coupled with high resolution data collection by the DTS, was utilized to identify any preferential zones for flow within the aquifer system and help constrain the thickness and depths of those zones. The perforations at CW-6 are continuous between 140 and 236 feet and the log for the well has very limited lithologic information. However, results from the DTS indicate that temperatures initially ranged up to 75^{o} F within CW-6 consistent with the temperature sensor data described above. As shown in Figure 8B, the temperature change (decrease) observed within CW-6 during recharge cycles is most striking between the depths of approximately 180 and 230 feet and correlates with the lower screened interval of TW-6A. During recharge cycle 1, the temperature between the depths of 180 and 230 feet at CW-6 began decreasing approximately two days after the onset of recharge due to the influence of the cooler water being introduced at TW-6A, while the temperatures above that depth interval remained relatively stable throughout the entire recharge cycle. During backflushing and recovery events, the entire vertical water column initially cools down before warming again as the cooler recharge water is extracted and replaced with warmer native groundwater. The gradual warming during the later stages of recovery periods is also much more pronounced between the depths of 180 and 230 feet. The less pronounced vertical variation in water temperature during the short-term backflushing events and early stages of recovery may be due to the turbulent nature of backflushing and the onset of pumping, which causes vertical mixing within the well casing.



A. Relative Temperature Variance with Depth at CW-6, Late March to Early June 2018

B. Temperature (° F) Distribution at CW-6, March 21 to 29, 2018

Figure 8. Distributed Temperature Sensing at Well CW-6

3.2 Hydraulic Evaluation

Groundwater levels and flow data demonstrate TW-6A and the local aquifer have the potential for long-term ASR operations. TW-6A was originally intended to be a monitor well for an ASR pilot test at CW-6 but the diameter of TW-6A was increased at the onset of construction work to allow for preliminary ASR testing. However, the screen material and slot size were not optimized to produce the most efficient well, and the 24-hour pumping test indicated that TW-6A was only 56 percent efficient (PWR, 2018 – Appendix D). The ASR pilot test provided additional insight into the efficiency of TW-6A, based on longer time periods (6 to 16 days) for the three recovery periods and the first injection period (6 days). The second and third injection periods were not included in the evaluation because these periods were preceded quickly by long periods of groundwater recovery with minimal time for groundwater level rebound. The first injection period data may have been affected by the numerous, relatively short-duration calibration tests that preceded it, but groundwater levels had more time to rebound during this 2-day calibration period.

The GEI Theis calculator was used to evaluate the observed aquifer conditions around TW-6A and CW-6, and the predicted effects of potential long-term ASR at TW-6A. The calculator is useful for predicting well and aquifer conditions via 'what if' scenarios and is not used for evaluation (curve-matching) of aquifer test data.

Input to the calculator includes 'fixed' parameters, such as the depth of static WL, screen length (aquifer thickness), radius, flow, time, and storage coefficient; and the primary 'adjustable' parameter of transmissivity. The output includes the depth of pumping water level, drawdown, and total volume. For injection, 'drawdown' is subtracted from the depth of static WL to show the depth to the higher WL due to injection rather than added to the depth of static WL to show the pumping WL depth.

For evaluation of observed conditions, the calculator was set up for TW-6A and another calculator was set up for CW-6. Input data were obtained from **Tables 3, 7, and 8**, including static water level, flow, and time. Screen lengths were 80 feet for TW-6A and 96 feet for CW-6. Radii were 0.333 feet for TW-A and 60 feet for CW-6. Storage coefficient was fixed at 10^{-7}, as estimated by PWR (2018). The transmissivity value was adjusted until the drawdown and pumping water levels nominally matched the actual values.

Table 7 presents the estimates of transmissivity for CW-6 (observation well) and for TW-6A (test well) and shows that the TW-6A values are 40 to 50 percent less than CW-6. The actual transmissivity at TW-6A is probably quite similar to the values for CW-6, as indicated by the PWR aquifer test evaluation, but the calculator requires a lower transmissivity value, due to inefficiency of pumping at TW-6A, to produce a drawdown and pumping WL that match observed conditions at TW-6A. Therefore, well efficiency can be estimated for TW-6A for various periods of the pilot test.

As shown in **Table 10**, a lower well efficiency occurred during the first recovery period. By the third recovery period, well efficiency appears to have increased slightly. This increase indicates that successive ASR cycles, including backflushing, may have provided additional development to the well. Injection data were only analyzed for the first injection period because subsequent injection periods occurred immediately after a recovery period (pumping) and WLs would be affected by these two modes of operation. Data does show however, that well efficiency is lower for injection than extraction, which is to be expected for future ASR wells.

Table 10. Theis Calculator Estimates of Transmissivity

Well: / Period	Transmissivity, gpd/ft CW-6 Observation at 60'	Transmissivity, gpd/ft TW-6A ASR Test	TW-6A Efficiency (TW-6A/CW-6)
Injection 1	9,500	4,750	50%
Recovery 1	9,550	5,310	56%
Recovery 2	9,480	5,290	56%
Recovery 3	9,100	5,330	59%

The Theis calculators were used to estimate changes in WLs at TW-6A and CW-6 due to a 181-day (6-month) injection period during the wet season (November through April) with starting WL depths of 67 feet bTOC at TW-6A and 70 feet TOC at CW-6. These static water levels were the observed conditions at the well prior to ASR pilot testing in February 2018. Aquifer parameters were used based on the results of PWR's aquifer parameter analysis of the pre-injection pumping test in February 2018: transmissivity of 9,240 gpd/ft, storativity of 2.63×10^{-7}, and a hydraulic conductivity calculated at 115 gpd/ft^2 (PWR, 2019). Using the assumed operational injection rate of 70 gpm over 181 days, a total of 55-AF volume of potable water could be injected at TW-6A. This effort would result in finish WLs of 20 feet bTOC at TW-6A, assuming a 50% efficient well, and 55.5 feet bTOC at CW-6 (respective 'draw-ups': 47 and 15 feet). While the WL rises at TW-6A are pushing the limits of the acceptable high-water level for injection operations (20 feet), if a new ASR well were constructed with higher efficiency, the finish WLs would be 33 feet bTOC (draw-up of 34 feet).

3.3 Geochemical Modeling

Water quality is an important consideration for an ASR program because the mixing of two waters can result in the precipitation of minerals that reduce the hydraulic conductivity of the aquifer and the performance of the well. Moreover, residual chlorine in the potable injection water can produce disinfection by-products (DBPs) in the aquifer.

Numerous samples were collected for this ASR pilot test, including 15 samples from TW-6A plus additional samples for DBP analysis, seven samples from CW-6, and three samples of the recharge water supply (injectate). Laboratory analyses were provided by TestAmerica Inc., which included a variety of constituent groups: general parameters, major anions and cations, nutrients, metals, miscellaneous, and DBPs. Some samples were analyzed for the complete list of constituents while other samples were analyzed for a partial list (e.g. DBPs), depending on the timing of an ASR period.

Tables 11, 12, and 13 provide the respective laboratory results for TW-6A, CW-6, and the potable water supply from Sonoma Water.

Table 11. Laboratory Data for Sonoma ASR Pilot Test – TW-6A

	ASR Period & Cycle:		Before ASR	Before ASR	Storage 1	Recovery 1	Recovery 1	Storage 2	Storage 2	Storage 2	Storage 2	Recovery 2	Recovery 2	Storage 3	Storage 3	Storage 3	Storage 3	Storage 3	Storage 3	Storage 3	Storage 3	Storage 3	Storage 3	Recovery 3		
	Well:		**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	**TW-6A**	
NA = No analysis	**Date:**		**16-Jun-16**	**09-Feb-18**	**03-Apr-18**	**05-Apr-18**	**09-Apr-18**	**01-May-18**	**10-May-18**	**17-May-18**	**21-May-18**	**29-May-18**	**04-Jun-18**	**28-Jun-18**	**05-Jul-18**	**12-Jul-18**	**23-Jul-18**	**01-Aug-18**	**09-Aug-18**	**15-Aug-18**	**28-Aug-18**	**04-Sep-18**	**06-Sep-18**	**20-Sep-18**	**30-Jan-20**	
Suspect value	Laboratory:		Eurofins	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	eurofins	
	Report #:			203147-1/2	208084-1	208201-1	208393-1	210275-1	211185-1	211674-1	211836-1	212383-1	212765-1	214704-1	215177-1	215740-1	216526-1	217281-1	217861-1	218211-1	219011-1	219384-1	219613-1	220586-1	852201	**Count**
Major Cations	Units																									
Calcium	mg/L	Ca	10	10	24	16	13	22	23	NA	22	NA	19	25	24	23	23	23	NA	NA	NA	21	NA	15	NA	15
Magnesium	mg/L	Mg	6.2	6.2	15	9.7	7.6	14	14	NA	14	NA	8.4	15	15	14	14	14	NA	NA	NA	13	NA	9.7	NA	15
Sodium	mg/L	Na	24	22	20	17	20	18	18	NA	19	NA	14	21	20	19	19	19	NA	NA	NA	19	NA	20	NA	15
Potassium	mg/L	K	3.4	3.5	1.5	1.7	3.1	1.0	0.064 J	NA	1.3	NA	2.2	1.3	1.2	1.3	1.4	1.5	NA	NA	NA	1.6	NA	2.5	NA	15
Major Anions																										
Alkalinity (HCO_3, CO_3, OH	mg/L	as $CaCO_3$	Estimate	86	130	110	94	130	130	NA	130	NA	99	130	130	130	140	NA	NA	NA	NA	140	NA	110	NA	14
Bicarbonate	mg/L	HCO_3	110	105	158	134	110	160	160	NA	160	NA	120	160	160	160	170	NA	NA	NA	NA	170	NA	130	NA	14
Sulfate	mg/L	SO_4	4.5	3.8	15	11	6.0	14	14	NA	15	NA	8.3	14	14	15	15	14	NA	15	13	13	NA	8.8	7.4	18
Chloride	mg/L	Cl	6.4	6.7	6.8	6.4	6.6	6.1	6.3	NA	6.5	NA	6.8	6.9	6.7	7.0	6.8	7.0	NA	7.1	7	6.8	NA	6.4	6.5	18
Fluoride	mg/L	F	NA	NA	<0.50	0.32 J	0.48 J	<0.50	<0.50	NA	<0.50	NA	<0.50	<0.50	<0.50	<0.50	0.27 J	NA	NA	NA	NA	0.28 J	NA	0.36 J	NA	13
General			Field																							
pH	units		*7.0*	7.6	8.3	8.0	7.5	8.3	8.2	NA	8.2	NA	7.7	8.4	8.3	8.2	8.2	8.1	NA	NA	NA	8.0	NA	7.5	NA	15
Specific Conductance	uS	EC	200	200	310	280	220	300	310	NA	250	NA	240	310	320	330	320	320	NA	NA	NA	300	NA	240	NA	15
Total Dissolved Solids	mg/L	TDS	210	180	180	180	180	190	180	NA	180	NA	210	180	190	190	180	200	NA	NA	NA	190	NA	220	NA	15
Dissolved Organic Carbon	mg/L	DOC	<1.5	0.30	0.75	0.60	0.15	NA	NA	NA	0.62	NA	0.33	NA	NA	NA	0.57	NA	NA	NA	NA	0.43	NA	0.35	NA	9
Total Organic Carbon	mg/L	TOC	<0.3	0.23	0.64	0.49	0.26	NA	NA	NA	0.67	NA	0.29	NA	NA	NA	0.63	NA	NA	NA	NA	0.38	NA	0.22	NA	9
Nutrients																										
Ammonia	mg/L	as N	<0.05	<0.20	<0.20	<0.20	<0.20	NA	NA	NA	<0.20	NA	<0.20	NA	NA	NA	<0.20	NA	NA	NA	NA	<0.50	NA	<0.50	NA	9
Nitrate	mg/L	NO_3	1.6	1.7	1.0	1.2	1.6	NA	NA	NA	1.4	NA	1.6	NA	NA	NA	1.1	NA	NA	NA	NA	1.0	NA	1.5	NA	9
Nitrite	mg/L	as N	<0.05	<0.15	0.073 J	<0.15	<0.15	NA	NA	NA	<0.15	NA	<0.15	NA	NA	NA	<0.15	NA	NA	NA	NA	<0.15	NA	<0.15	NA	9
Total Kjehldahl Nitrogen	mg/L	TKN as N	<0.2	<0.20	<0.20	<0.20	<0.20	NA	NA	NA	<0.20	NA	<0.20	NA	NA	NA	<0.20	NA	NA	NA	NA	<0.20	NA	0.46	NA	9
Orthophosphate	mg/L	as P	NA	0.14	0.034 J	0.088	0.11	NA	NA	NA	0.027 J	NA	0.092	NA	NA	NA	0.059	NA	NA	NA	NA	0.064	NA	0.090	NA	9
Total Nitrogen	mg/L		NA	NA	0.30	0.27	0.36	NA	NA	NA	NA	NA	0.36	NA	NA	NA		NA	NA	NA	NA	NA	NA	NA	NA	4
Total Phosphorous	mg/L		NA	0.12	0.032 J	0.065	0.087	NA	NA	NA	0.027 J	NA	0.070	NA	NA	NA	0.030	NA	NA	NA	NA	0.057	NA	0.073	NA	9
Metals																										
Aluminum	mg/L	Al	NA	NA	NA	<0.10	0.063 J	NA	NA	NA	0.074 J	NA	0.062 J	NA	NA	NA	0.057 J	NA	NA	NA	NA	0.45	NA	<0.10	NA	7
Antimony	mg/L	Sb	NA	NA	NA	<0.01	<0.010	NA	NA	NA	<0.010	NA	<0.010	NA	NA	NA	<0.010	NA	NA	NA	NA	<0.010	NA	<0.010	NA	7
Arsenic	ug/L	As	7.8	7.4	NA	3.2	5.0	NA	NA	NA	1.3	NA	4.9	NA	NA	NA	1.6	NA	NA	NA	NA	2.6	NA	4.2	NA	8
Barium	mg/L	Ba	0.0058	0.0062 J	NA	0.029	0.019	NA	NA	NA	0.068	NA	0.026	NA	NA	NA	0.076	NA	NA	NA	NA	0.070	NA	0.033	NA	8
Beryllium	mg/L	Be	NA	NA	NA	<0.0020	<0.0020	NA	NA	NA	<0.0020	NA	<0.0020	NA	NA	NA	<0.0020	NA	NA	NA	NA	<0.0020	NA	<0.0020	NA	7
Cadmium	mg/L	Cd	NA	NA	NA	<0.0050	<0.0050	NA	NA	NA	<0.0050	NA	<0.0050	NA	NA	NA	<0.0050	NA	NA	NA	NA	<0.0050	NA	<0.0050	NA	7
Chromium	mg/L	Cr	NA	NA	NA	<0.0050	<0.0050	NA	NA	NA	0.010	NA	<0.0050	NA	NA	NA	0.015	NA	NA	NA	NA	0.010	NA	<0.0050	NA	7
Iron - dissolved	mg/L	Fe	<0.02	<0.10	NA	<0.10	<0.10	NA	NA	NA	<0.10	NA	0.073 J	NA	NA	NA	<0.10	NA	NA	NA	NA	<0.10	NA	<0.10	NA	8
Iron - total	mg/L	Fe	<0.02	<0.10	NA	<0.10	<0.10	NA	NA	NA	<0.10	NA	<0.10	NA	NA	NA	<0.10	NA	NA	NA	NA	0.35	NA	<0.10	NA	8
Lithium	mg/L	Li	0.031	0.032 J	NA	0.028 J	<0.50	NA	NA	NA	<0.50	NA	<0.50	NA	NA	NA	<0.50	NA	NA	NA	NA	<0.50	NA	<0.50	NA	8
Manganese - dissolved	mg/L	Mn	0.0024	<0.020	NA	<0.020	<0.020	NA	NA	NA	<0.020	NA	<0.020	NA	NA	NA	<0.020	NA	NA	NA	NA	<0.020	NA	<0.020	NA	8
Manganese - total	mg/L	Mn	0.0020	<0.020	NA	<0.020	<0.020	NA	NA	NA	<0.020	NA	<0.020	NA	NA	NA	<0.020	NA	NA	NA	NA	<0.020	NA	<0.020	NA	8
Mercury	mg/L	Hg	NA	NA	0.00010 J	<0.00020	<0.00020	NA	NA	NA	<0.00020	NA	<0.00020	NA	NA	NA	<0.00020	NA	NA	NA	NA	<0.00020	NA	<0.00020	NA	8
Molybdenum	ug/L	Mo	NA	2.9	NA	1.7 J	1.9 J	NA	NA	NA	1.2 J	NA	2.7	NA	NA	NA	2.5	NA	NA	NA	NA	2.6	NA	2.1	NA	8
Nickel	mg/L	Ni	<5	<0.010	NA	<0.010	<0.010	NA	NA	NA	<0.010	NA	<0.010	NA	NA	NA	<0.010	NA	NA	NA	NA	<0.010	NA	<0.010	NA	8
Selenium	ug/L	Se	<5	<2.0	NA	<2.0	<2.0	NA	NA	NA	<2.0	NA	1.3 J	NA	NA	NA	1.0 J	NA	NA	NA	NA	0.73 J	NA	<2.0	NA	8
Strontium	mg/L	Sr	0.032	0.033	NA	0.100	0.066	NA	NA	NA	0.200	NA	0.084	NA	NA	NA	0.210	NA	NA	NA	NA	0.180	NA	0.098	NA	8
Thallium	mg/L	Th	NA	NA	NA	<0.010	<0.010	NA	NA	NA	<0.010	NA	<0.010	NA	NA	NA	<0.010	NA	NA	NA	NA	<0.010	NA	<0.010	NA	7
Uranium	pCi/L	U	<0.7	<0.67	NA	<0.67	<0.67	NA	NA	NA	<0.67	NA	<0.67	NA	NA	NA	<0.67	NA	NA	NA	NA	<0.67	NA	<0.67	NA	8
Vanadium	mg/L	V	NA	0.033	NA	0.012	0.024	NA	NA	NA	0.0052 J	NA	0.017	NA	NA	NA	<0.010	NA	NA	NA	NA	0.0078 J	NA	0.019	NA	8
Zinc	ug/L	Zn	NA	40	NA	26	28	NA	NA	NA	61	NA	23	NA	NA	NA	33	NA	NA	NA	NA	46	NA	25	NA	8
Miscellaneous																										
Boron	mg/L	B	0.17	0.10	NA	0.17	0.15	NA	NA	NA	0.22	NA	0.15	NA	NA	NA	0.27	NA	NA	NA	NA	0.25	NA	0.17	NA	8
Cyanide, Total	mg/L	CN	NA	NA	NA	<0.025	<0.025	NA	NA	NA	<0.025	NA	<0.025	NA	NA	NA	<0.020	NA	NA	NA	NA	<0.025	NA	<0.025	NA	7
Dissolved Methane	mg/L		0.73	<0.00099	NA	<0.00099	<0.00099	NA	NA	NA	<0.00099	NA	<0.00099	NA	NA	NA	<0.00099	NA	NA	NA	NA	<0.002	NA	<0.00099	NA	8
Dissolved Sulfide	mg/L		NA	<0.050	NA	<0.050	<0.050	NA	NA	NA	<0.050	NA	<0.050	NA	NA	NA	<0.050	NA	NA	NA	NA	<0.050	NA	<0.050	NA	8
Hydrogen Sulfide	mg/L	H_2S	NA	NA	NA	<0.10	<0.10	NA	NA	NA	<0.10	NA	<0.10	NA	NA	NA	<0.10	NA	NA	NA	NA	<0.10	NA	<0.10	NA	7
Perchlorate	ug/L	ClO_4	NA	NA	NA	<4.0	<4.0	NA	NA	NA	<4.0	NA	<4.0	NA	NA	NA	<4.0	NA	NA	NA	NA	<4.0	NA	<4.0	NA	7
Gross Alpha	pCi/L		NA	NA	NA	<3	<3	NA	NA	NA	<3	NA	<3	NA	NA	NA	2.5 J	NA	NA	NA	NA	<3	NA	<3	NA	7
Radium-226	pCi/L	Ra	NA	<1	NA	<1	<1	NA	NA	NA	<1	NA	<1	NA	NA	NA	0.3 J	NA	NA	NA	NA	<1	NA	<1	NA	7
Silica	mg/L	SiO_2	NA	NA	NA	59	84	23	28	NA	32	NA	73	26	27	28	31	33	NA	NA	NA	41	NA	75	NA	13
Disinfection By-products / Organic Analyses																										
Chloramines, Total	mg/L		NA	NA	<0.10	<0.10	<0.10	NA	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	NA	<0.10	NA	<0.10	NA	17
Chlorine Residual (free)	mg/L		NA	<0.10	<0.10	<0.10	<0.10	NA	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	NA	<0.10	NA	<0.10	NA	18
Total Trihalomethanes	ug/L	THM	<0.5	<1.0	26	16	5.3	32	38	39	37	17	11	34	38	35	42	47	38	42	32	31	27	14	5.3	22
Bromodichloromethane	ug/L		<0.5	<1.0	7.2	4.7	1.5	8.4	9.5	8.8	9.5	4.5	3.1	10	11	9.1	11	13	10	11	8.8	8.0	8.0	4.0	<0.5	22
Dibromochloromethane	ug/L		<0.5	<1.0	4.4	3.0	1.0	4.3	4.7	4.3	5	2.6	1.7	6.9	6.9	5.3	8.0	8.8	7.6	8.4	6.7	6.7	5.8	3.0	<0.5	22
Bromoform	ug/L		<0.5	<1.0	0.72 J	0.55 J	0.24 J	0.47 J	0.53 J	0.45 J	0.51 J	0.32 J	0.24 J	1.4	1.4	0.83 J	1.3	1.7	1.6	1.9	1.2	1.4	1.1	0.57 J	<0.5	22
Chloroform	ug/L		<0.5	<1.0	14	7.9	2.6	19	24	25	22	10	6.3	16	19	20	22	24	19	21	15	15	12	6.3	5.3	22
Haloacetic Acids		HAA	<2.0	<1.0	7.7	4.8	0.8	6.8	7.9	7.9	11	4.1	0.8 J	6.5	11	8.7	9.8	7.1	8.2	6.8	4.1	6.1	NA	<1.0	<2.0	21
Monobromoacetic Acid	ug/L		<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	NA	<1.0	<1.0	21
Monochloroacetic Acid	ug/L		<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	NA	<1.0	<2.0	21
Dibromoacetic Acid	ug/L		<1.0	<1.0	0.81 J	0.64 J	<1.0	<1.0	<1.0	<1.0	0.56 J	<1.0	<1.0	0.75 J	1.6	1.1	1.1	0.58 J	0.75 J	0.55 J	<1.0	0.43 J	NA	<1.0	<1.0	21
Dichloroacetic Acid	ug/L		<1.0	<1.0	3.8	2.4	<1.0	3.1	3.2	3.8	4.7	<1.0	<1.0	3.5	5.9	4.9	5.5	2.1	2.6	1.9	1.3	1.7	NA	<1.0	<1.0	21
Trichloroacetic Acid	ug/L		<1.0	<1.0	3.1	1.8	0.77 J	3.7	4.7	4.1	5.4	4.1	0.80 J	2.2	3.9	2.7	3.2	4.4	4.8	4.3	2.8	4.0	NA	<1.0	<1.0	21

Table 12. Laboratory Data for Sonoma ASR Pilot Test – CW-6

		ASR Period & Cycle:	Before ASR		Injection 1	Recovery 1	Injection 2	Storage 2	Recovery 2	Injection 3	Storage 3	Recovery 3			Storage 3	Storage 3
		Well:	**CW-6**	**CW-6**	**CW-6**	**CW-6**	**CW-6**	**CW-6**	**CW-6**	**CW-6**	**CW-6**	**CW-6**	**CW-6**		**CW-3**	**CW-8**
NA = No analysis		**Date:**	**19-Mar-18**	**19-Mar-18**	**29-Mar-18**	**09-Apr-18**	**27-Apr-18**	**21-May-18**	**04-Jun-18**	**22-Jun-18**	**12-Jul-18**	**20-Sep-18**	**30-Jan-20**		**12-Jul-18**	**12-Jul-18**
		Laboratory:	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	TestAmerica	eurofins		TestAmerica	TestAmerica
		Report #:	206459-1	206542-1	207592-1	208393-2	210279-2	211836-2	212765-2	214301-2	215740-3	220600-1	852201	**Count**	215740-4	215740-2
Major Cations	Units															
Calcium	mg/L	Ca	9.9	NA	12	10	16	NA	10	18	NA	12	NA	7	NA	NA
Magnesium	mg/L	Mg	5.6	NA	7.2	5.9	9.7	NA	6.1	11	NA	7.1	NA	7	NA	NA
Sodium	mg/L	Na	19	NA	20	20	24	NA	20	24	NA	22	NA	7	NA	NA
Potassium	mg/L	K	3.1	NA	3.2	3.3	3.5	NA	2.9	3.5	NA	3.4	NA	7	NA	NA
Major Anions																
Alkalinity (HCO_3, CO_3, OH	mg/L	as $CaCO_3$	80	NA	89	84	100	NA	89	110	NA	98	NA	7	NA	NA
Bicarbonate	mg/L	HCO_3	98	NA	110	100	130	NA	110	140	NA	120	NA	7	NA	NA
Sulfate	mg/L	SO_4	5.2	NA	11	5.1	14	NA	6.3	14	13	7.1	5.5	9	4.3	4.3
Chloride	mg/L	Cl	7.1	NA	6.6	6.8	6.3	NA	6.9	7.3	7.0	6.4	7.3	9	6.5	6.5
Fluoride	mg/L	F	0.33 J	<0.50	0.39 J	0.51	0.45 J	NA	NA	0.28 J	NA	0.36 J	NA	7	NA	NA
General																
pH	units		7.7	NA	8.7	7.5	7.9	NA	7.7	8.1	NA	7.5	NA	7	NA	NA
Specific Conductance	uS	EC	210	NA	230	210	260	NA	220	280	NA	230	NA	7	NA	NA
Total Dissolved Solids	mg/L	TDS	180	NA	190	170	190	NA	200	210	NA	210	NA	7	NA	NA
Dissolved Organic Carbon	mg/L	DOC	1.2	NA	1.8	0.27	0.58	NA	0.42	0.51	NA	0.18	NA	7	NA	NA
Total Organic Carbon	mg/L	TOC	1.1	NA	1.3	0.27	0.60	NA	0.22	0.48	NA	0.16	NA	7	NA	NA
Nutrients																
Ammonia	mg/L	as N	<0.50	NA	0.12 J	<0.20	0.15 J	NA	<0.20	<0.20	NA	<0.20	NA	7	NA	NA
Nitrate	mg/L	NO_3	1.2	NA	1.0	1.6	1.3	NA	1.8	1.1	NA	1.7	NA	7	NA	NA
Nitrite	mg/L	as N	<0.15	NA	<0.15	<0.15	<0.15	NA	<0.15	<0.15	NA	<0.15	NA	7	NA	NA
Total Kjehldahl Nitrogen	mg/L	TKN as N	<0.20	NA	5.0	<0.20	<0.20	NA	<0.20	<0.20	NA	<0.20	NA	7	NA	NA
Orthophosphate	mg/L	as P	0.097	NA	0.069	0.11	0.063	NA	0.12	0.068	NA	0.088	NA	7	NA	NA
Total Nitrogen	mg/L		0.27	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1	NA	NA
Total Phosphorous	mg/L		0.073	NA	0.053	0.075	0.043 J	NA	0.076	0.044 J	NA	0.078	NA	7	NA	NA
Metals																
Aluminum	mg/L	Al	0.31	0.17	NA	0.089 J	0.056 J	NA	0.071 J	<0.10	NA	NA	NA	6	NA	NA
Antimony	mg/L	Sb	<0.010	0.0061 J	NA	<0.010	<0.010	NA	<0.010	<0.010	NA	NA	NA	6	NA	NA
Arsenic	ug/L	As	5.0	NA	NA	5.8	3.0	NA	6.6	2.9	NA	NA	NA	5	NA	NA
Barium	mg/L	Ba	0.013	NA	NA	0.011	0.015	NA	0.0096 J	0.016	NA	NA	NA	5	NA	NA
Beryllium	mg/L	Be	<0.0020	<0.0020	NA	<0.0020	<0.0020	NA	<0.0020	<0.0020	NA	NA	NA	6	NA	NA
Cadmium	mg/L	Cd	<0.0050	<0.0050	NA	<0.0050	<0.0050	NA	<0.0050	<0.0050	NA	NA	NA	6	NA	NA
Chromium	mg/L	Cr	0.0077	<0.0050	NA	0.0030 J	<0.0050	NA	<0.0050	<0.0050	NA	NA	NA	6	NA	NA
Iron - dissolved	mg/L	Fe	0.090 J	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1	NA	NA
Iron - total	mg/L	Fe	0.25	NA	NA	<0.010	<0.010	NA	<0.010	<0.010	NA	NA	NA	5	NA	NA
Lithium	mg/L	Li	0.025 J	NA	NA	0.026 J	<0.050	NA	<0.050	0.035 J	NA	NA	NA	5	NA	NA
Manganese - dissolved	mg/L	Mn	<0.020	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1	NA	NA
Manganese - total	mg/L	Mn	<0.020	NA	NA	<0.020	<0.020	NA	<0.020	<0.020	NA	NA	NA	5	NA	NA
Mercury	mg/L	Hg	<0.00020	<0.00020	NA	<0.00020	0.00015 J	NA	<0.00020	<0.00020	NA	NA	NA	6	NA	NA
Molybdenum	ug/L	Mo	2.4	NA	NA	2.2	0.74 J	NA	2.6	0.79 J	NA	NA	NA	5	NA	NA
Nickel	mg/L	Ni	<0.010	NA	NA	<0.010	<0.010	NA	<0.010	<0.010	NA	NA	NA	5	NA	NA
Selenium	ug/L	Se	<2.0	NA	NA	<2.0	<2.0	NA	<2.0	<2.0	NA	NA	NA	5	NA	NA
Strontium	mg/L	Sr	0.042	NA	NA	0.043	0.065	NA	0.043	0.07	NA	NA	NA	5	NA	NA
Thallium	mg/L	Th	<0.010	<0.010	NA	<0.010	<0.010	NA	<0.010	<0.010	NA	NA	NA	6	NA	NA
Uranium	pCi/L	U	<0.67	NA	NA	<0.67	<0.67	NA	<0.67	<0.67	NA	NA	NA	5	NA	NA
Vanadium	mg/L	V	0.021	NA	NA	0.023	0.014	NA	0.020	0.015	NA	NA	NA	5	NA	NA
Zinc	ug/L	Zn	57	NA	NA	21	24	NA	18 J	22	NA	NA	NA	5	NA	NA
Miscellaneous																
Boron	mg/L	B	0.11	NA	NA	0.13	0.19	NA	0.13	0.24	NA	NA	NA	5	NA	NA
Cyanide, Total	mg/L	CN	<0.025	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1	NA	NA
Dissolved Methane	mg/L		<0.00099	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1	NA	NA
Dissolved Sulfide	mg/L		0.057	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1	NA	NA
Hydrogen Sulfide	mg/L	H_2S	<0.10	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1	NA	NA
Perchlorate	ug/L	ClO_4	<4.0	<4.0	NA	<4.0	<4.0	NA	<4.0	<4.0	NA	NA	NA	6	NA	NA
Gross Alpha	pCi/L		<3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1	NA	NA
Radium-226	pCi/L	Ra	<1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1	NA	NA
Silica	mg/L	SiO_2	87	96	81	88	68	NA	84	70	NA	92	NA	8	NA	NA
Disinfection By-products / Organic Analyses																
Chloramines, Total	mg/L		<0.10	NA	NA	<0.10	<0.10	<0.10	NA	<0.10	NA	<0.10	NA	6	NA	NA
Chlorine Residual (free)	mg/L		<0.10	NA	NA	<0.10	<0.10	<0.10	NA	<0.10	NA	<0.10	NA	6	NA	NA
Total Trihalomethanes	ug/L	THM	<1.0	NA	NA	2.1	26	25	NA	24	22	8.4	0.83	8	<1.0	<1.0
Bromodichloromethane	ug/L		<1.0	NA	NA	0.56 J	7.1	6.4	NA	7.1	5.7	2.4	<0.5	8	<1.0	<1.0
Dibromochloromethane	ug/L		<1.0	NA	NA	0.40 J	3.5	3.5	NA	6.0	3.3	1.7	<0.5	8	<1.0	<1.0
Bromoform	ug/L		<1.0	NA	NA	<1.0	0.41 J	0.44 J	NA	1.2	0.53 J	0.33 J	<0.5	8	<1.0	<1.0
Chloroform	ug/L		<1.0	NA	NA	1.1	15	14	NA	9.9	12	4.0	0.83	8	<1.0	<1.0
Haloacetic Acids		HAA	<1.0	NA	NA	0.4	5.1	<1.0	NA	5.4	NA	<1.0	<2.0	7	NA	NA
Monobromoacetic Acid	ug/L		<1.0	NA	NA	<1.0	<1.0	<1.0	NA	<1.0	NA	<1.0	<1.0	7	NA	NA
Monochloroacetic Acid	ug/L		<1.0	NA	NA	<1.0	<1.0	<1.0	NA	<1.0	NA	<1.0	<2.0	7	NA	NA
Dibromoacetic Acid	ug/L		<1.0	NA	NA	<1.0	<1.0	<1.0	NA	1.0	NA	<1.0	<1.0	7	NA	NA
Dichloroacetic Acid	ug/L		<1.0	NA	NA	<1.0	2.1	<1.0	NA	2.9	NA	<1.0	<1.0	7	NA	NA
Trichloroacetic Acid	ug/L		<1.0	NA	NA	0.40 J	3.0	<1.0	NA	1.5	NA	<1.0	<1.0	7	NA	NA

Table 13. Laboratory Data for Sonoma ASR Pilot Test – Potable Water Supply

		ASR Period & Cycle:	Pre-ASR Activities		Injection 2	Injection 3	
		SCWA Transmission Pipeline:	**Injection Water**	**Injection Water**	**Injection Water**	**Injection Water**	
NA = No analysis		**Date:**	**20-Mar-18**	**20-Mar-18**	**27-Apr-18**	**22-Jun-18**	
		Laboratory:	TestAmerica	TestAmerica	TestAmerica	TestAmerica	**2018**
		Report #:	206459-2	206542-1	210279-1	214301-1	**Count**
Major Cations	Units						
Calcium	mg/L	Ca	21	NA	23	26	3
Magnesium	mg/L	Mg	13	NA	14	15	3
Sodium	mg/L	Na	16	NA	18	20	3
Potassium	mg/L	K	0.87	NA	1.0	1.1	3
Major Anions							
Alkalinity (HCO_3, CO_3, OH)	mg/L	as $CaCO_3$	140	NA	140	140	3
Bicarbonate	mg/L	HCO_3	160	NA	170	160	3
Sulfate	mg/L	SO_4	15	NA	16	15	3
Chloride	mg/L	Cl	6.6	NA	6.0	7.1	3
Fluoride	mg/L	F	<0.50	0.40 J	0.25 J	<0.50	4
General							
pH	units		8.3	NA	8.3	8.4	3
Specific Conductance	uS	EC	310	NA	300	320	3
Total Dissolved Solids	mg/L	TDS	190	NA	170	180	3
Dissolved Organic Carbon	mg/L	DOC	0.80	NA	0.69	0.54	3
Total Organic Carbon	mg/L	TOC	0.72	NA	0.69	0.53	3
Nutrients							
Ammonia	mg/L	as N	<0.050	NA	0.17 J	<0.20	3
Nitrate	mg/L	NO_3	1.1	NA	1.4	0.89	3
Nitrite	mg/L	as N	<0.15	NA	<0.15	<0.15	3
Total Kjehldahl Nitrogen	mg/L	TKN as N	<0.20	NA	<0.20	<0.20	3
Orthophosphate	mg/L	as P	<0.050	NA	<0.050	0.022 J	3
Total Nitrogen	mg/L		0.24	NA	NA	NA	1
Total Phosphorous	mg/L		<0.050	NA	<0.050	<0.050	3
Metals							
Aluminum	mg/L	Al	0.092 J	0.054 J	0.059 J	<0.10	4
Antimony	mg/L	Sb	<0.010	<0.010	<0.010	<0.010	4
Arsenic	ug/L	As	<1.0	NA	<1.0	<1.0	3
Barium	mg/L	Ba	0.077	NA	0.083	0.093	3
Beryllium	mg/L	Be	0.0011 J	<0.0020	<0.0020	<0.0020	4
Cadmium	mg/L	Cd	<0.0050	<0.0050	<0.0050	<0.0050	4
Chromium	mg/L	Cr	<0.0050	<0.0050	<0.0050	<0.0050	4
Iron - dissolved	mg/L	Fe	<0.10	NA	<0.10	<0.10	3
Iron - total	mg/L	Fe	<0.10	NA	<0.10	<0.10	3
Lithium	mg/L	Li	<0.50	NA	<0.50	<0.50	3
Manganese - dissolved	mg/L	Mn	<0.020	NA	<0.020	<0.020	3
Manganese - total	mg/L	Mn	<0.020	NA	<0.020	<0.020	3
Mercury	mg/L	Hg	<0.00020	<0.00020	<0.00020	<0.00020	4
Molybdenum	ug/L	Mo	<2.0	NA	0.81 J	0.88 J	3
Nickel	mg/L	Ni	<0.010	NA	<0.010	<0.010	3
Selenium	ug/L	Se	<2.0	NA	<2.0	<2.0	3
Strontium	mg/L	Sr	0.20	NA	0.22	0.24	3
Thallium	mg/L	Th	<0.010	<0.010	<0.010	<0.010	4
Uranium	pCi/L	U	<0.67	NA	<0.67	<0.67	3
Vanadium	mg/L	V	<0.010	NA	<0.010	<0.010	3
Zinc	ug/L	Zn	8.0 J	NA	3.9 J	3.4 J	3
Miscellaneous							
Boron	mg/L	B	0.22	NA	0.21	0.28	3
Cyanide, Total	mg/L	CN	<0.025	NA	<0.025	<0.025	3
Dissolved Methane	mg/L		<0.00099	NA	<0.00099		2
Dissolved Sulfide	mg/L		<0.050	NA	<0.050	<0.050	3
Hydrogen Sulfide	mg/L	H_2S	<0.10	NA	NA	<0.10	2
Perchlorate	ug/L	ClO_4	<4.0	<4.0	<4.0	<4.0	4
Gross Alpha	pCi/L		<3	NA	<3	<3	3
Radium-226	pCi/L	Ra	<1	NA	<1	<1	3
Silica	mg/L	SiO_2	15	17	16	17	4
Disinfection By-products / Organic Analyses							
Chloramines, Total	mg/L		<0.10	NA	<0.10	0.13	3
Chlorine Residual (free)	mg/L		0.49	NA	0.42	0.19	3
Total Trihalomethanes	ug/L	THM	20	NA	25	22	3
Bromodichloromethane	ug/L		6.2	NA	6.9	6.4	3
Dibromochloromethane	ug/L		4.3	NA	4.0	6.2	3
Bromoform	ug/L		0.67 J	NA	0.46 J	1.2	3
Chloroform	ug/L		9.1	NA	14	8	3
Haloacetic Acids		HAA	7.3	NA	6.2	5.4	3
Monobromoacetic Acid	ug/L		<1.0	NA	<1.0	<1.0	3
Monochloroacetic Acid	ug/L		<1.0	NA	<1.0	<1.0	3
Dibromoacetic Acid	ug/L		1.2	NA	0.58 J	1.5	3
Dichloroacetic Acid	ug/L		4.0	NA	2.5	2.6	3
Trichloroacetic Acid	ug/L		2.1	NA	3.1	1.3	3

Overall, the quality of the three waters is excellent and appear to be compatible for an ASR program. The recharge water exhibited a dilute mixed cation-bicarbonate character with total dissolved solids (TDS) concentrations between 170 and 190 milligrams per liter (mg/l) or parts per million (ppm). These water quality data are similar to the 2011 data that was provided in the 2017 Technical Report. Prior to the ASR pilot test, both TW-6A and CW-6 exhibited a dilute sodium-dominated, mixed cation-bicarbonate character with TDS concentrations between 180 and 210 mg/l.

The pH of the recharge water was somewhat more alkaline (8.3 to 8.4) than the native groundwater (7.0 to 7.7). Nitrate was present in both the recharge water at concentrations between 0.9 and 1.4 mg-NO_3/l and in the groundwaters at concentrations between 1.2 and 1.7 mg-NO_3/l. Arsenic was not detected in the recharge water, based on a reporting limit of 1 microgram per liter (ug/l) or parts per billion (ppb) but was present in the native groundwaters at concentrations between 5 and 8 ug/l – less than the maximum contaminant level (MCL) of 10 ug/l. DBPs were present in the recharge water at concentrations between 20 and 25 ug/l for total trihalomethanes (THMs) and between 5.4 and 7.8 ug/l for total haloacetic acids – well below the cumulative MCL of 80 ug/l for these DBP constituents. These DBPs were not detected in the native groundwaters prior to the ASR pilot test, based on constituent reporting limits between 0.5 and 2 ug/l.

Figure 8 uses Stiff patterns (Stiff, 1951) to illustrate the similarities/differences in the overall quality of the recharge water, TW-6A groundwater, and CW-6 groundwater. Each pattern or shape is based on the concentrations of the major anions and cations, in milliequivalents per million, on four horizontal scales (interior scales not shown), where anions extend to the right and cations extend to the left. A distinctive shape is produced by a perimeter line connecting the ends of each scale.

The blue-line shapes at the top of **Figure 8** represent the recharge water (RW) and are fairly consistent in size and shape during the ASR pilot test. Black lines represent TW-6A and red lines represent CW-6 and, starting on the left, these shapes are smaller in shape and have a more ‘hour-glass’ shape due to their cation composition. The bicarbonate dominance of the anion compositions creates the large spike to the right in all shapes.

During the first storage (S-1) period, the shape for TW-6A is quite similar to the RW shape because over 0.48 M-gallons of recharge water were injected to the well. Whereas, the shape for CW-6 has not changed significantly but appears to be slightly larger, which indicates minimal impact from the RW injection. During the first recovery (R-1) period, the first shape for TW-6A is smaller and midway between the two end-members after the recovery of more than 0.2 M-gallons. At the end of R-2, the shapes for TW-6A and CW-6 are quite similar to their starting shapes due to the recovery of more than 0.72 M-gallons of groundwater from TW-6A, including a relatively small volume for sampling. This recovery volume is 50% greater than the injection volume

For the second injection (I-2) period, the shape for CW-6 is clearly intermediate between its original shape and the RW shape after injecting over 1.73 M-gallons. During the second storage (S-2) period, the shape for TW-6A is quite similar to the size and shape for recharge water, and then shifts to an intermediate shape by the end of the second recovery (R-2) period, indicating a residual presence of the recharge water.

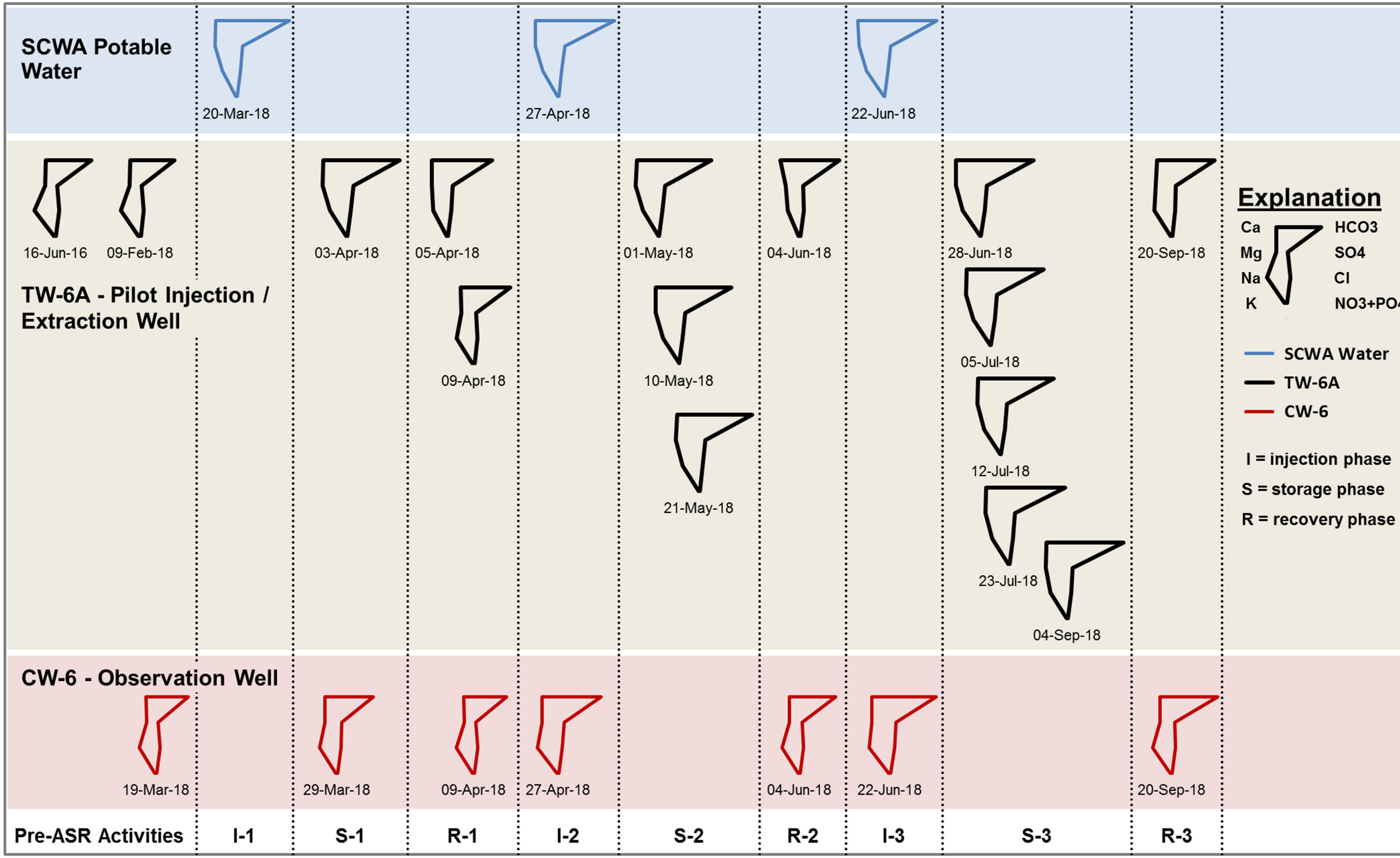


Figure 8. Stiff Patterns for Anion / Cation Data

The CW-6 shape is slightly larger but similar to the original shape, which indicates a smaller residual. Only about 1.66 M-gallons were recovered during the second cycle, including sampling, which is about 4% less than the injection volume.

For the third cycle, the shapes are similar to the second cycle and the final shapes for TW-6A and CW-6 indicate the residual presence of recharge water around TW-6A. Nearly 1.82 M-gallons were injected into TW-6A while only 1.76 M-gallons were recovered from the well – about 3% less than the injection volume.

Figure 9 is a Piper diagram of the anion and cation composition and provides an alternate illustration of the chemistry of the recharge water and native groundwaters. Cation in compositions in percent are plotted in the left triangle and anion compositions in percent are plotted in the right triangle. These locations are then projected into the diamond area. The large blue circles represent the recharge water as one end-member and the large red diamond symbols represent the native groundwater at TW-6A before ASR activities as the other end-member. The large yellow triangles represent the native groundwater at CW-6, which is quite similar to TW-6A. The cluster of symbols in the lower left corner of the right triangle illustrates the dominance of the bicarbonate anion. The left-skew of the blue circles in the middle of the left triangle illustrates the calcium/magnesium dominance of the cations in the recharge water while the right-skew of the TW-6A and CW-6 shows the dominance of sodium.

The purple diamonds represent TW-6A at various times during the ASR pilot test and, similarly, the green triangles represent CW-6. As expected, these symbols plot in a line between the two end-members. The purple diamonds extent all the way to the blue circles because the recharge water replaces the native groundwater at TW-6A at different times during the test. Whereas, the green triangles only extend partway to the blue circles because a mixture of native groundwater and recharge groundwater remained at CW-6.

The presence of native groundwater versus injected recharge water can be identified from other chemical characteristics, including pH, sulfate to chloride ratio, and THMs. **Figures 10, 11, and 12** illustrate the differences between native groundwater and the recharge water for each constituent during the ASR pilot test.

Figure 10 shows a relatively steady pH – 8.3 to 8.4, for recharge water during the ASR pilot test, while the pH values of native groundwater were less than 8.0 before the test. The pH of the two wells were found to be higher, generally greater than 8.0, at the end of the injection periods, during the storage periods, and during the early recovery periods. At the end of each recovery period, the pH values of the wells were similar to or lower than the pre-test values.

Figure 11 illustrates the sulfate-chloride ratios during the pilot test and shows that the recharge water ratio is greater than 2 – sulfate concentrations are twice chloride concentrations. Prior to the ASR pilot test, the ratios for native groundwater were less than 1, and were found to increase to between 1.6 and 2.3 during the storage and early recovery periods. These native groundwater ratios were much lower at the end of the recovery periods – less than 1 for both wells after the first cycle but higher than the pre-test ratio, especially for TW-6A (0.9 versus 0.6, respectively) which indicates a residual of recharge water. The respective ratios for CW-6 were 0.7 and 0.8, also suggesting a slight residual. For the second and third recovery cycles, the respective ratios were 1.2 and 1.4 for TW-6A and 0.9 and 1.1 for CW-6, -- indicative of residual of recharge water.

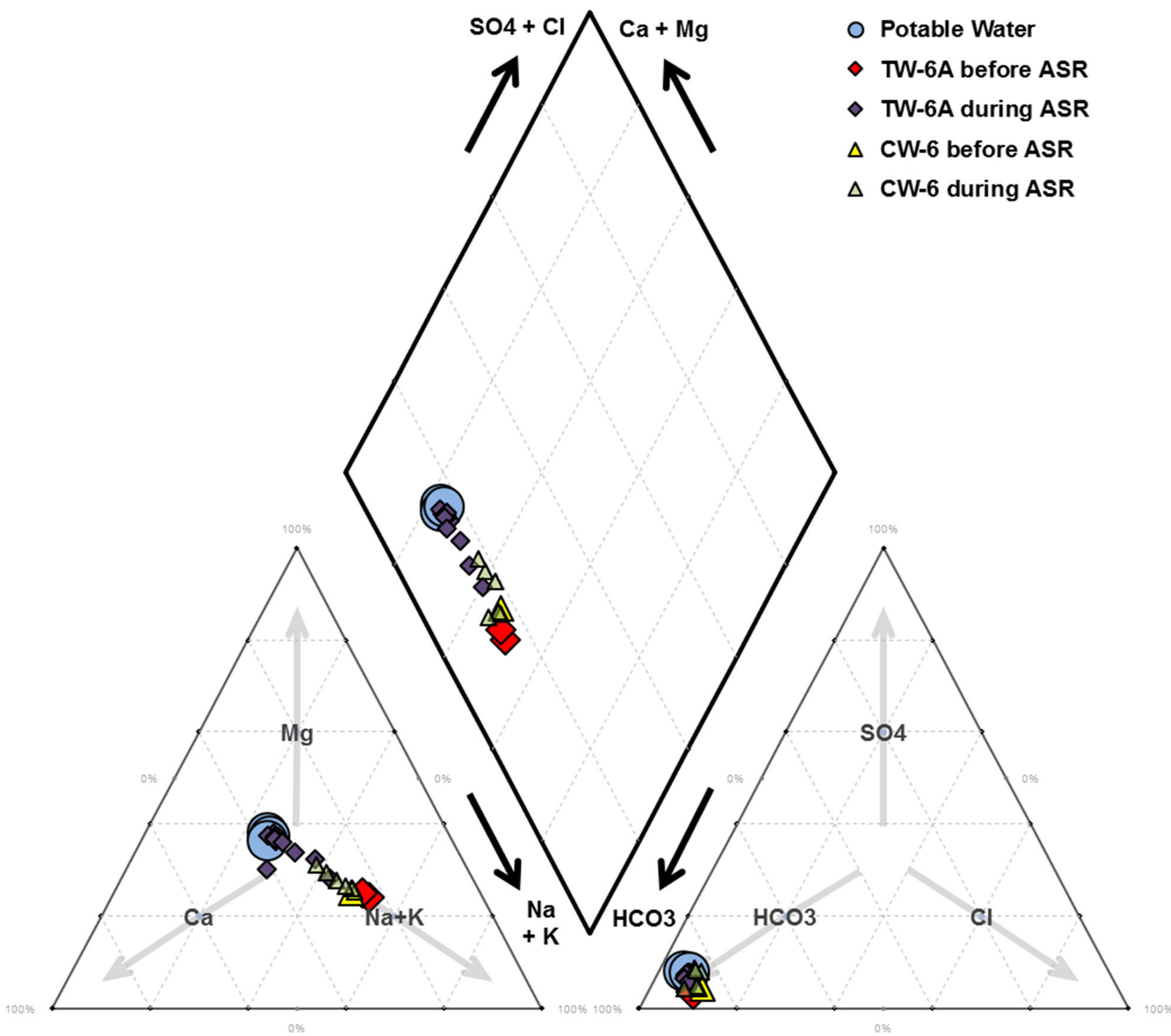


Figure 9. Piper Diagram of Anion / Cation Data

Disinfection by-products result from the interaction of chlorine (disinfectant) and trace organic matter in the aquifer and in the groundwater. The laboratory data include nine DBP compounds, which are grouped as trihalomethanes (THM) and haloacetic acids (HAAs). Overall, the average Total THM concentrations for recharge water, TW-6A, and CW-6 were four to five times greater than the Total HAA concentrations. Chloroform was the dominant THM, followed by bromodichloromethane, dibromochloromethane, and then bromoform. For the HAAs, dichloroacetic acid was dominant, followed by trichloroacetic acid, and then dibromoacetic acid. Two of HAA compounds were not detected in any of the samples: monobromoacetic and monochloroacetic acids. Further discussion of DBPs will be based on the Total THM data.

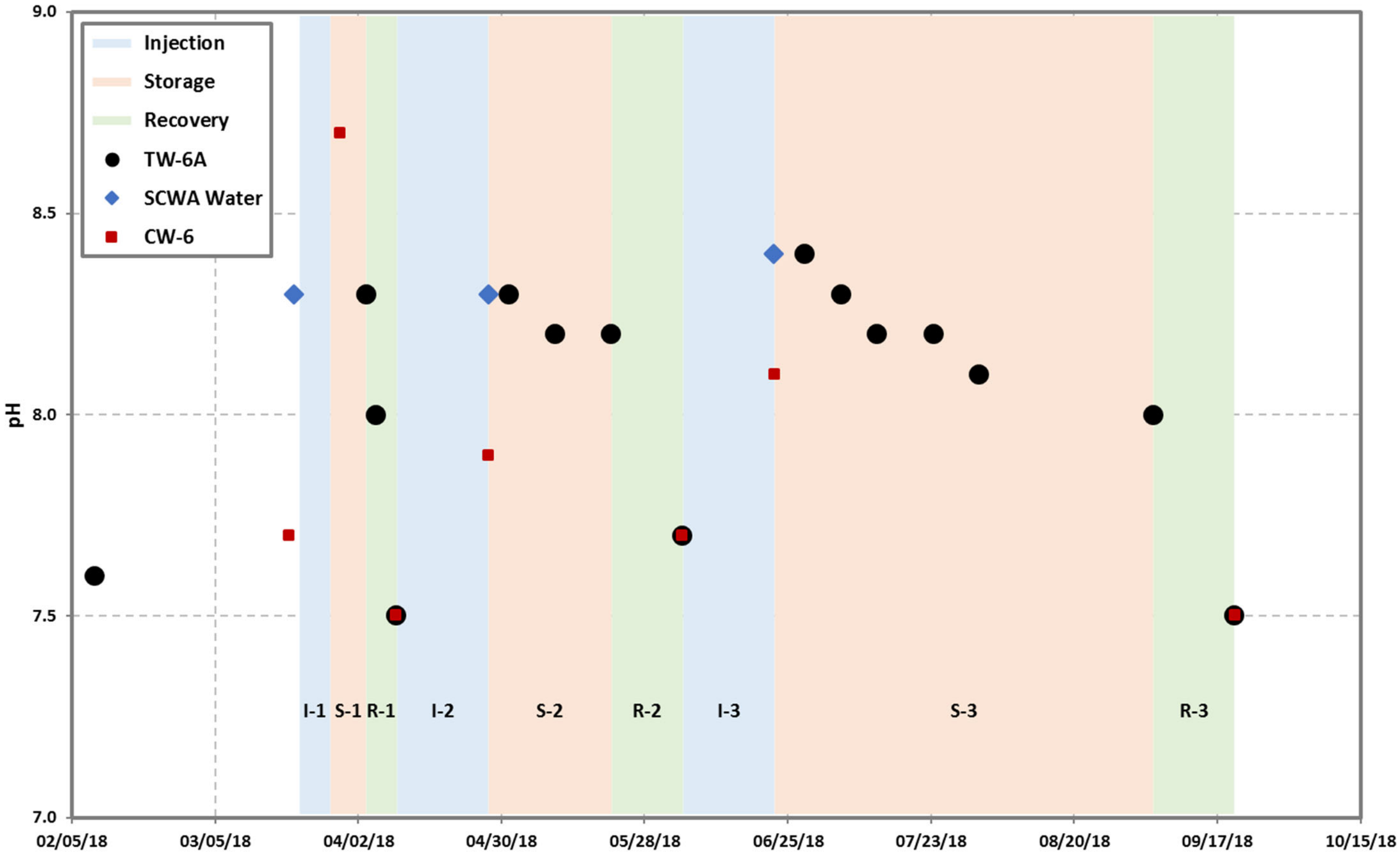


Figure 10. Recharge Water pH versus Native Groundwater pH

Figure 12 is a plot of THM concentrations during the pilot test and shows that TMH concentrations were relatively steady for the recharge water – 20 to 25 ug/l, and THMs were not detected in the native groundwater. During the first injection and storage periods, THMs formed rapidly at TW-6A with the initial concentration (26 ug/l) at the onset of the recovery period exceeding the initial RW concentration (20 ug/l). Thereafter, the THM concentrations decreased rapidly but THMs were still detected at the end of first recovery period at TW-6A (~5 ug/l), and at CW-6 (~2 ug/l).

During the second cycle, THM concentrations increased from 32 ug/l at the beginning of the storage period to 39 ug/l at the end and then decreased to 11 ug/l by the start of the third injection period. Only two samples were collected at CW-6 – at the beginning and end of the storage period, and the THM concentrations were 26 and 25 ug/l. Additional sampling at CW-6 would likely have found THM concentrations following a subdued trend consistent with the TW-6 trend.

During the third cycle, the THM concentrations at TW-6A appeared to be increasing at the end of the planned 30-day storage period so the duration of period was extended (+44 days) to better define the THM characteristics at TW-6A. The THM concentrations increased from 34 ug/l to 47 ug/l by the middle of the extended storage period and then decreased to 31 ug/l by the end of storage period. The THM concentration decreased to 14 ug/l at the end of the third and final recovery period. A projection of the last three THM values indicates that an additional 13 days of groundwater recovery would have been required to reduce the THM concentration to non-detect, based on a linear decline. This latter assumption is probably not valid and groundwater recovery might have extended well into October to achieve non-detect THM data. Additional samples were not collected at CW-6 but THMs would probably have trended similar to the TW-6A trend but at lower concentrations. The two wells were sampled again during late January 2020 for THMs, chloride, and sulfate, and one THM (chloroform) was detected at low concentrations – 5.3 ug/L at TW-6A and 0.8 ug/L at CW-6.

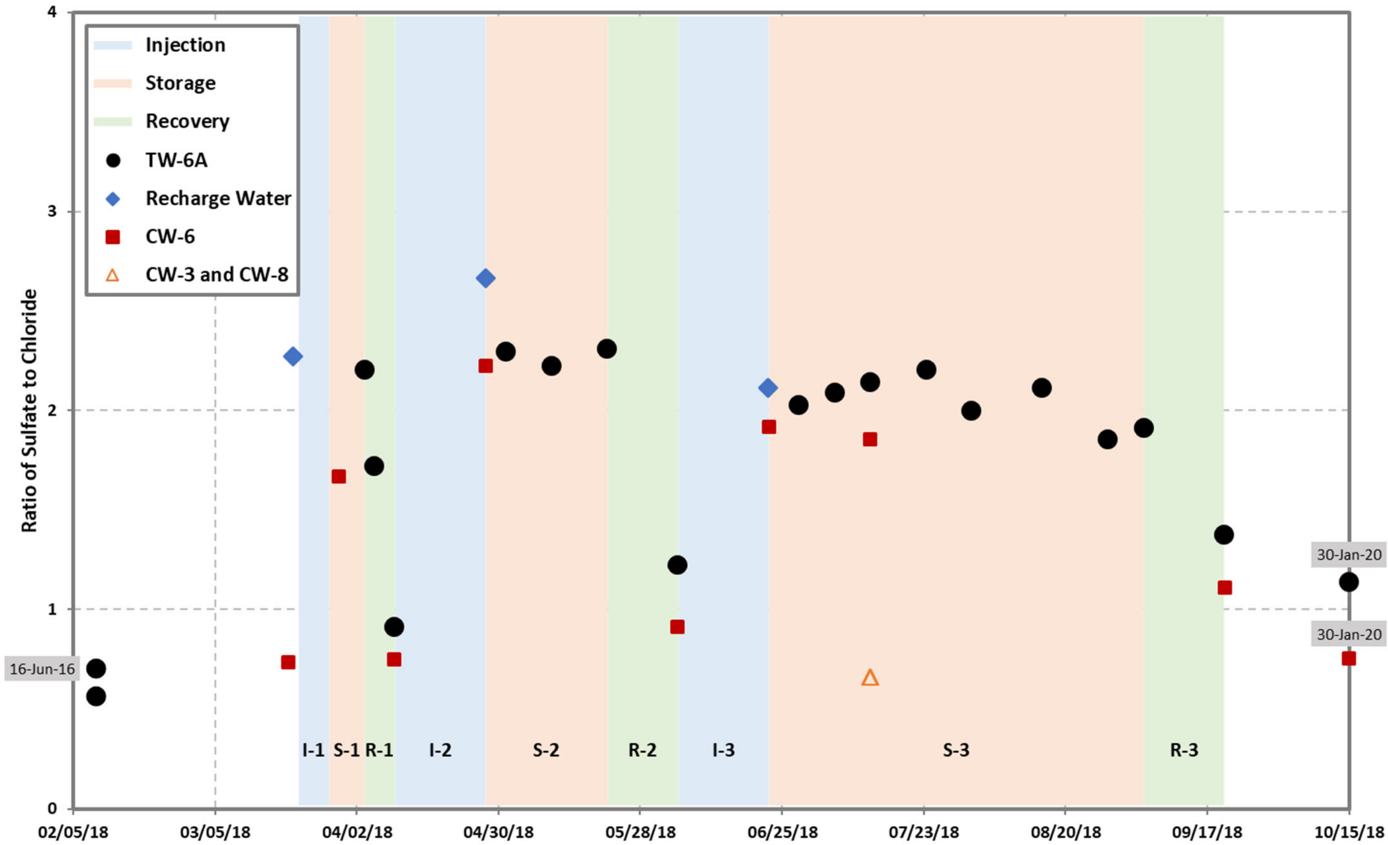


Figure 11. Sulfate-Chloride Ratio for Recharge Water and Native Groundwater

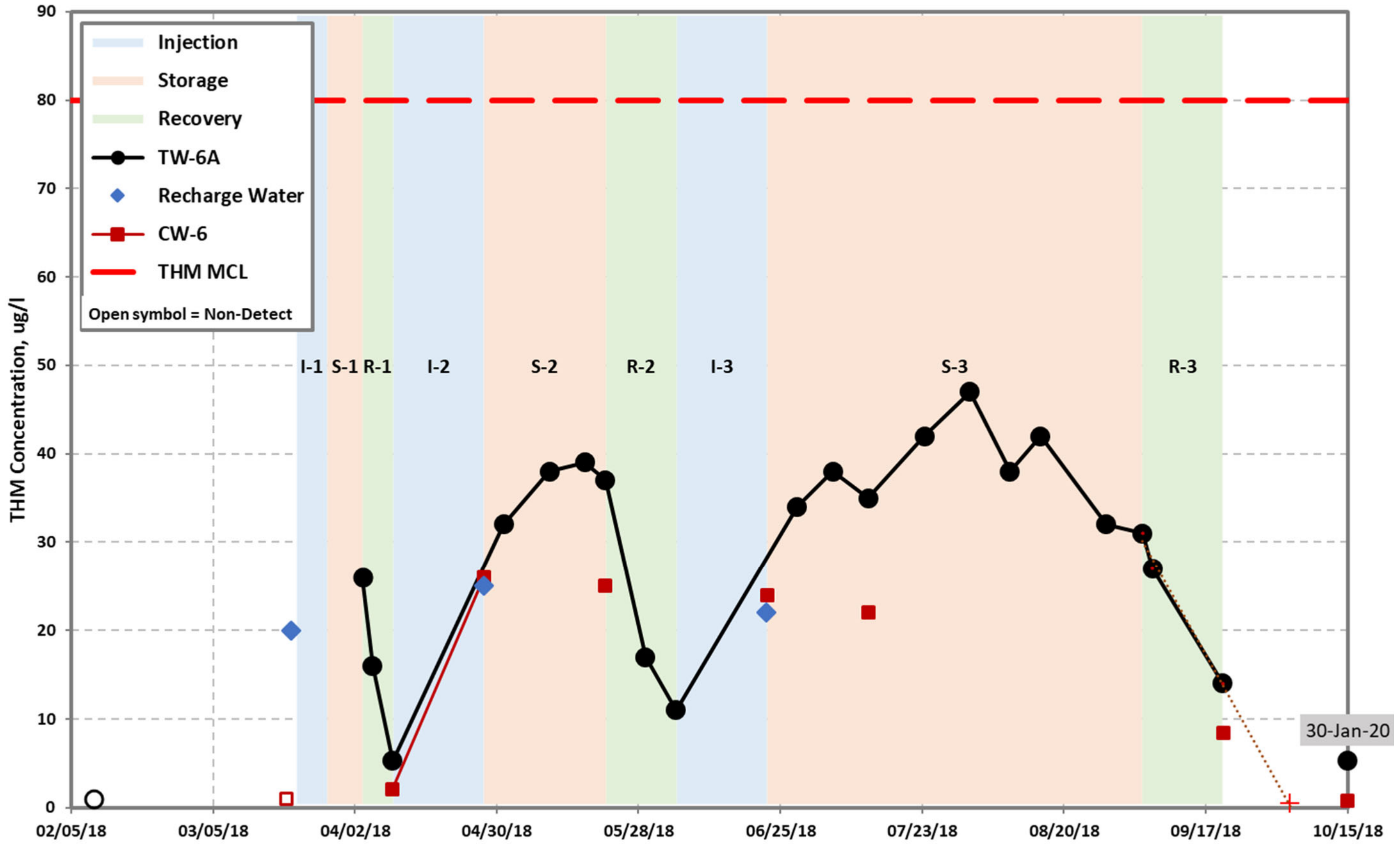


Figure 12. Total Trihalomethane Concentrations

4. Conclusions

A 6-month ASR pilot test was conducted with an 8-inch diameter, 230-foot deep, PVC well (TW-6A) that was constructed near the margin of the Sonoma Valley Subbasin. The local aquifer system appears to be comprised of fractured volcanic rocks interbedded with volcanic sedimentary rocks. The results of the pilot test allow for the following conclusions.

- Sonoma Water produces a consistent and excellent quality water from its Russian River treatment facility, and this potable water appears to be suitable as recharge water for long-term ASR applications.

- The recharge water and the native groundwater are both dilute (low TDS) and are dominated by the bicarbonate anion but exhibit several differences that distinguish the origins of the two waters. These differences include pH, cation composition, minor anion constituents, and disinfection by-products (DBPs).

- DBPs were present in the recharge water and were generated during the injection and storage period of each ASR cycle due to residual chlorine in the recharge water and organic carbon in the native groundwater. The DBP concentrations nearly doubled to approximately 50 micrograms per liter (ug/l) – less than the maximum contaminant level of 80 ug/l, before declining during the latter portion of the storage periods.

- A residual mixture of recharge water and native groundwater remained at TW-6A and, to a lesser extent, at City Well 6 after the pilot test, as indicated by the low level detects of DBPs and other chemical indicators.

- Although the efficiency of the PVC test well is about 50%, the well could be used to inject approximately 55 acre-feet of potable water during a 6-month period (November through April) of high flows on the Russian River. This volume might be increased through the use of a new ASR well with a higher (70%) efficiency. These volume estimates are based on aquifer characteristics determined by PWR (2019).

- Pilot testing followed guidelines and requirements outlined in the SWRCB ASR General Order and Notice of Applicability (NOA), including operations schedules monitoring requirements, along with NPDES requirements for discharges from TW-6A and CW-6.

- Active plugging rates were observed at very low values averaging approximately 0.2 ft/d (normalized rate of 0.8 ft/d). This low rate is attributed largely to the low particulate content of the injectate, based on calculations of the Silt Density Index (PWR, 2019).

- Residual plugging was not observed at TW-6A, indicating that backflushing procedures were effective in maintaining overall well performance. Performance of the well actually showed an improvement over time (as measured by 10-minute specific capacity) suggesting that flow reversals associated with ASR cycles of recharge and pumping had an ancillary benefit in providing additional well development and improved well efficiency (PWR, 2019).

- Geochemical results of the pilot program were in general agreement with the geochemical modeling study performed by PWR in September 2016. The model results were conservative in estimations of minimal scaling and adverse geochemical reactions between the Sonoma Water recharge water and native groundwaters; this conservatism is expected due to modeling predictions based on full equilibrium conditions being achieved (PWR, 2019).

- Program results verified that stored water met full Title 22 compliance for drinking water at the conclusion of the three ASR cycles. This observation is applicable for both recovered waters and water remaining in the aquifer (PWR, 2019).

- Water quality changes were observed in TW-6A and CW-6 during ASR operations as dilute, treated surface water (recharge water) was injected into the aquifer system. These changes resulted from simple dilution and from a combination of ion exchange, redox, and dissolution reactions; although these changes were minor and did not affect well hydraulics or recovered water potability (PWR, 2019).

- Significant biochemical activity was not observed during pilot testing, likely due to the relative absence of nutrients in the injectate water and the native groundwater (PWR, 2019).

5. Recommendations

Based on the results of the ASR pilot testing at TW-6A, the following are recommendations for any future ASR operations at this site:

- An injection rate of 70 gpm is recommended for future long-term operations of TW-6A (PWR, 2019).
- Consider the construction of additional monitoring wells for future longer-term testing or full-scale operations to evaluate variations in groundwater flow gradients (horizontal and vertical) and water quality.
- Future water quality monitoring should address chemical interactions such as ion exchange, dissolution, and leaching along with microbial activity as well as the fate of disinfection by-products.
- Construct new ASR wells using stainless steel, wire-wrap screen and silica beads as filter pack to maximize open area and the efficient movement of water between the well and aquifer. Maximize the time for well development, including numerous alternating cycles of surging and pumping, to produce an optimal filter pack for injection and recovery.
- Backflushing must be a routine operation during all recharge periods on a nominal bi-weekly basis to limit residual plugging and maintain long-term well performance. The backflushing procedure should consist of the same triple-backflush procedure implemented during the pilot test program (PWR, 2019).

Additionally, in order more fully evaluate the feasibility of ASR to address groundwater depletion in Sonoma Valley, pilot testing should be performed in other regions of the Subbasin to determine ASR suitability for different aquifer conditions (i.e. within alluvial or sedimentary formations).

6. References

GEI Consultants. 2016. *Monitoring Well Construction and Testing*. Prepared for the Sonoma County Water Agency. September.

GEI Consultants, Pueblo Water Resources, and Sonoma County Water Agency. 2017. *Technical Report, Aquifer Storage and Recovery, Pilot Test at Sonoma Test Well #6A*. Prepared for the Sonoma County Water Agency. December.

Heath, Ralph C. 1983. *Basic Ground-Water Hydrology*. USGS Water-Supply Paper 2220.

Pueblo Water Resources. 2018. *Injection Capacity and Constraints Analysis for Sonoma Test Well 6A*. Prepared for GEI Consultants, Inc. February.

Pueblo Water Resources, 2019. *Sonoma TW-6A ASR Pilot Test Project; Well and Aquifer Hydraulics Analysis and Water Quality Evaluation*. Prepared for GEI Consultants, Inc. March.

Appendix A. Pueblo Water Resources Memoranda – Hydraulic Evaluation and Geochemical Modeling

TECHNICAL MEMORANDUM
Pueblo Water Resources, Inc.
4478 Market St., Suite 705 Tel: 805.644.0470
Ventura, CA 93003 Fax: 805.644.0480

To:	GEI Consultants, Inc.	Date:	March 31, 2019
Attention:	Rodney Fricke, P.G., C.Hg. Senior Hydrogeologist	Project No:	09-0092
Copy to:	Chris Petersen, P.G., C.Hg. Principal Hydrogeologist Marcus Trotta, P.G., C.Hg. Sonoma County Water Agency		
From:	Robert Marks, P.G., C.Hg. Principal Hydrogeologist Stephen Tanner, P.E. Principal Engineer		
Subject:	Sonoma TW-6A ASR Pilot Test Project; Well and Aquifer Hydraulics Analysis and Water-Quality Evaluation		

INTRODUCTION

Presented in this Technical Memorandum (TM) is a summary of operations and analysis of well and aquifer water-level and water-quality data developed from an Aquifer Storage and Recovery (ASR) pilot demonstration project implemented at the City of Sonoma's (City) Test Well 6A (TW-6A), located at 150 First Street, Sonoma, California. The project was implemented by the City of Sonoma (City) with the assistance of the Sonoma County Water Agency (SCWA), and generally involved cyclic recharge, storage and subsequent recovery of treated drinking water originating from the SCWA's Russian River production and treatment facilities into the Sonoma Volcanics within the Sonoma Valley ground water basin via recharge and pumping of TW-6A. The overall objective of the project was to verify and empirically determine specific hydrogeologic and water quality factors that will allow a technical and economic assessment of ASR technology in the City of Sonoma.

BACKGROUND

As-Built Well Construction

TW-6A is located in the Sonoma Valley groundwater basin and completed within the Sonoma Volcanic aquifer system. The well was constructed in June 2016 to a depth of 230 feet below ground surface (bgs) with an 8-inch-diameter, Schedule 80 PVC casing and perforations placed between the intervals of 130 - 160 and 170 - 220 feet bgs. The annular seal was placed to a depth of 109 feet bgs. A summary of the as-built well construction features of TW-6A is presented below in **Table 1** and an as-built schematic is shown on **Figure 1**:

Table 1. As-Built Construction Summary

Design Feature	As-Built	Comment
Total Well Depth (ft. bgs)	230	
Static Water Level (ft. bgs)	69.3	February 2018
Seal Depth (ft. bgs)	109	
Casing Diameter (in)	8	7.565 ID
Casing Material	PVC	Schedule 80
Screen Intervals (ft. bgs)	130 - 160 170 - 220	
Total Screen Length (feet)	80	
Perforation Aperture	0.040-inch slots	Machine-cut horizontal
Gravel Pack (gradation)	8 x 16	
Cellar Section (ft bgs)	220 - 230	

Aquifer Parameter Analysis

Drawdown data developed from a pre-injection pumping test performed at TW-6A and the City Well #6 (used as an observation well) in February 2018 were analyzed to derive aquifer parameters of transmissivity and storativity. Jacob's approximation (Cooper and Jacob, 1946) to the Theis non-equilibrium well equation (Theis, 1935) was used to derive aquifer parameters. The analyses of the drawdown and recovery data are presented on **Figures 2 and 3**. The results of the analyses are summarized below in **Table 2**:

Table 2. Summary of Aquifer Parameter Estimates

Pumping Well	Aquifer[1]	Aquifer Parameter	Units[2]	Data Set		Average
				TW-6A	Well #6	
TW-6A	Tsv	Transmissivity	gpd/ft	9,240	9,100	9,170
		Storativity	dimensionless	--	2.63E-07	--

Notes:
1 - Sonoma Volcanics (Tsv).
2 - gallons per day per foot (gpd/ft).

As shown in **Table 2**, aquifer testing of TW-6A yielded transmissivity values averaging 9,170 gpd/ft. The storage coefficient derived from the monitor well data was estimated to be 2.63×10^{-7} (dimensionless), which is indicative of highly confined aquifer conditions. Utilizing a saturated thickness of 80 feet (i.e., thickness of screened interval), an average hydraulic conductivity value of the aquifer materials was calculated to be 115 gpd/ft^2 (15.4 feet/day [ft/d]), which is typical of fractured volcanics, a clean medium-grained sand, or a coarse-grained silty sand (Heath, 1983).

Well Efficiency

Well efficiency is defined as the ratio of the actual to the theoretical specific capacity, expressed as a percentage. The theoretical specific capacity is the specific capacity that would be observed if no additional hydraulic losses occur as water moves through the aquifer / well interface (i.e., well losses). Well efficiency is an important consideration for both pumping and injection wells, as inefficient wells create excessive drawdown and higher pumping lifts, which increase the power consumption and costs per unit of production during pumping, and creates excessive drawup during injection, which can decrease injection capacity.

There are always some hydraulic well losses associated with water moving through the near-bore, invaded zone of the aquifer, gravel pack, and well screen openings. Therefore, in practice, a 100-percent efficient, gravel-envelope production well does not exist. These hydraulic losses can be minimized through well design (e.g., gravel pack and screen selection) and construction techniques (e.g., control of drilling-fluid properties and adequate well development). Typical well efficiencies for properly drilled and developed municipal production wells are in the range of 70 to 80 percent (Driscoll, 1986).

Utilizing the aquifer parameters derived from the testing of the TW-6A, the theoretical specific capacity can be determined from equations presented by Walton (1991). The result of the well-efficiency estimate is presented in **Table 3** below:

Table 3. Well-Efficiency Estimate

24-hr Specific Capacity (gpm/ft)		Efficiency (%)
Actual	Theoretical	
1.83	3.27	56

As shown, the estimated efficiency of TW-6A is approximately 56 percent, which is below typical values. The relatively low efficiency of TW-6A is likely attributable to significant aquifer damage during drilling and/or insufficient development of the completed well. These observations suggest, however, that a rigorous well re-development program would likely be capable of increasing the hydraulic efficiency and specific capacity of the well.

Preliminary Injection Capacity Constraints Analysis

The injection capacity of any given aquifer storage and recovery (ASR) well is dependent on a variety of site-specific factors, which can be generally categorized into issues associated with; 1) well response to injection, and 2) aquifer response to injection. Examples of issues associated with the well response include allowable drawup within the well casing before some head limitation is reached, and the available drawdown for well backflushing. Issues associated with aquifer response to injection involve the available "freeboard" in the aquifer for water levels (piezometric head) to be increased without inducing undesirable results. To the extent possible, ASR wells should be operated to maximize injection and production rates while operating within the constraints of these site-specific factors. An evaluation of each of these factors and their influence on the potential injection capacity of TW-6A was presented in a previous TM developed prior to initiation of the ASR pilot test program, the details of which will not be repeated here, but is included as **Appendix A** (not included in draft) for reference. A summary of all the injection capacity constraints for TW-6A is presented in **Table 4** below:

Table 4. Injection Capacity Constraints Summary

Well	Injection Capacity (gpm) vs. Constraint					
	Well Response		Backflushing Capacity	Downhole Velocity	Hydro-Fracturing	Offsite Impacts
	Min (gs)	Max (30 psi)				
TW-6A	118	238	**56**	140	100	320

Notes:
Primary limiting factor shown in **bold** type.

As shown, analysis of the various hydrogeologic and operational factors that limit the theoretical injection capacity of TW-6A shows that the Backflushing Capacity criterion represents the primary constraint on the injection capacity, with an injection rate of approximately 55 gpm. If TW-6A had a higher efficiency of 80 percent, the backflushing capacity would increase to approximately 160 gpm with a corresponding recharge capacity of 80 gpm.

FINDINGS

ASR PILOT TEST SUMMARY OF OPERATIONS

The primary purpose of the ASR pilot testing was to demonstrate injection well hydraulics and operational performance characteristics of TW-6A and to monitor the local aquifer hydraulic and geochemical responses to recharge and recovery operations. These data can then be used to both assess the economic and logistical viability of ASR and as a basis for environmental planning and permitting documentation for a long-term, full-scale ASR project. The primary issues investigated can be generally categorized into two areas of investigation:

1. Well and Aquifer Hydraulics:
    - Determination of injection well efficiency and specific capacity.
    - Evaluation of injection well plugging rates (both active and residual).
    - Determination of optimal rates, frequency, and duration of backflushing in order to maintain long-term injection capacity.
    - Determination of long-term sustainable injection rates.
    - Determination of local aquifer response to injection at the TW-6A site.
2. Water Quality:
    - Monitor geochemical reaction mechanisms
    - Evaluate water quality changes during storage

- Monitor recovery efficiency
- Monitor injected water quality stability and equalization in the aquifer.
- Monitor THM and HAA fate.
- Quantify aquifer mixing/dispersion parameters.
- Monitor recovered water 'post extraction' for re-chlorination and THM/HAA reformation.

As presented above, under current conditions the aquifer system at the site is theoretically capable of supporting a long-term continuous injection rates ranging between approximately 55 to 100 gpm. The testing program was designed around these rates, and is summarized in **Table 5** below:

Table 5. ASR Pilot Test Program Summary

ASR Cycle	ASR Phase	Dates / Times		Duration	Total Volume		Avg Rate
		Start	End	(days)	(gals)	(af)	(gpm)
Initial CR Test	Injection	3/20/18 15:30	3/21/18 9:30	0.8	59,239	0.18	54.9
1	Injection	3/21/18 13:30	3/27/18 13:30	6.0	482,947	1.48	55.9
	Storage	3/27/18 13:30	4/3/18 12:55	7.0	--	--	--
	Recovery	4/3/18 12:55	4/9/18 12:05	6.0	712,323	2.19	82.9
2	Injection	4/9/18 15:10	4/27/18 10:35	17.8	1,735,965	5.33	67.7
	Storage	4/27/18 10:35	5/21/18 12:30	24.1	--	--	--
	Recovery	5/21/18 12:30	6/4/18 9:55	13.9	1,644,890	5.05	82.2
3	Injection	6/4/18 11:55	6/22/18 8:45	17.9	1,817,772	5.58	70.6
	Storage	6/22/18 8:45	9/4/18 13:00	74.2	--	--	--
	Recovery	9/4/18 13:00	9/20/18 8:30	15.8	1,736,016	5.33	76.2

In addition, the well was thoroughly backflushed following each of the injection tests to limit residual plugging of the well due to injection and assess the efficacy of well backflushing (discussed in a following section).

Procedures and Monitoring Program

ASR pilot testing of TW-6A was performed between March 20 and September 20, 2018. Injection feed water was potable water provided from the SCWA distribution system. Injection rates were controlled by several ball valves on the temporary piping system. Injection flow rates and total injected volumes were measured with a totalizing meter. Injection operations were performed through five 1-inch diameter Schedule 40 PVC drop tubes fitted with fixed orifice caps at the bottom of each tube. Positive pressures were maintained within the piping system and drop tubes during injection testing to prevent water cascading and cavitation in the well.

Water levels in TW-6A, City Well 6 (CW-6) and City Well 8 (CW-8) were measured during testing program with pressure transducers and data loggers and were periodically verified with a manual electric sounder. Water-level data collected from the three wells during the course of the ASR pilot test program are shown on **Figure 4**. A summary of the construction details of the test program wells is presented in **Table 6** below:

Table 6. Well Construction Summary

Well ID	Distance from TW-6A (feet)	Screen Intervals (ft bgs)		Aquifer Completed
TW-6A	0	130 - 160	170 - 220	Sonoma Volcanics
CW-6	36 ?	140 - 236	--	Sonoma Volcanics
CW-8	800 ?	155 - 295	--	Sonoma Volcanics

WELL AND AQUIFER HYDRAULICS

1000-minute Constant Rate Injection Test

An initial constant rate injection test was initiated on March 20, 2018 and continued overnight until March 21, 2018. This phase of testing consisted of a continuous rate injection test performed at an average injection rate of approximately 54.9 gpm, with a total volume of approximately 0.00633 million gallons (0.18 acre-feet) injected.

Water-level data for the 1000-minute constant-rate injection test are graphically presented on **Figure 5**. As shown, the static water level in the well prior to injection was 67.2 feet below ground surface (bgs). The injection water level recorded after 1000 minutes was 34.2 feet bgs, corresponding to a drawup of 33.0 feet and a 1000-minute specific injectivity of approximately 1.66 gpm/ft. This value represents approximately 91 percent of the 24-hour pumping specific capacity of 1.83 gpm/ft.

Response to injection at TW-6A was measured at CW-6, with approximately 10.1 feet of drawup observed at the end of the test. No discernable response was observed at CW-8.

ASR Cycle 1 Injection

Following termination of the 1000-minute injection test, backflushing (discussed below) and a period of water level recovery, ASR Cycle 1 Injection Test was initiated later in the day on March 21, 2018 and continued until March 27, 2018. This phase of testing consisted of a continuous rate injection test performed at an average injection rate of approximately 55.9 gpm, with a total volume of approximately 0.0656 million gallons (1.48 acre-feet) injected.

Water-level data for ASR Cycle 1 Injection Test are graphically presented on **Figure 6**. As shown, the static water level in the well prior to injection was 66.5 feet below ground surface (bgs). During injection, drawup in the well was approximately 33.3 and 36.3 feet after 1000 minutes and 6 days of injection; respectively, corresponding to specific injectivities of approximately 1.67 and 1.54 gpm/ft, respectively. The 1000-minute value is essentially the same as the specific injectivity observed during the 1000-minute injection test, indicating that backflushing of the well (discussed below) was effective and no residual plugging of the well occurred following the initial 1000-minute injection test.

ASR Cycle 1 Recovery

Following an approximate 7-day period of aquifer storage, ASR Cycle 1 Recovery Test was initiated on April 3, 2018 and continued until April 9, 2018. The discharge rate was maintained at an average rate of approximately 82.9 gpm during the 6-day test and a total volume of 0.207 million gallons (2.19 acre-feet) was extracted, equivalent to approximately 150 percent of the previously injected volume.

Water-level data for ASR Cycle 1 Recovery Test are graphically presented on **Figure 7**. As shown, the static water level in TW-6A prior to pumping was approximately 67.9 feet bgs. The pumping level recorded after 24-hours was approximately 114.7 feet, corresponding to a drawdown of 46.8 feet, and a 24-hour specific capacity of approximately 1.77 gpm/ft. This 24-hr specific capacity value is slightly less (6 percent) than the pre-injection 24-hour specific capacity of 1.83 gpm/ft. The final pumping level at the end of the 6-day test was 115.1 feet bgs.

Response to the ASR Cycle 1 continuous discharge test was observed at CW-6, with approximately 19.6 feet of drawdown observed at the end of the 6-day test. It is noted that the levels recorded by the CW-8 transducer during the initial 4265 minutes of the test were in error; therefore, the hydraulic response to this test could not be calculated.

ASR Cycle 2 Injection

Following termination of ASR Cycle 1 Recovery and a brief period of water-level recovery, ASR Cycle 2 Injection Test was initiated on April 9, 2018 and continued until April 27, 2018. This phase of testing consisted of a continuous rate injection test performed at an average injection rate of approximately 67.3 gpm, with a total volume of approximately 1.74 million gallons (5.33 acre-feet) injected. It is noted that the injection rate for this injection test was increased by about 20 percent compared to ASR Cycle 1 (i.e., approximately 67.3 vs. 55.9 gpm) based on analysis of the Cycle 1 injection performance and lack of residual plugging.

Water-level data for ASR Cycle 2 Injection Test are graphically presented on **Figure 8**. As shown, the static water level in the well prior to injection was 70.2 feet bgs. It is noted that the static water level had not fully recovered after ASR Cycle 1 Recovery pumping prior to initiating ASR Cycle 2 Injection (i.e., the well was not left idle for a period of 6 days following termination of pumping) but did recover adequately to a level of approximately 95 percent. During injection, drawup in the well was approximately 43.3, 48.3 and 53.9 feet after 1000 minutes, 6 days and 18 days of injection; respectively, corresponding to specific injectivities of approximately 1.55, 1.39 and 1.24 gpm/ft, respectively. These 1000-minute and 6-day specific injectivity values are approximately 10 percent less that as those observed during the Cycle 1 injection test, indicating that the increased injection rate resulted in slightly greater hydraulic losses.

Immediate response to the ASR Cycle 2 Injection Test was observed at CW-6, with approximately 20.2 feet of water level increase observed at the end of the 18-day test. CW-8 water-level data show a discernable response (i.e., greater than 1 ft) to injection at TW-6A after approximately 1.4 days (2000 minutes) of injection, with approximately 2.24 feet of response observed at the end of the 18-day test.

ASR Cycle 2 Recovery

Following an approximate 24-day period of aquifer storage, ASR Cycle 2 Recovery Test was initiated on May 21, 2018 and continued until June 4, 2018. The discharge rate was maintained at an average rate of approximately 82.2 gpm during the test and a total volume of 1.64 million gallons (5.05 acre-feet) was extracted, equivalent to approximately 95 percent of the Cycle 2 injected volume.

Water-level data for ASR Cycle 2 Recovery Test are graphically presented on **Figure 9**. As shown, the static water level in TW-6A prior to pumping was approximately 65.9 feet bgs. The pumping level recorded after 24-hours was approximately 110.8 feet, corresponding to a drawdown of 44.8 feet, and a 24-hour specific capacity of approximately 1.83 gpm/ft. This 24-hr specific capacity value is identical to the pre-injection 24-hour specific capacity of 1.83 gpm/ft, indicating that no residual plugging (discussed in more detail in later section) of the well had occurred as result of the previous injection tests. The final pumping level at the end of the 14-day test was 115.4 feet bgs.

Response to the ASR Cycle 2 Recovery pumping was observed at CW-6 and CW-8, with approximately 17.4 and 1.77 feet of drawdown, respectively, observed at the end of the 14-day test.

ASR Cycle 3 Injection

Following termination of ASR Cycle 2 Recovery and a brief period of water-level recovery, ASR Cycle 3 Injection Test was initiated on June 4, 2018 and continued until June 22, 2018. This phase of testing consisted of a continuous rate injection test performed at an average injection rate of approximately 70.6 gpm, with a total volume of approximately 1.82 million gallons (5.58 acre-feet) injected.

Water-level data for ASR Cycle 3 Injection Test are graphically presented on **Figure 10**. As shown, the static water level in the well prior to injection was 71.9 feet bgs (a recovery level of approximately 88 percent). During injection, drawup in the well was approximately 40.8, 48.9 and 50.9 feet after 1000 minutes, 6 days and 18 days of injection; respectively, corresponding to specific injectivities of approximately 1.73, 1.44 and 1.38 gpm/ft, respectively. These specific injectivity values are approximately 5 to 10 percent greater than those observed during the Cycle 2 injection test, indicating that the wells performance improved slightly as a result of the pumping that occurred during Cycle 2 storage sampling and recovery (i.e., as discussed in the background section, the well had a relatively low efficiency prior to the test program, and the injection/pumping cycles had a beneficial development effect on the well's hydraulic efficiency).

Response to the ASR Cycle 3 Injection Test was observed at CW-6 and CW-8, with approximately 18.7 and 2.10 feet, respectively, of water level increase observed at the end of the 18-day test.

ASR Cycle 3 Recovery

Following an approximate 74-day period of aquifer storage, ASR Cycle 3 Recovery Test was initiated on September 4, 2018 and continued until September 22, 2018. The discharge rate was maintained at an average rate of approximately 76.2 gpm during the test and a total volume of 1.74 million gallons (5.33 acre-feet) was extracted, equivalent to approximately 95 percent of the Cycle 3 injected volume.

Water-level data for ASR Cycle 3 Recovery Test are graphically presented on **Figure 11**. As shown, the static water level in TW-6A prior to pumping was approximately 73.7 feet bgs. The pumping level recorded after 24-hours was approximately 114.8 feet, corresponding to a drawdown of 38.6 feet, and a 24-hour specific capacity of approximately 1.97 gpm/ft. This 24-hr specific capacity value is approximately 8 percent greater than the pre-injection 24-hour specific capacity of 1.83 gpm/ft, further indicating that not only was no residual plugging (discussed in more detail in later section) of the well had occurred as result of the previous injection tests, but had actually improved (refer to the discussions above about well efficiency). The final pumping level at the end of the 16-day test was 120.2 feet bgs.

Response to the ASR Cycle 3 Recovery pumping was observed at CW-6 and CW-8, with approximately 17.9 and 2.06 feet of drawdown, respectively, observed at the end of the 16-day test.

Backflushing

Following each injection test, backflushing was performed on the well. Backflushing operations generally consisted of pumping the well to waste at a rates ranging between approximately 100 and 120 gpm for a period of 15 minutes. The pump was then shut off and the water contained in the pump column pipe allowed to surge back into the well, followed by a 15 minute idle period. The pump was then restarted and pumped to waste for another 15 minutes, and the process was then repeated resulting in a triple-backflush procedure. During each backflushing pumping event, the well discharge was initially very slightly turbid (approximately 5 to 10 NTU) and of light brown color for the first 10 minutes or so, followed by a decrease in turbidity. Discharge water during thee subsequent backflushing cycles was essentially clear (approximately 1 to 3 NTU), indicating that the majority of particulates were removed from the well during the initial 15 minutes of backflushing.

Following each backflushing event controlled 10-minute specific capacity tests were performed to track well performance and the efficacy of backflushing. Additional specific 10-minute capacity data were developed during the storage period water-quality sampling events. The 10-minute specific capacity results are summarized in **Table 7** below and presented graphically on **Figure 12**:

Table 7. 10-Minute Specific Capacity Summary

Date / Time	SWL (ft btoc)	PWL (ft btoc)	DDN (ft)	Q (gpm)	Q/s (gpm/ft)	% Change*	Comments
3/19/18 11:00	67.2	116.1	48.9	102	2.09	--	Pre-Injection Baseline Test
3/20/18 13:25	66.1	121.9	55.8	116	2.08	-0.39	Post Initial system hydraulics test
3/21/18 11:30	68.7	124.2	55.5	112	2.02	-3.23	Post Initial 24-hr CR test and 3x backflush
3/27/18 15:30	66.7	110.7	44.0	85	1.93	-7.37	Post Cycle 1 Injection and 3x backflush
4/3/18 11:30	66.2	103.9	37.7	80	2.12	1.75	Start of Cycle 1 Recovery
4/27/18 12:30	64.0	105.7	41.7	85	2.04	-2.26	Post Cycle 2 Injection and 3x backflush
5/10/18 9:20	64.2	106.1	41.9	85	2.03	-2.72	Cycle 2 Storage sampling
5/17/18 9:05	65.2	106.3	41.1	85	2.07	-0.83	Cycle 2 Storage sampling
5/21/18 9:45	65.1	106.1	41.0	85	2.07	-0.59	Start of Cycle 2 Recovery
6/22/18 10:35	63.2	100.6	37.4	80	2.14	2.57	Post Cycle 3 Injection and 3x backflush
7/5/18 8:15	66.2	102.4	36.3	80	2.21	5.74	Cycle 3 Storage sampling
8/9/18 8:10	68.2	103.8	35.6	80	2.25	7.85	Cycle 3 Storage sampling
8/28/18 8:50	75.1	111.1	36.0	80	2.22	6.56	Cycle 3 Storage sampling
9/4/18 13:10	73.7	107.0	33.3	80	2.40	15.20	Start of Cycle 3 Recovery

Notes:
SWL - Static Water Level
ft btoc - feet below top of casing
PWL - Pumping Water Level
DDN - Drawdown
Q - Discharge Rate
gpm - gallons per minute
Q/s - Specific Capacity
* - compared to baseline

As shown, the well displayed a pre-injection 10-minute specific capacity of 2.09 gpm/ft. Following the initial 1000-minute injection test and ASR Cycle 1 Injection, the specific capacity displayed a slightly declining trend down to 1.93 gpm/ft, a decline of approximately 7 percent; however, upon initiation of ASR Cycle 1 Recovery pumping, the specific capacity had increased to 2.12 gpm/ft, a value commensurate with the pre-injection baseline performance. The specific capacity remained essentially stable through ASR Cycle 2. Following ASR Cycle 3 Injection, the specific capacity began a distinct increasing trend, ending at value of 2.40 gpm/ft, an overall increase of approximately 15 percent compared to the baseline performance. These results indicate that that backflushing was not only effective at removing particulates introduced into the well during injection, but suggest that the flow reversals associated with the injection and pumping cycles effectively increased the well efficiency by providing additional development of the well.

Plugging Rate Analysis

Experience at injection sites around the world shows that all injection wells are subject to some amount of plugging because no water source is completely free of particulates. During injection, trace amounts of suspended solids are continually being deposited in the gravel pack and aquifer pore spaces, much as a media filter captures particulates in the filter bed. The effect of plugging is to impede the flow of water from the injection well into the aquifer, causing increased injection heads in the well to maintain a given injection rate, or reduced injection rates at a given head level. Well plugging reduces injection and extraction capacity, and consequently, well life.

Plugging can occur due to water quality issues, improper system operation, or poor well design practices. In general, plugging issues fall into four general categories: physical plugging (by particulate matter), chemical reaction (between the injectate and native waters or aquifer minerals), biofouling (the proliferation of bacteria in the gravel pack or aquifer), and gas binding (the vapor locking of the aquifer by entrained or evolved gasses in the injectate).

Silt Density Index Testing. Relative measurements of the particulate matter in the injectate were made through silt density index (SDI) testing during injection. The SDI was originally developed to quantitatively assess particulate concentrations in reverse osmosis feed waters. The SDI involves pressure filtration of source water through a 0.45-micron membrane, and observation of the decrease in flow over time; the resulting value of SDI is dimensionless, and used as a comparative value for tracking relative well plugging rates versus water quality or other parameters. SDI test results are summarized in **Table 8** below:

Table 8. Summary of Silt Density Index (SDI) Test Results

Date / Time	t_0 (secs)	t_{15} (secs)	SDI (unitless)	Comments
3/20/18 9:00	26	27	0.25	Pre-Injection line flushing
3/20/18 9:30	25	27	0.49	Pre-Injection line flushing
3/21/18 14:10	41	43	0.31	Cycle 1 Injection
3/22/18 8:30	43	45	0.30	Cycle 1 Injection
3/22/18 15:30	28	30	0.44	Cycle 1 Injection
3/23/18 8:05	28	30	0.44	Cycle 1 Injection
3/27/18 12:20	23	25	0.49	Cycle 1 Injection
4/9/18 14:00	23	53	3.77	Pre-Injection line flushing
4/9/18 14:30	22	33	2.22	Pre-Injection line flushing
4/9/18 16:40	20	22	0.61	Cycle 2 Injection
4/18/19 10:35	22	26	1.03	Cycle 2 Injection
6/4/18 12:05	21	31	2.15	Cycle 3 Injection
6/4/18 12:35	22	26	1.03	Cycle 3 Injection
6/22/18 7:50	21	24	0.83	Cycle 3 Injection

Notes:

t_0 - elapsed time 0 minutes

t_{15} - elapsed time 15 minutes

secs - seconds

SDI - Silt Density Index

As shown, SDI values during injection testing were very consistent, ranging between approximately 0.30 and 2.15. Values within this range are generally representative of source waters with very low amounts of particulates and, therefore, very favorable for injection.

Active Plugging Rates. Active plugging rates during injection testing of TW-6A were estimated utilizing the Graphical Observed vs. Theoretical Drawup Method. Water level rise in an injection well is a combination of both aquifer response and well losses. Theoretically, at any given constant injection rate, well losses should remain constant; therefore, in the absence of plugging, any water level rise in the well would be due only to aquifer response. The difference between the theoretical water level and the observed water can be presumed to be caused by plugging.

It is important to note that the theoretical water level rise corresponds to the water level that would occur if well losses were negligible. In order to account for well efficiency losses, the graphical method involves drawing a straight line through moderate elapsed time data points (e.g., 100 to 1000 minutes). Assuming no plugging is occurring, the theoretical water level rise during injection would plot on along a straight line on a semi-log plot. The variance from the straight line is assumed to be indicative of the amount of plugging.

The amount of plugging, in feet of water level rise, was calculated for the ASR Cycles 1 through 3 injection tests. The plugging rate analyses for these long-term continuous rate injection tests are presented graphically on **Figures 13 through 15**. As shown, no discernable plugging was observed during the 6-day ASR Cycle 1 Injection Test. During the longer-term 18-day ASR Cycle 2 and 3 Injection Tests, however, measurable amounts of plugging were observed. For example, at the end of ASR Cycle 2 Injection, the observed water level rise was 53.9 feet. The theoretical water level rise was estimated to be approximately 50.6 feet. Total water level rise due to plugging was, therefore, approximately 3.30 feet, yielding an average plugging rate of approximately 0.183 feet per day (ft/day) for ASR Cycle 2 Injection Test. As shown on **Figure 15**, calculated plugging rate for ASR Cycle 3 Injection Test was a comparable value of 0.242 ft/day.

Normalized Plugging Rates. Normalizing plugging rates to a reference velocity at the well screen of 3 feet per hour and a water temperature of 20 degrees allows for comparison of data from wells that have different constructions, injection rates, and water temperatures. The observed plugging rate is normalized by the following equation (Olsthoorn, 1982):

$$PR_{norm} = PR_{obs}\,(Vs/V)^2\,(n_{20}/n) \qquad \text{(Eq.2)}$$

Where:

PR_{norm}	=	plugging rate in feet/day normalized to 20 degrees Celsius and a borehole velocity of 3 ft/hr
PR_{obs}	=	calculated observed plugging rate in ft/day
Vs	=	standard velocity at borehole wall of 3 ft/hr
V	=	calculated velocity at borehole wall in ft/hr
n_{20}	=	viscosity (in centipose) at standard temperature of 20 degrees Celsius
n	=	viscosity (in centipose) at measured temperature

A summary of the plugging rate calculations in presented in Table 9 below:

Table 9. Summary of Pugging Rate Calculations

ASR Cycle Injection Test	Injectate Temp (^{0}C)	Injection Rate (gpm)	Duration of Injection (days)	Flux at B.H. Wall (ft/hr)	Obs. Plug Rate (ft/day)	Norm. Plug Rate (ft/day)
1	13.8	55.9	6.0	1.43	0.000	0.000
2	15.1	67.3	17.9	1.72	0.183	0.773
3	18.8	70.6	17.9	1.80	0.242	0.988

As shown, the observed plugging rates during ASR Cycles 2 and 3 Injection Tests ranged between approximately 0.183 and 0.242 ft/d, averaging approximately 0.213 ft/d. Normalization of these observed plugging rates yields plugging rates of approximately 0.773 and 0.988 ft/d. Both the observed active and normalized plugging rates are considered quite low and compare favorably with other ASR well sites Pueblo Water Resources has studies in California.

Residual Plugging. As discussed previously, following backflushing operations controlled 10-minute specific-capacity tests were performed to track well pumping performance. Residual plugging is the plugging that remains following backflush pumping. Residual plugging increases drawdown during pumping and drawup during injection, and is manifested as declining specific capacity / injectivity. The presence of residual plugging is indicative of incomplete removal of plugging particulates during backflushing and has the cumulative effect of reducing well performance and capacity over time. Presented in **Table 10** below is a summary of the residual plugging calculations for the TW-6A ASR pilot test program:

Table 10. Residual Plugging Summary

Date / Time	Pumping Rate (gpm)	10-min Drawdown (ft)	10-min Q/s[1] (gpm/ft)	Normalization Ratio[2]	Normalized Drawdown[2] (ft)	Residual Plugging (ft)
3/19/18 11:00	102	48.9	2.1	0.83	40.8	--
3/20/18 13:25	116	55.8	2.1	0.73	40.9	0.2
3/21/18 11:30	112	55.5	2.0	0.76	42.1	1.4
3/27/18 15:30	85	44.0	1.9	1.00	44.0	3.2
4/3/18 11:30	80	37.7	2.1	1.06	40.1	-0.7
4/27/18 12:30	85	41.7	2.0	1.00	41.7	0.9
5/10/18 9:20	85	41.9	2.0	1.00	41.9	1.1
5/17/18 9:05	85	41.1	2.1	1.00	41.1	0.3
5/21/18 9:45	85	41.0	2.1	1.00	41.0	0.2
6/22/18 10:35	80	37.4	2.1	1.06	39.7	-1.0
7/5/18 8:15	80	36.3	2.2	1.06	38.5	-2.2
8/9/18 8:10	80	35.6	2.2	1.06	37.8	-3.0
8/28/18 8:50	80	36.0	2.2	1.06	38.3	-2.5
9/4/18 13:10	80	33.3	2.4	1.06	35.4	-5.4

Notes:

1 - Specific Capacity. Ratio of pumping rate to drawdown.

2 - Normalized based on ratio of 85 gpm to actual test pumping rate.

As shown, there was a negative amount of approximately 5.4 feet of residual plugging observed over the course of the pilot test program; in other words, not only did no residual plugging occur as a result of injection, but some additional development of the well occurred (as discussed previously). These results indicate that the approximate bi-weekly schedule of a triple-backflush operation was successful at limiting residual plugging and maintaining injection well performance.

WATER QUALITY ISSUES

A critical component of the ASR pilot demonstration program was the empirical assessment of water quality (WQ) issues through the recharge-aquifer storage-recovery cycles of ASR operations. For the Sonoma ASR program, potable, Title-22 compliant water from the SCWA transmission system was used to recharge the aquifer. The pilot program was designed to monitor and verify that potability was maintained throughout the ASR cycle sequence of injection, aquifer storage, and recovery operations.

The principal focus of the WQ investigation was on parameters associated with potability; however additional WQ parameters were monitored that are known to affect well and aquifer performance vis-à-vis well screen and/or aquifer plugging. Such adverse reactions can occur between the (SCWA) recharge water and the native ground water (NGW); the recharge water and the geologic matrix of the aquifer; or both. (Beneficial reactions may also occur, but are not the primary focus of initial pilot demonstration testing.)

The reactions between recharge waters, native ground waters, and aquifer matrix minerals can be classified into the following general categories:

- ***Precipitation reactions*** result from aqueous reactions which create oversaturated mineral conditions and produce precipitates of minerals in order to balance geochemical equilibrium. Such reactions can occur as a result of chemical mixing between disparate waters, or via temperature or pressure changes that may occur during ASR operations. The result on ASR operations is the same; a reduction in well performance due to well screen or aquifer porosity plugging and/or water quality degradation via color or turbidity increases from the formation of colloidal or suspended solids.

- ***Ion Exchange reactions*** can occur when recharge waters interact with aquifer minerals facilitating a substitution of cations (or anions) based on their relative affinity for geochemical equilibrium in the aquifer mineral matrix. The most common ion exchange reactions in ASR operations are cationic exchanges between Na and Ca ions, and are especially problematic in the presence of smectite or montmorillonite clays; if high-sodium recharge waters displace native ground waters in a high-clay content matrix, swelling can occur and result in lower aquifer permeability.

- ***Redox reactions*** occur when significant differentials in oxidation states are present in the recharge water, native ground water, and aquifer minerals. Redox reactions can demerit water quality, cause decreases in aquifer permeability, release soluble contaminants, or mobilize otherwise stable elements present in aquifer minerals.

- ***Solubilization reactions*** can also leach undesirable elements from aquifer minerals and contaminate stored waters in the aquifer. Leaching processes can occur when recharge waters are significantly undersaturated and/or unbuffered with respect to various minerals. Common leaching processes that adversely affect stored water quality include Fe, Mn, As, or U; major cations such as Ca, Mg, or K, while susceptible to leaching, generally do not render waters non-potable.

- ***Biochemical reactions*** can be significant and especially detrimental to ASR operations. Microbial populations, whether indigenous within the aquifer or introduced via ASR operations can proliferate under certain environmental and nutritional conditions; this can result in mineral precipitation, taste and/or odor creation, corrosion of well screens and piping, and formation of slimes and biomass which can significantly plug well screens and near-well porosity.

It is common for many of these mechanisms to occur simultaneously in natural waters; however, the identification of reaction processes is useful in assessing and mitigating potential water quality issues that could adversely affect ASR operations.

Previous Studies

PWR performed a preliminary geochemical assessment of the City's proposed ASR program in 2016 based on water quality monitoring of TW-6A native ground water and the SCWA recharge water. The investigation included assessment of the geochemical stability of these waters individually, and in mixtures of 25:75, 50:50, and 75:25 ratios to assess the geochemical reactions that could potentially occur during aquifer storage. The assessment and modeling utilized the USGS PHREEQEC v 3.3 geochemical model and the BRGM THERMODEM thermodynamic database. The results of the investigation were documented in a September 2016 Technical Memorandum, which is included as **Appendix B** (not included in draft) to this TM. The principal findings of the geochemical modeling assessment included the following:

1. The SCWA recharge water was found to be geochemically stable; however the Well 6A native ground water was found to be oversaturated with $Fe(OH)_3$.

2. Because of the high Si content of the Well 6A NGW, the creation of siliceous scales was possible upon mixing with SCWA recharge waters if pH's dropped to less than 7.0 during aquifer storage.

3. The potential for precipitation reactions, including Calcite, Magnesite, and Dolomite were unlikely due to the low ionic content of both waters.

4. The precipitation of Fluorapatite ($Ca_5(PO_4)_3F$) was possible if sufficient phosphorous or fluoride was present in the aquifer matrix or SCWA recharge water.

5. Overall, the modeling predicted that the potential for significant adverse geochemical reactions during ASR operations were unlikely except as noted above, and the minor precipitation reactions noted were based on the attainment of full geochemical equilibrium.

The geochemical investigation did not assess the fate of Disinfection Byproducts (DBP's), as DBP equilibrium data are not included in the geochemical database. Similarly, microbially mediated reactions were not assessed in the geochemical modeling. These processes are necessarily assessed empirically during ASR operations.

ASR Pilot Test Program Results

The following discussion highlights the geochemical parameters principally affecting the ASR pilot program at TW-6A.

General. As noted previously, the pilot demonstration program was preceded by an extensive assessment of geochemical interactions between the recharge and native ground waters. The focus of the water quality investigation was directed to monitoring the Title 22 compliance of stored and recovered waters and geochemical issues affecting ASR well hydraulics and ASR operations. In order to track and differentiate between mixtures of recharge and native waters, the concentrations of conservative anionic compounds were evaluated, and sulfate ion ($SO_4^{=}$) was selected based on its geochemical stability and favorable differential concentrations between the two waters, averaging 3.8 mg/L in the NGW and 15.3 mg/L in the SCWA recharge water. By comparing measured laboratory values of $SO_4^{=}$ in stored and recovered waters the amount of mixing and dilution can be quantified, and more importantly can be used to calculate and quantify changes in water quality caused by geochemical reactions rather than by simple mixing or dilution effects.

Overall, the 2016 geochemical modeling predictions were borne out during the ASR pilot test program, with the 2016 model results generally overstating the actual chemical behavior observed. This general trend is unremarkable and expected, as the model simulations calculate full equilibrium conditions and do not account for incremental levels of aqueous geochemistry driving forces (i.e., Chemical Thermodynamics, Gibbs Free Energy, etc.,). Thus, the model generally predicts a "worst case" of chemical reactivity.

The empirical results of the TW-6A ASR pilot test program generally indicated the following:

1. The generally low levels of active well plugging during ASR operations, and the full restoration of well performance after well backflushing, support the lack of well and/or aquifer porosity plugging.

2. The above evidence of low/no well plugging is especially convincing in the case of TW-6A due to the extant low transmissivity of the subject aquifer system; plugging mechanisms are especially amplified in low-permeability aquifer systems, and if present would be highly evident in well performance reduction.

3. The relative similarities between the two waters (one of which being in chemical equilibrium with the aquifer mineral matrix) generally suggests a low driving force for significant geochemical reactivity.

4. The evaluation of changes in water quality constituents during ASR pilot testing were found to be predominantly the result of simple dilution/mixing mechanisms, further supporting the lack of significant geochemical interaction. (Noteworthy deviations from this generalization are discussed in detail below).

An important consideration of the ASR pilot test is that this program was necessarily brief due to schedule and budget constraints; the three ASR cycles ranged in duration from 1 to 10 weeks of aquifer storage, which limit the assessment of long term (years) and kinetically slower geochemical interactions. These processes will require monitoring in longer-term testing and/or permanent ASR programs, and are discussed in the individual water quality parameter sections below.

Observed Geochemical Interactions. For the discussion of geochemical interactions during aquifer storage, it is useful to define several quantities to provide a distinction between actual and theoretical values of compounds. The differential between measured concentrations and the theoretical cases of no mixing and no reaction provide a means to identify the likely reaction mechanism occurring and/or the geochemical process(es) taking place in the subsurface environment.

The following terms utilized in this discussion are explained below:

- **Initial Concentration (IC).** This is the laboratory measured concentration of the compound at the time of injection into the ASR well. It is typically calculated as the average of all periodic measurements during the recharge phase of a given ASR cycle.

- **Measured Concentration (MC).** This is the laboratory measured concentration of a compound, and includes the effects of Recharge/NGW intermixing, aquifer storage time, and geochemical reaction processes. Although it is a realistic representation of compound concentration for the specific program conditions under which the sample was collected, it does not always accurately represent the true concentration throughout the aquifer.

- **Dilution-Corrected Concentration (DCC).** This value is calculated from the Initial Concentration and the fractional intermixing value calculated from the evaluation of a stable tracer compound (in this case SO_4). The DCC represents the theoretical value of concentration if the compound were stable and non-reactive, and only dilution processes were affecting the original concentration at the time of recharge. This value is important as a base comparator of MC and Normalized values in the assessment of stability, ingrowth, or degradation of DBP compounds, or in ion exchange reactions.

- **Normalized Concentration (NC).** This value is calculated by correcting the MC for dilution effects caused by aquifer intermixing or differentials between the productivity of individual zones within the aquifer. This value is important in that it is representative of the potential maximum concentration of a compound at the specific sampling conditions. It also allows the quantitative assessment of DBP ingrowth and decay over time, as it corrects the laboratory derived results for dilution/intermixing effects.

In addition to the definition of terms used to characterize the results of the water quality analyses, the following interactions which were observed during the pilot program are considered important as they relate to the preservation of Title 22 water quality and to ongoing ASR operations.

Ion Exchange (IX). The occurrence of minor cation exchange reactivity was apparent in the first and second ASR cycles. Concentrations of Calcium (Ca^{2+}), Magnesium (Mg^{2+}) and Sodium (Na^{+}) were observed to change in inverse relation in the stored and recovered waters when corrected for mixing/dilution effects, with Ca (predominantly) and Mg present at higher levels, and Na present at lower levels than accounted for by simple mixing. The differential between actual and predicted Ca/Mg/Na levels based on SO_4 data indicate that the recharge water likely displaced Ca ions on aquifer clays, releasing Ca^{2+} into solution in exchange for Na^{+} ions attaching to vacant sites on the clay molecules. The process is:

$$\textit{Ca-clay} + 2\,Na^{+}\ \textit{(in SCWA recharge water)} \rightarrow 2\ \textit{Na-clay} + Ca^{2+}$$

The increase in Ca and decrease in Na was observed at low levels in ASR Cycles 1 and 2 but only minimally in Cycle 3, suggesting that the clay content of the aquifer minerals is small and therefore the continuation of such reactions will also be limited in magnitude and duration. Confirmation and quantification of IX magnitude by comparison with results at the Proximate CW-6 well could not be made due to the absence of monitoring data. While IX mechanisms can result in swelling of clays and reduction in aquifer transmissivity, the lack of observed well performance decline and of low clay content in the aquifer matrix support the conclusion that these reactions did not measurably affect ASR operations, and at these low levels of reactivity such reactions will not affect recovered water potability. It is also important to note that although the trend of higher Ca and Mg with lower Na levels were observed, the calculation of stoichiometric ratios for the reactions did not precisely match an ion-exchange-only differential; we therefore conclude that some level of Ca/Mg dissolution is also likely occurring (discussed below).

Solubilization/Leaching Reactions*.* The occurrence of mineral dissolution was observed to a very minor extent during pilot test operations, however the minerals affected and change in stored/recovered water quality were relatively minor. The effects were observed in all ASR cycles, which suggest that solubilization occurred relatively quickly, but to a minor extent. **Table 11** below highlights the few compounds which showed mineral dissolution when saturated with SCWA recharge water.

Table 11. Mineral Solubilization Examples

Item	ASR Cycle	Cycle Phase	SCWA Conc. (ug/L)	NGW Conc. (ug/L)	Measured Conc. (ug/L)	Dilution Corrected Conc. (ug/L)	Notes
Zn	3	Storage	3.4	40	**33**	**4.5**	Significant leaching
Zn	2	Storage	3.9	40	**61**	**5.0**	Significant leaching
As	3	Storage	ND	7.6	**1.6**	**0.23**	leaching
As	2	Storage	ND	7.6	**4.9**	**0.23**	leaching
Ca (in mg/L)	3	Storage	23	10	**14**	**21.5**	Leaching and/or IX

Although the above compounds showed measurable leaching during aquifer storage, the amount of solubilization decreased over time and with increased NGW intermixing; the level of dissolution typically returned to nil as ASR recovery progressed and NGW conditions were restored.

Biochemical Reactions. No direct microbial analyses or bioassays were performed during the pilot testing program, however examination of other laboratory data through the ASR cycling operations provides some qualitative information on these processes. The decline in dissolved O_2 and ORP through aquifer storage indicates the presence of chemical and/or biochemical oxygen demand processes, albeit at relatively low levels. The lack of dissolved sulfides (H_2S) before and after ASR cycling, along with the continued presence of O_2 at the end of the pilot test program indicates a lack of anoxic and anaerobic activity. Review of the presence of available bionutrients in both the SCWA recharge water and the NGW also suggest that the likelihood of significant bioactivity is low. The lack of iron (Fe) in the recharge and NGW suggests that the occurrence of Iron Related Bacteria (IRB's) is also unlikely.

These data, in addition to the lack of well plugging observed during the pilot program, suggest that biochemical reactions and biometabolism processes are insignificant at this time.

Disinfection Byproducts (A Redox Reaction). The occurrence and fate of Disinfection Byproducts (DBP's) has been the subject of concern for ASR programs. Both Trihalomethanes (TTHMs) and Haloacetic acids (HAAs) occur as a result of free chlorine reacting with organic materials present in the recharge water; these compounds are regulated within Title 22 standards due to their known carcinogenic potential in humans. For ASR operations, it is generally desirable to maintain a free chlorine residual in recharge waters to both maintain potability and to mitigate biofouling in the well screens and near-borehole aquifer zone. Unfortunately, the presence of free chlorine residual in recharge waters also supports the continued creation of DBP's due to the presence of even minor amounts of organic compounds in the recharge water, the NGW, and even in the aquifer geologic matrix. This continued DBP creation is referred to as "ingrowth" and can continue during aquifer storage operations until the supply of free chlorine or organic material is exhausted.

DBP reactivity typically includes both ingrowth and decay processes; however, they can vary substantially based on the specific DBP compound, the character of the recharge and NGW waters, the aquifer mineralogy and environmental conditions, and other factors.

For the TW-6A ASR pilot test program we focused our evaluation of DBP occurrence on the ASR 3 cycle, as the ASR-1 and -2 cycles were of insufficient duration to effectively assess DBP processes. **Figure 16** graphically presents the DBP data for ASR Cycle 3 for both THM and HAA compounds. The data and trends in DBP behavior exhibited in the pilot test program are considered fairly typical for ASR programs in slightly anoxic aquifer conditions. Both THM and HAA compounds showed characteristic ingrowth patterns resulting from the consumption of free chlorine residual in the SCWA recharge water. Although the measured concentrations of all DBP's fell well below Title 22 limits, the Normalized values show that true ingrowth peaks reached up to 200% of the initial recharge water concentrations.

THM behavior during ASR Cycle 3 showed the following trends:

- THM ingrowth commenced immediately, with Normalized THM levels peaking at slightly over 200% of initial SCWA recharge water levels.
- Normalized THM values peaked after approximately 6-7 weeks of storage, followed by a slow decay.

- Migration of the recharge water and its DBP content was observed at the City's proximate CW-6 production well; at 20 days of aquifer storage the CW-6 sample showed an 80% influence of SCWA recharge water and a Normalized THM concentration of 27.5 ug/L, while concurrent sampling at the ASR test well showed a normalized value of 36 ug/L. This attenuation could be the result of aquifer matrix absorption or other geochemical reactions.
- The onset of THM decay corresponds with a decline in redox conditions; ORP values declined to approximately +0 mV as THM degradation commenced. This correlation between declining redox potential and THM degradation is consistent with the majority of other ASR operations observed by PWR.
- The observed pattern of THM ingrowth followed by decay is consistent with most ASR operations observed by PWR.
- The complete decay of THM's was not reached by the end of the 10-week aquifer storage period; however, complete degradation typically requires 3-5 months of aquifer storage based on observations from other ASR sites.

HAA behavior followed a similar trend of ingrowth and decay; however, the cycle was more rapid than with THMs. This accelerated behavior is typical of HAA reactivity in our experience. Specific HAA trends apparent in **Figure 16** include the following:

- HAA ingrowth commenced immediately, with Normalized HAA levels peaking at approximately 200% of the original SCWA recharge water HAA concentration.
- Normalized HAA values peaked after approximately 2 weeks of storage, followed by a slow decay. Complete HAA degradation did not occur during the 10-week aquifer storage period. This slower decay rate is atypical of HAA degradation at other ASR sites; however, there is insufficient data to identify the cause(s) of this slower behavior.
- Although Normalized HHA's did not completely degrade during aquifer storage, measurements at the conclusion of the recovery portion of ASR-3 Cycle 3 showed no measurable HAAs (in MC; NC values could not be calculated due to the absence of $SO_4^{=}$ data for that sample event). Unfortunately, no intermediate samples were collected during the recovery phase, so no conclusions can be made regarding the nature of final HAA declines.

Overall, the behavior of DBP's was generally consistent with other ASR programs utilizing slightly anoxic aquifer systems. It should be noted that DBP degradation may be associated with subsurface microbial activity, which may not be fully developed at the TW-6A site. DBP fate should be carefully monitored in subsequent long-term ASR testing or permanent ASR programs, concurrent with redox conditions and bioassay monitoring.

CONCLUSIONS

Based on our evaluation of the data and findings developed from TW-6A ASR Pilot Test program, we conclude the following:

WELL AND AQUIFER HYDRAULICS

- Based on our preliminary analysis of the various factors affecting theoretical injection capacity performed by PWR in February 2018, it was estimated that TW-6A has a long-term injection capacity ranging between approximately 55 to 100 gpm. The ASR pilot test injection testing program results successfully demonstrated that 70 gpm is a sustainable injection rate at TW-6A while maintaining water levels below ground surface. On a seasonal storage basis, this is equivalent to injecting approximately 55 acre-feet of surplus water over a 6-month injection season.
- Observed active plugging rates were very low, averaging approximately 0.2 ft/d (normalized rate of 0.8 ft/d). The low plugging rates are due largely to the low particulate content (as measured by Silt Density Index) of the SCWA source water.
- No residual plugging of TW-6A was observed, indicating that the triple-backflush routine was effective at maintaining overall well performance; indeed, the overall improvement in well performance (as measured by 10-minute specific capacity) observed over the course of the injection testing program suggests that the multiple flow reversals associated with ASR cycles of recharge and pumping had an ancillary benefit of providing additional well development and improved well efficiency.
- The observed responses of the aquifer system to injection at various rates and durations at TW-6A were generally consistent with the expected responses, and maintained below ground surface at all times, indicating that the aquifer system is capable of receiving recharge at TW-6A without unexpected or undesirable results.

WATER QUALITY

- The pilot demonstration program results were in general agreement with the geochemical modeling study performed by PWR in September 2016. The model results were conservative in their estimation of minimal scaling and adverse geochemical interaction between the SCWA recharge water and native ground waters; this conservatism is expected due to modeling predictions based on full equilibrium conditions being achieved.
- The use of SCWA produced waters appears to be highly suitable for ASR operations utilizing the City's underlying aquifers.
- The program results verified that stored waters maintained full Title 22 compliance at the conclusion of all three ASR Cycles, both in the recovered waters and remaining waters stored in the aquifer.

- Water-quality changes during aquifer storage were observed, including Ion Exchange, Redox, and Dissolution reactions; however, these reactions were minor and did not affect well hydraulics or recovered water potability.
- Significant Biochemical activity was not observed during pilot testing, likely due to the relative absence of bionutrients in the SCWA recharge water and the NGW.
- DBP increases (ingrowth) were observed with both THM and HAA compounds of approximately 200%; however, both were observed to decay (although not completely) during aquifer storage.
- Overall, the test program results did not identify any fatal flaws or critical issues with respect to water quality that would jeopardize the feasibility of long-term ASR program implementation.

RECOMMENDATIONS

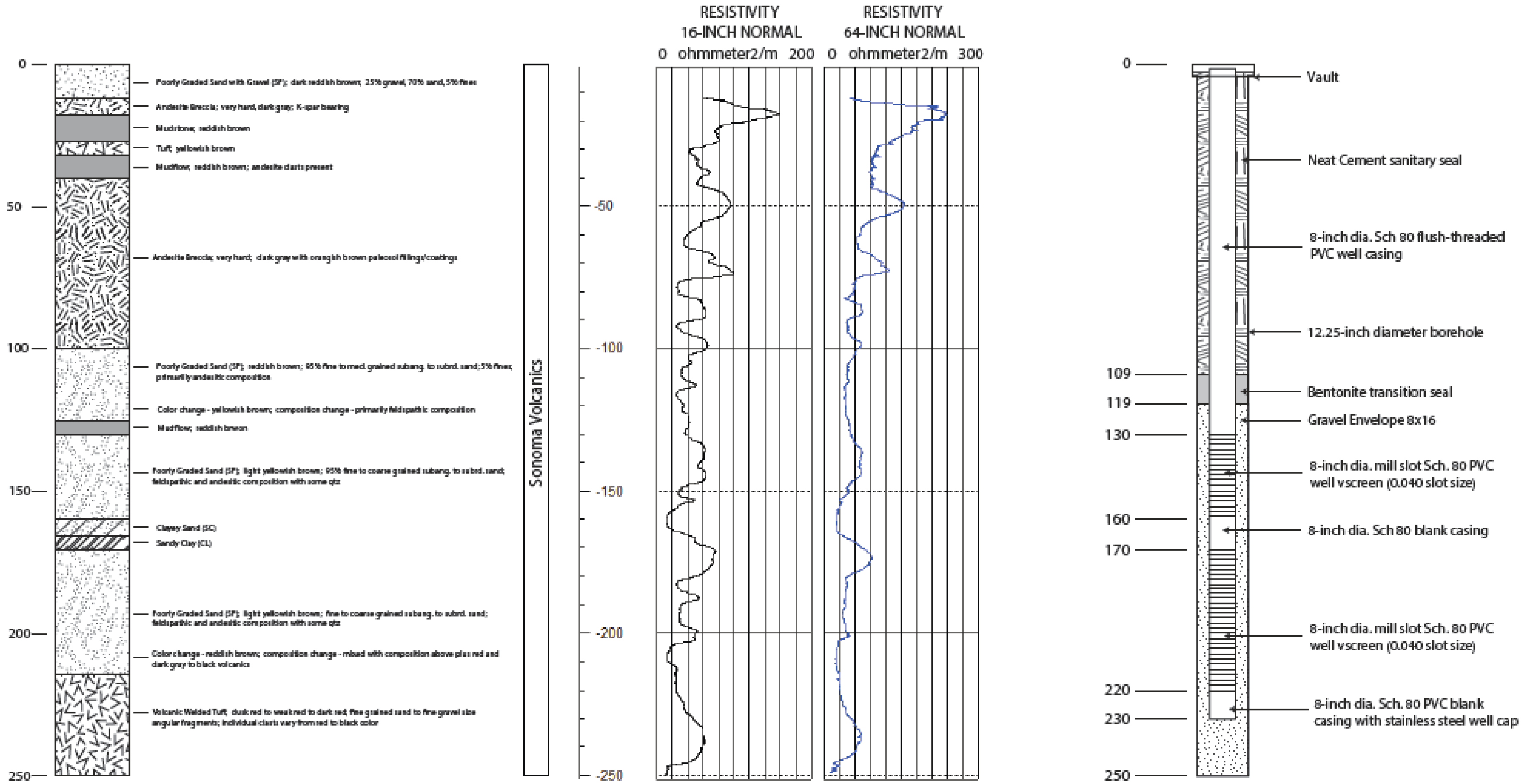
Based on the findings and conclusions developed from the TW-6A ASR Pilot Test program, and our experience with similar ASR projects, we offer the following recommendations:

- For planning purposes, a long-term operational recharge capacity of approximately 70 gpm is recommended.
- During recharge periods, routine backflushing should be performed on an approximate bi-weekly basis to limit residual plugging and maintain long-term well performance. The backflushing procedure should consist of the same triple-backflush procedure developed for and implemented during the pilot test program.
- The use of SCWA produced waters as a source for aquifer recharge and seasonal or long-term storage should be continued based on geochemical model results and empirical pilot demonstration testing.
- Continuation of ASR operations should include additional monitoring for geochemical interaction during aquifer storage and ASR recovery, with particular focus on long-term water-quality interactions such as solubilization/leaching, DBP fate, subsurface microbial activity and biometabolism, and ion exchange processes. Additional monitoring at proximate and similarly perforated wells should be included to better ascertain geochemical interactions during aquifer migration.

CLOSURE

This technical memorandum has been prepared exclusively for GEI Consultants, Inc. for the specific application to the Sonoma County Water Agency and City of Sonoma TW-6A ASR Pilot Test Project. The findings, conclusions, and recommendations presented herein were prepared in accordance with generally accepted hydrogeologic and civil engineering practices. No other warranty, express or implied, is made.

-- o --



SOURCE: GEI CONSULTANTS, INC (2016)

PUEBLO water resources

FIGURE 1. GRAPHIC LOGS AND AS-BUILT COMPLETION
Sonoma TW-6A ASR Pilot Test Project
GEI Consultants, Inc. / Sonoma County Water Agency

March 2019
Project No. 09-0092

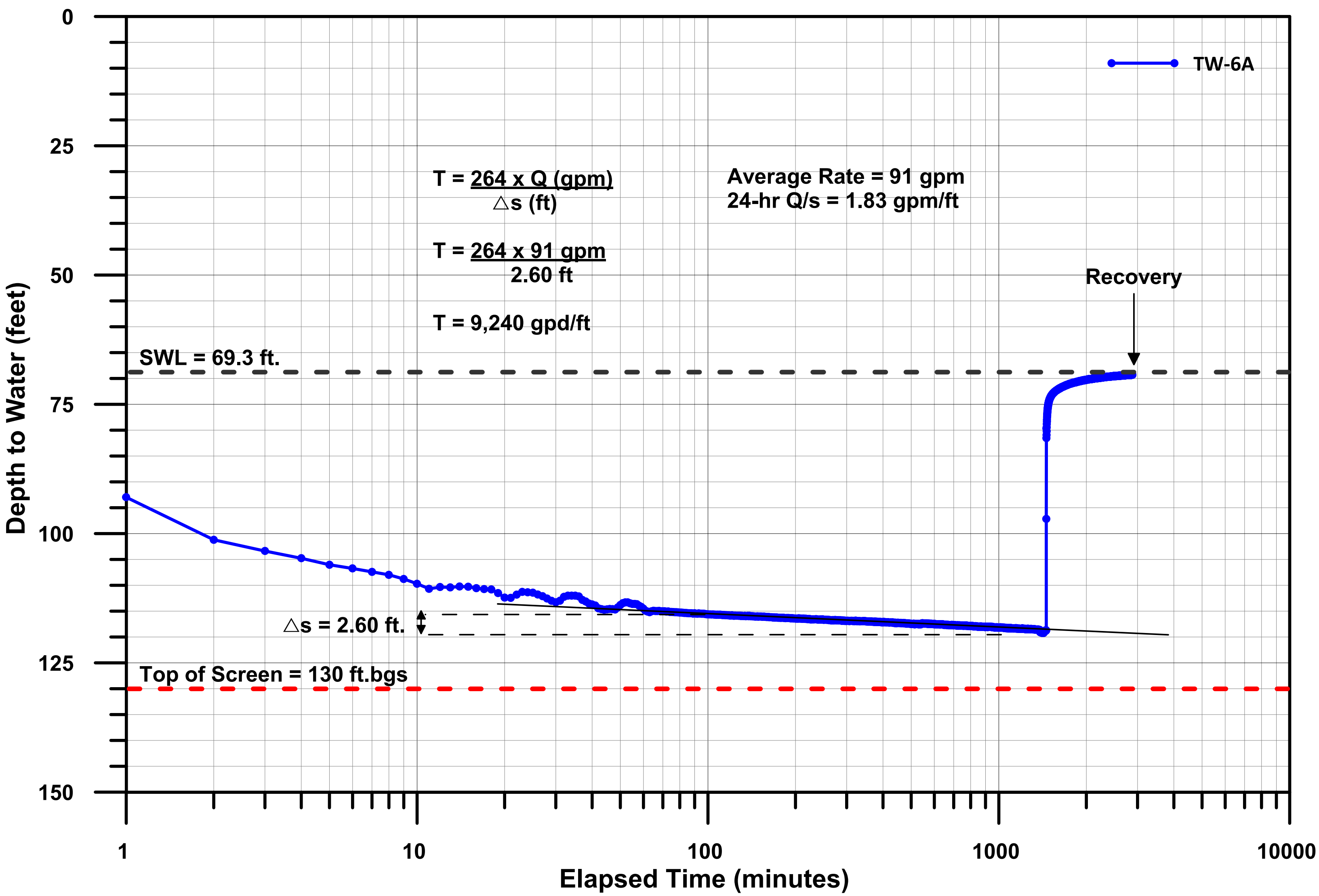
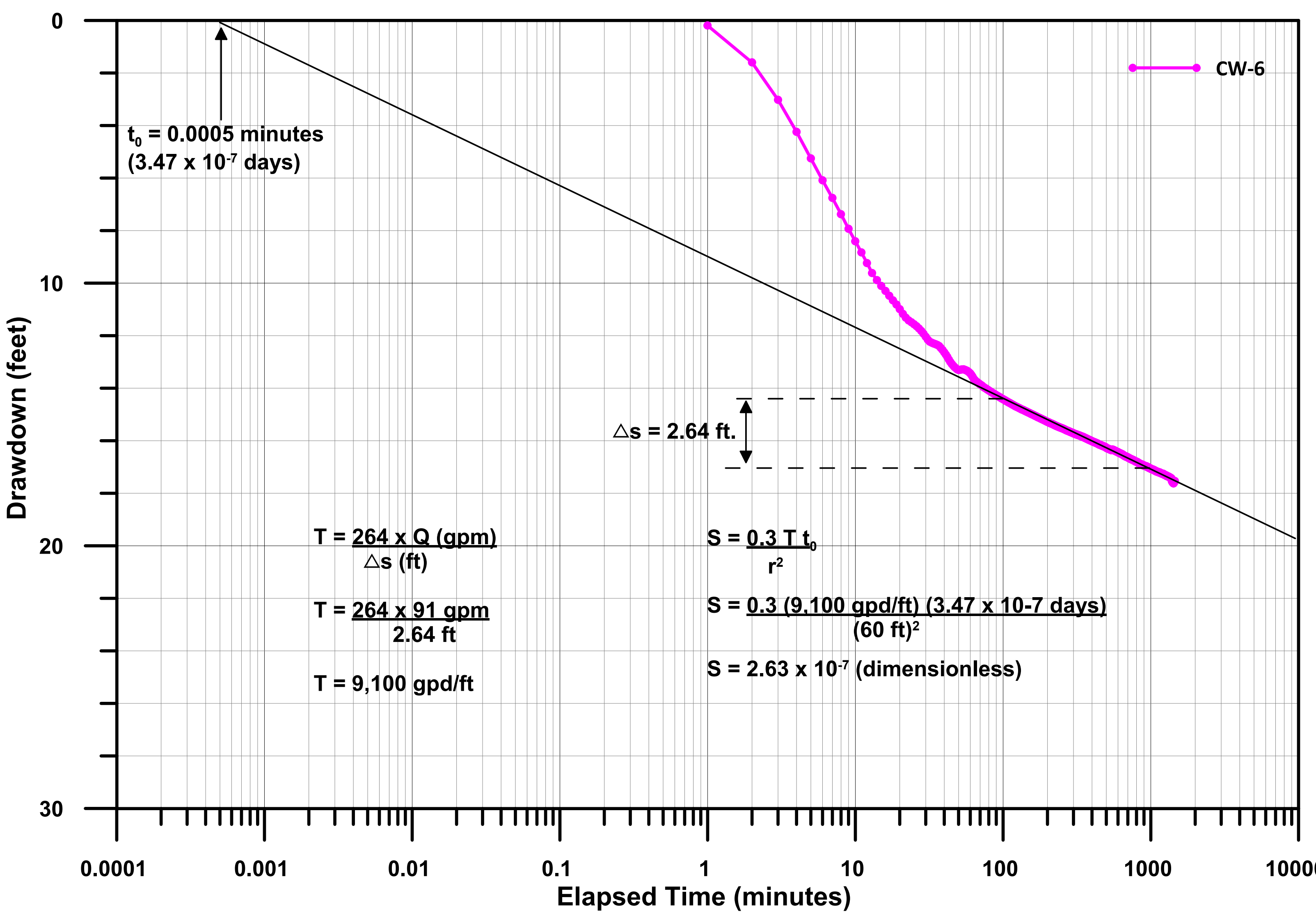


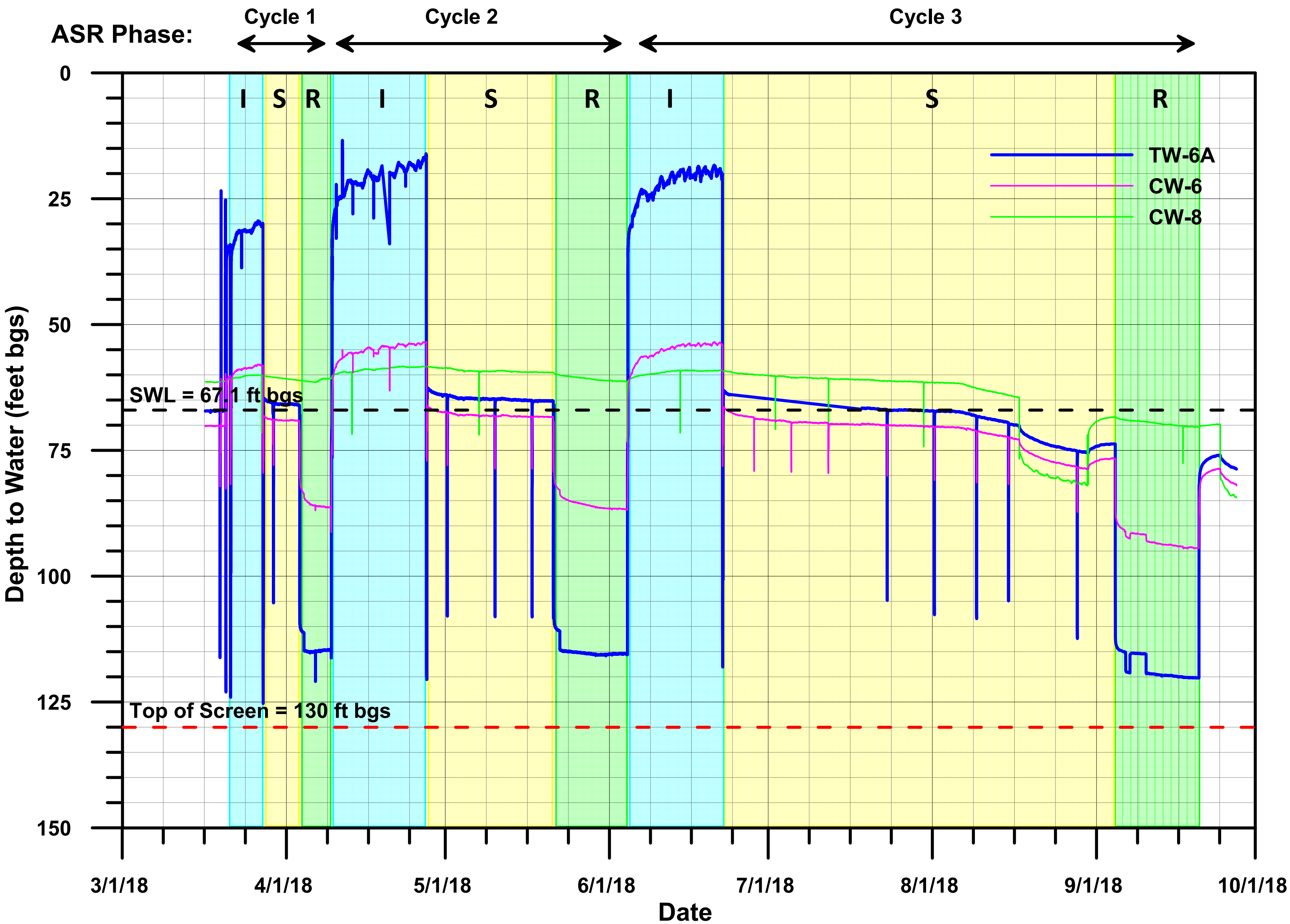
FIGURE 2. PRE-INJECTION 24-HOUR CONSTANT RATE PRODUCTION TEST (TW-6A)
Sonoma TW-6A ASR Pilot Test Project
GEI Consultants, Inc. / Sonoma County Water Agency



PUEBLO
water resources

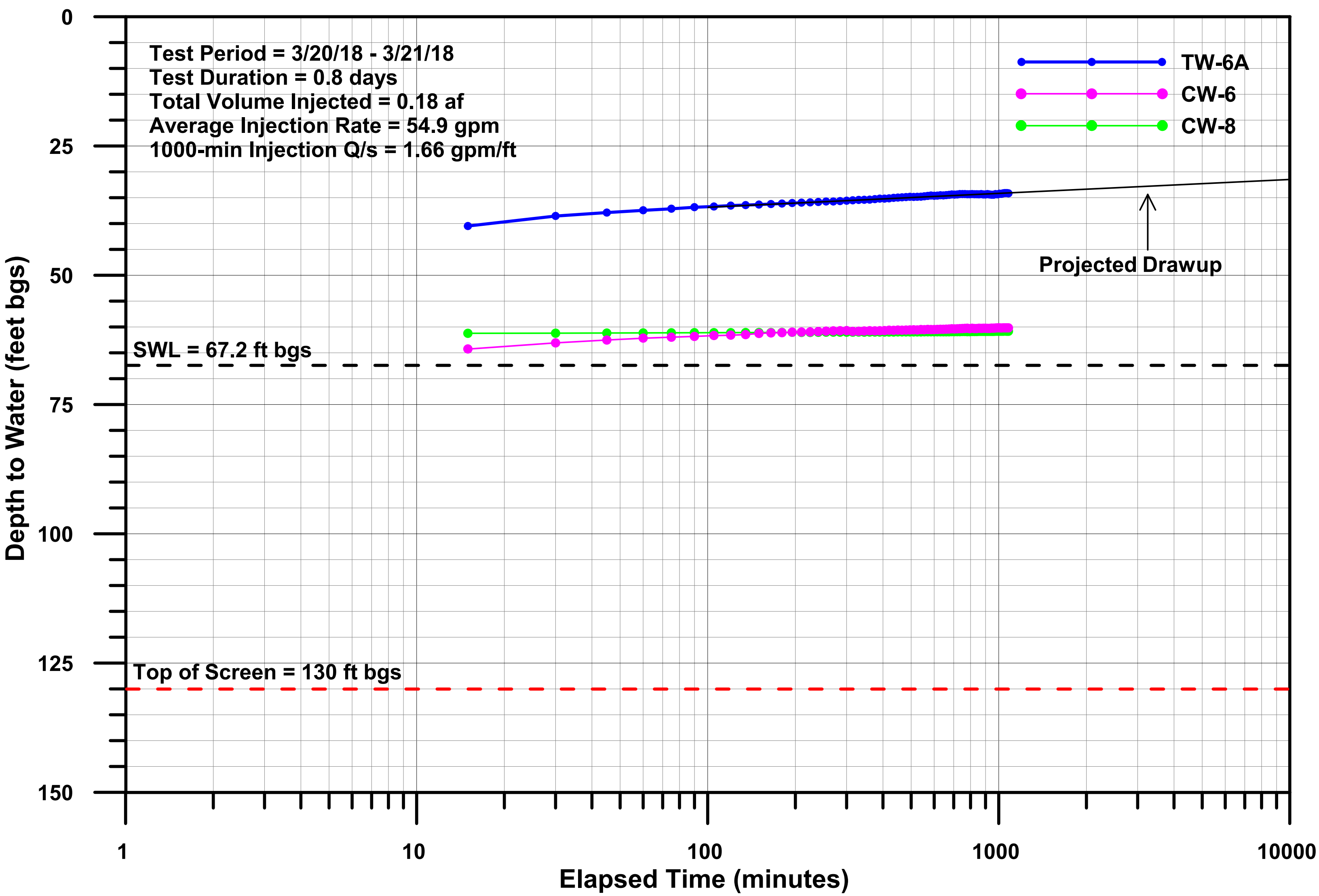
FIGURE 3. 24-HOUR CONSTANT RATE PRODUCTION TEST (CW-6)
Sonoma TW-6A ASR Pilot Test Project
GEI Consultants, Inc. / Sonoma County Water Agency

March 2019
Project No. 09-0092



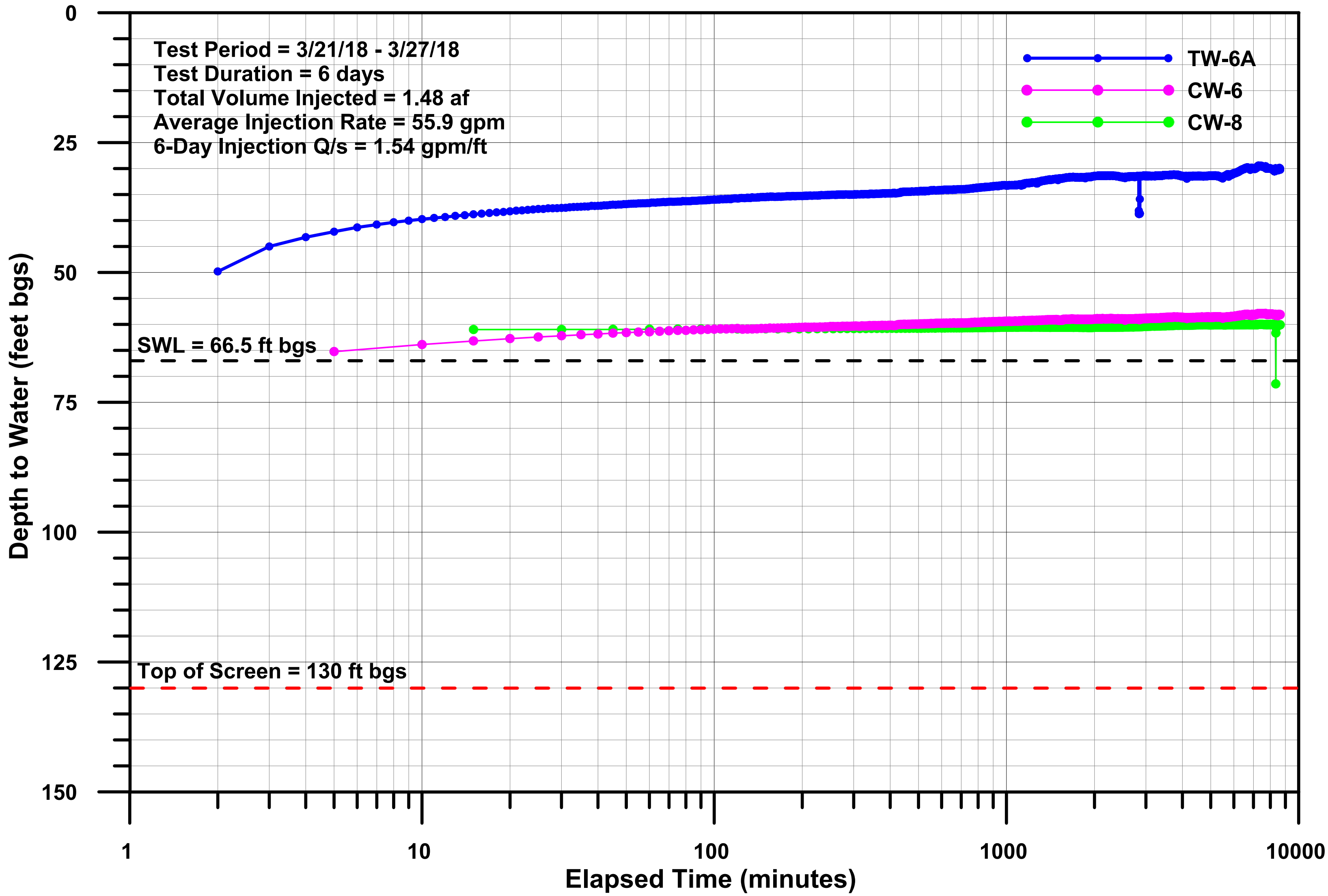
PUEBLO water resources

FIGURE 4. WATER-LEVEL DATA
Sonoma TW-6A ASR Pilot Test Project
GEI Consultants, Inc. / Sonoma County Water Agency



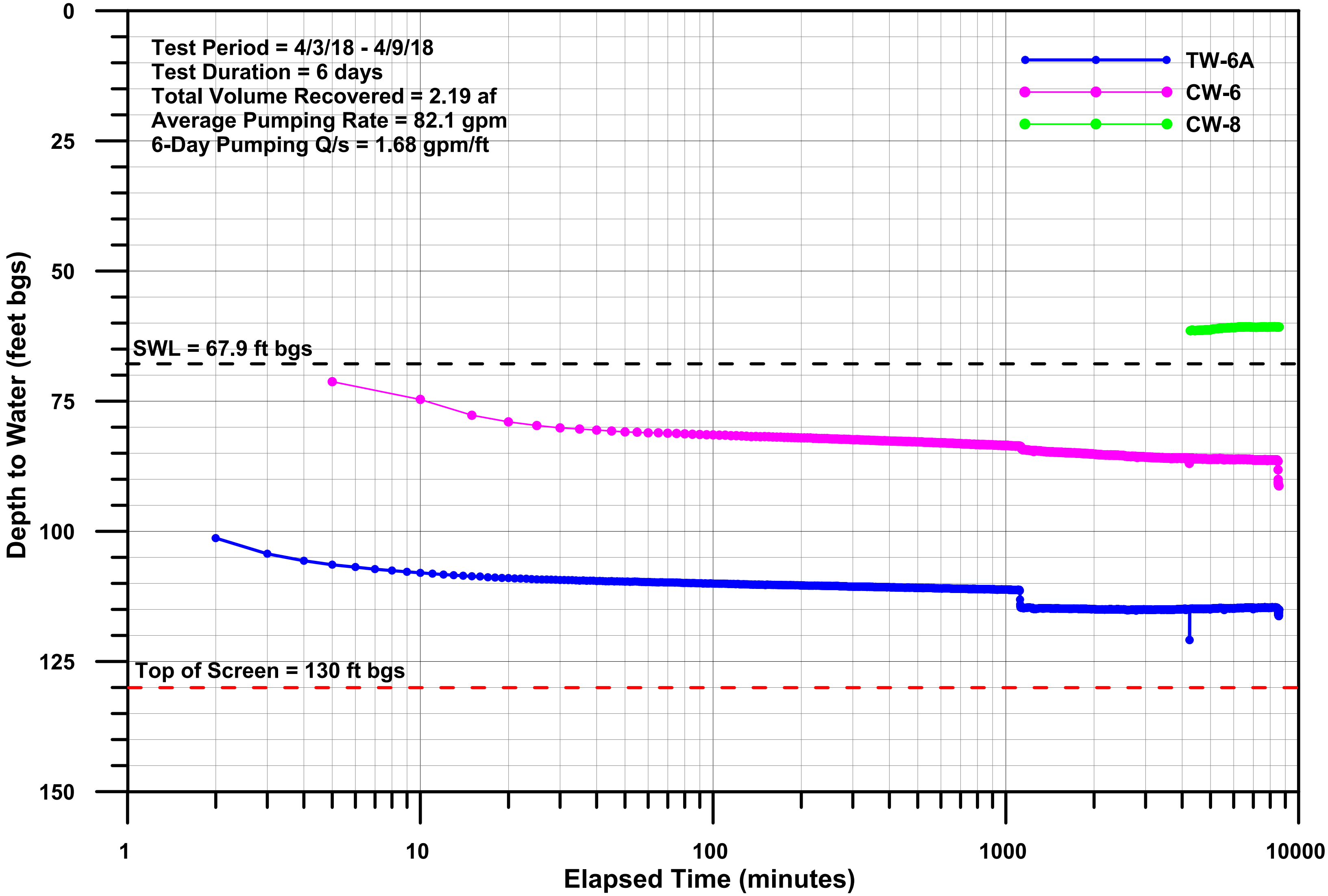
PUEBLO water resources

FIGURE 5. 1000-MINUTE INJECTION TEST
Sonoma TW-6A ASR Pilot Test Project
GEI Consultants, Inc. / Sonoma County Water Agency



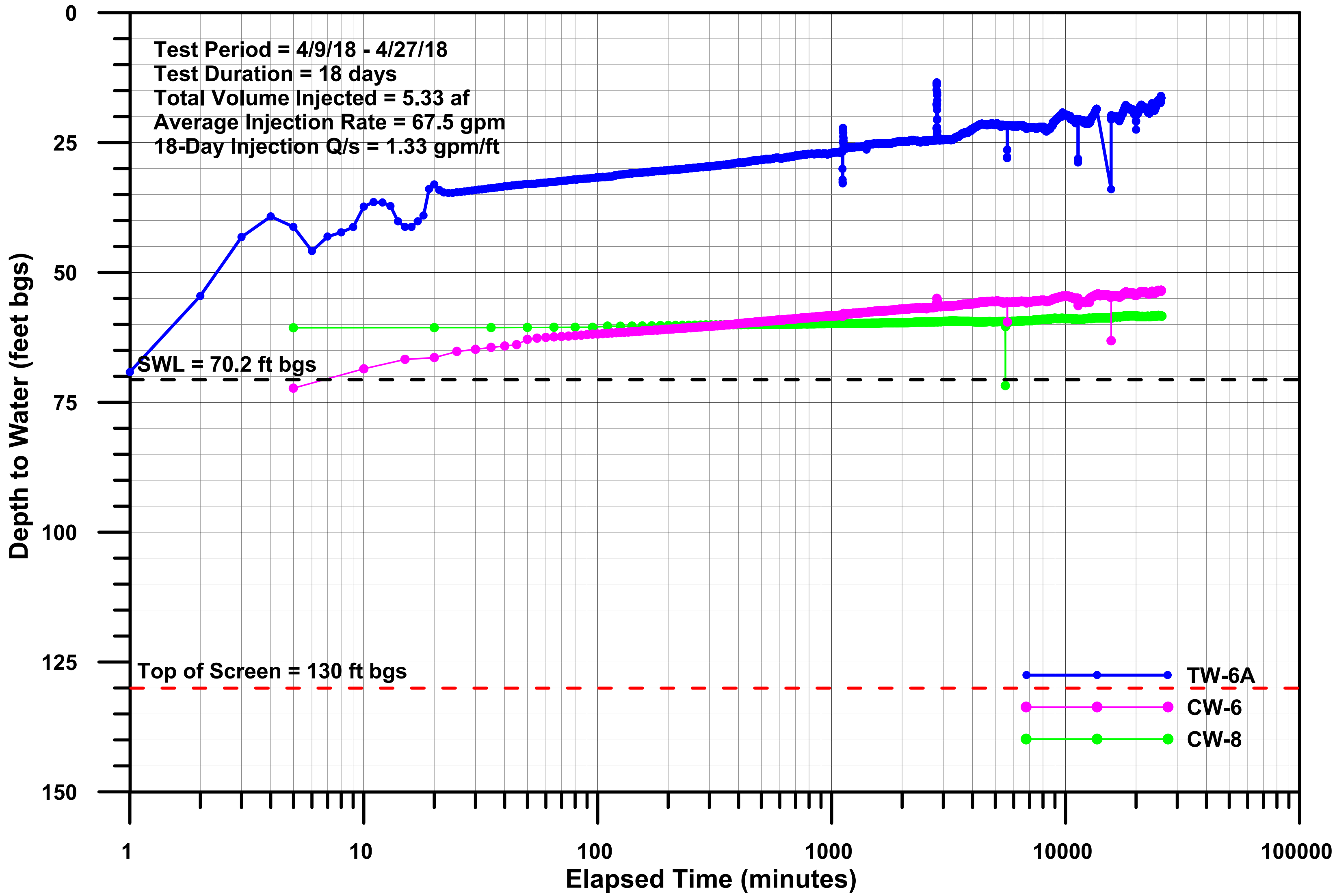
PUEBLO water resources

FIGURE 6. ASR CYCLE 1 - INJECTION
Sonoma TW-6A ASR Pilot Test Project
GEI Consultants, Inc. / Sonoma County Water Agency



PUEBLO water resources

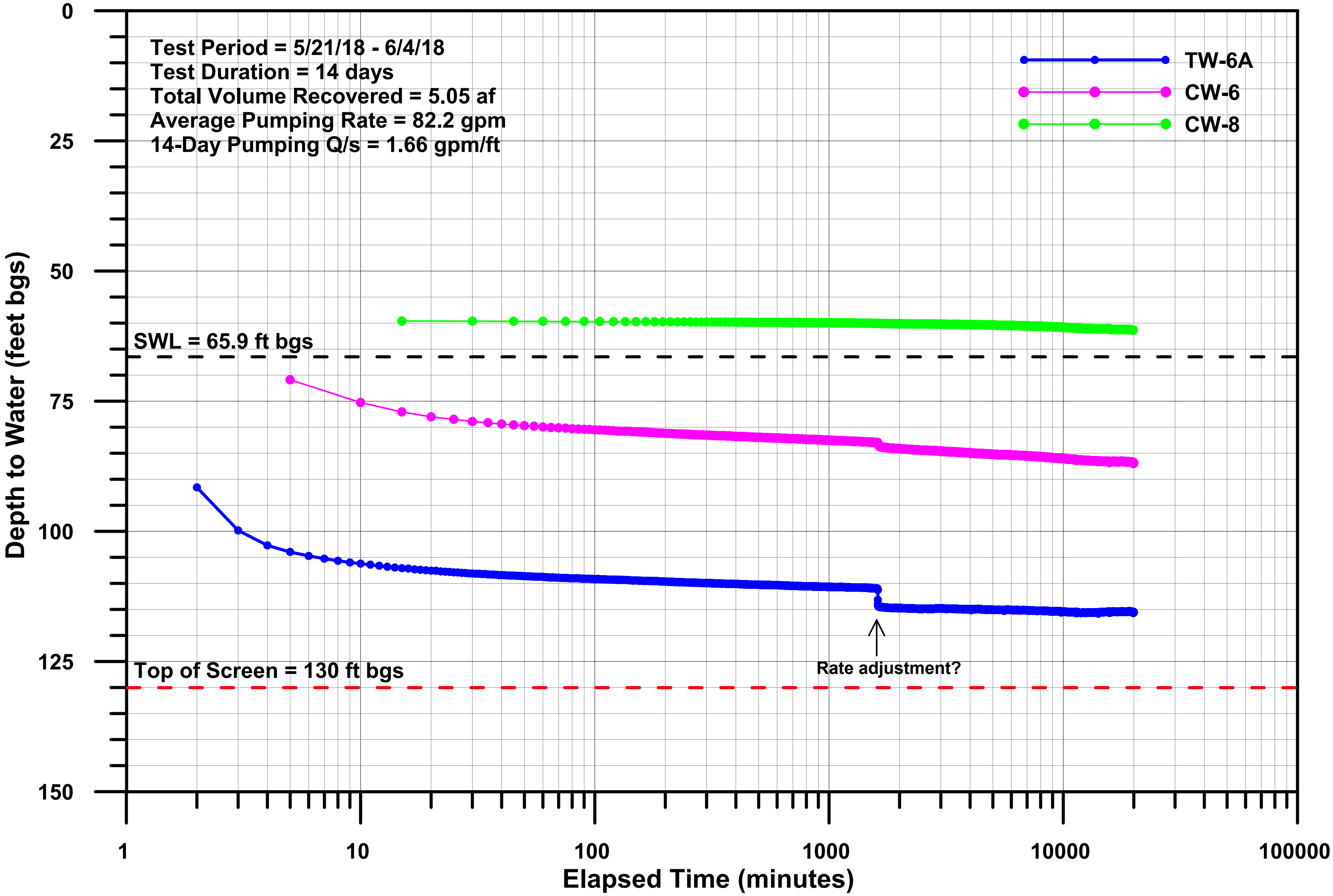
FIGURE 7. ASR CYCLE 1 - RECOVERY
Sonoma TW-6A ASR Pilot Test Project
GEI Consultants, Inc. / Sonoma County Water Agency



PUEBLO water resources

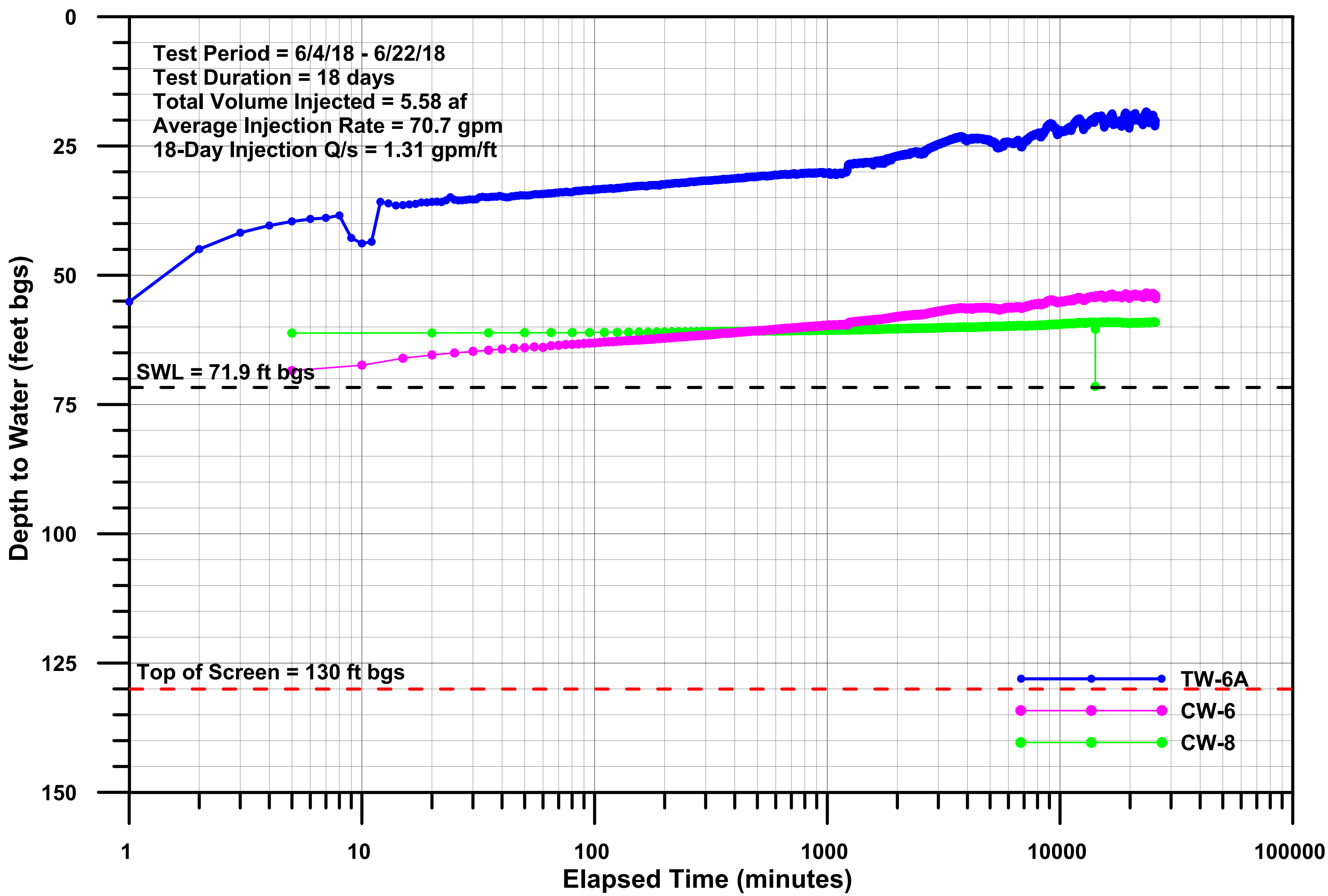
FIGURE 8. ASR CYCLE 2 - INJECTION
Sonoma TW-6A ASR Pilot Test Project
GEI Consultants, Inc. / Sonoma County Water Agency

March 2019
Project No. 09-0092



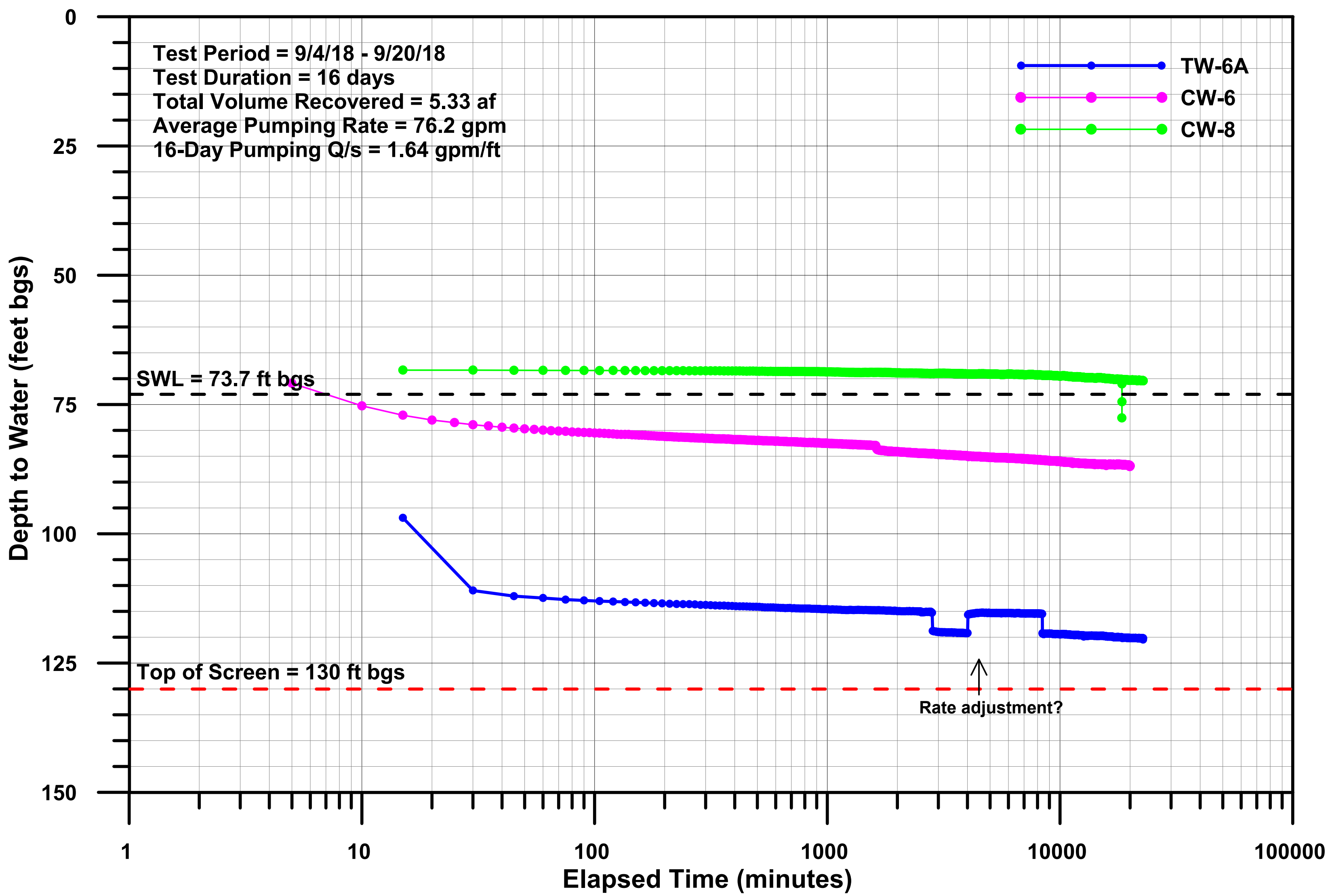
PUEBLO water resources

FIGURE 9. ASR CYCLE 2 - RECOVERY
Sonoma TW-6A ASR Pilot Test Project
GEI Consultants, Inc. / Sonoma County Water Agency



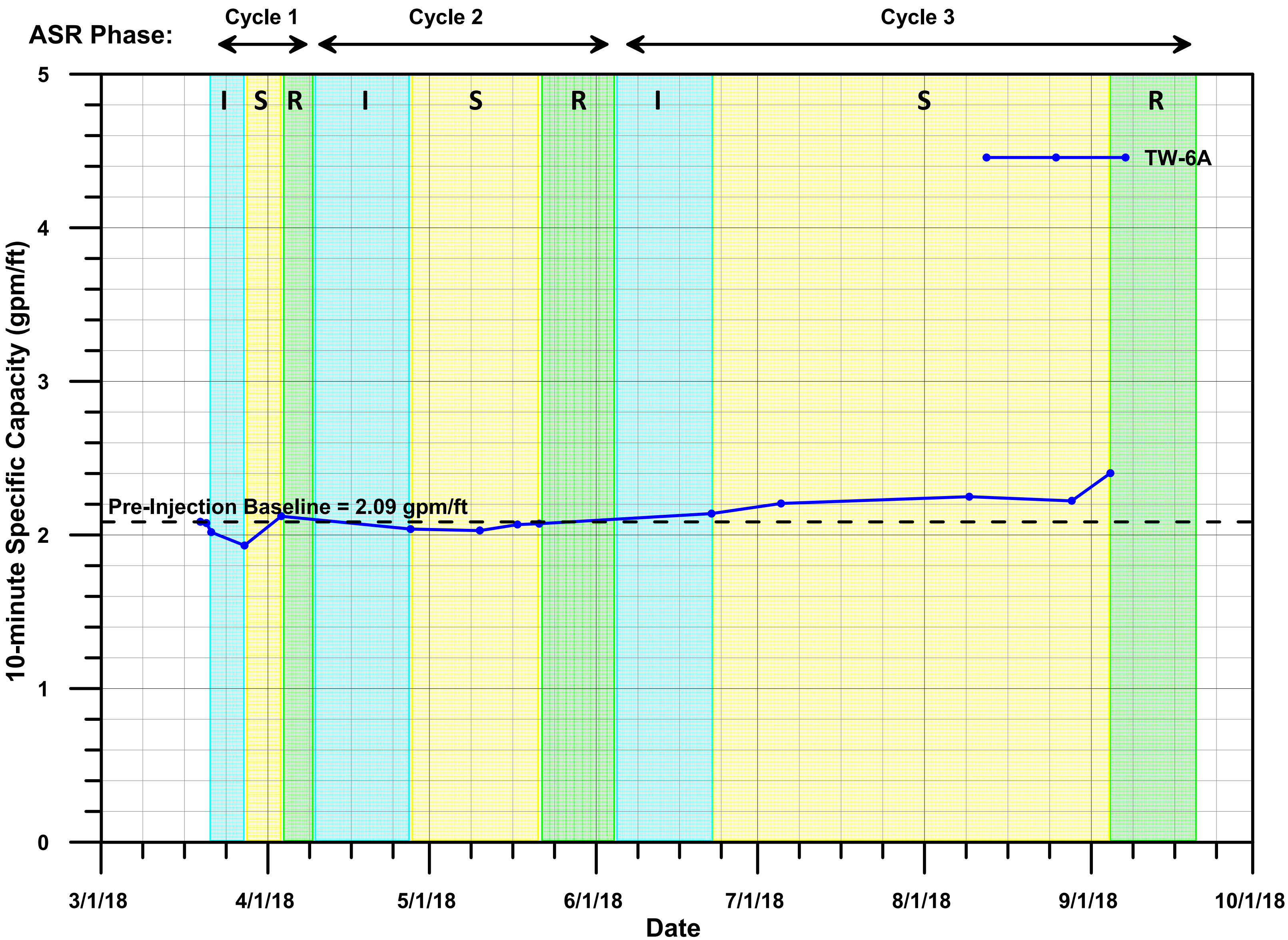
PUEBLO water resources

FIGURE 10. ASR CYCLE 3 - INJECTION
Sonoma TW-6A ASR Pilot Test Project
GEI Consultants, Inc. / Sonoma County Water Agency



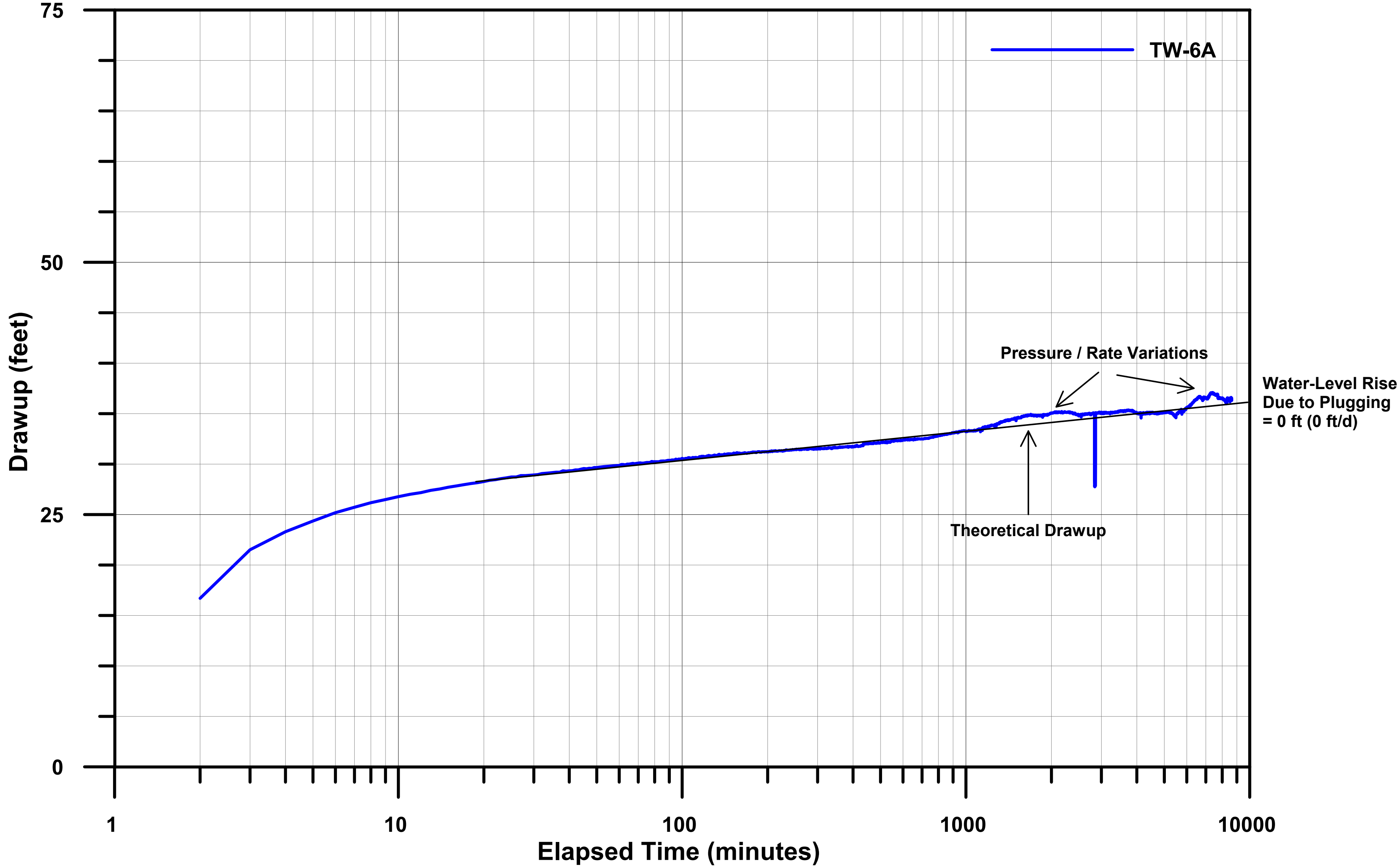
PUEBLO water resources

FIGURE 11. ASR CYCLE 3 - RECOVERY
Sonoma TW-6A ASR Pilot Test Project
GEI Consultants, Inc. / Sonoma County Water Agency



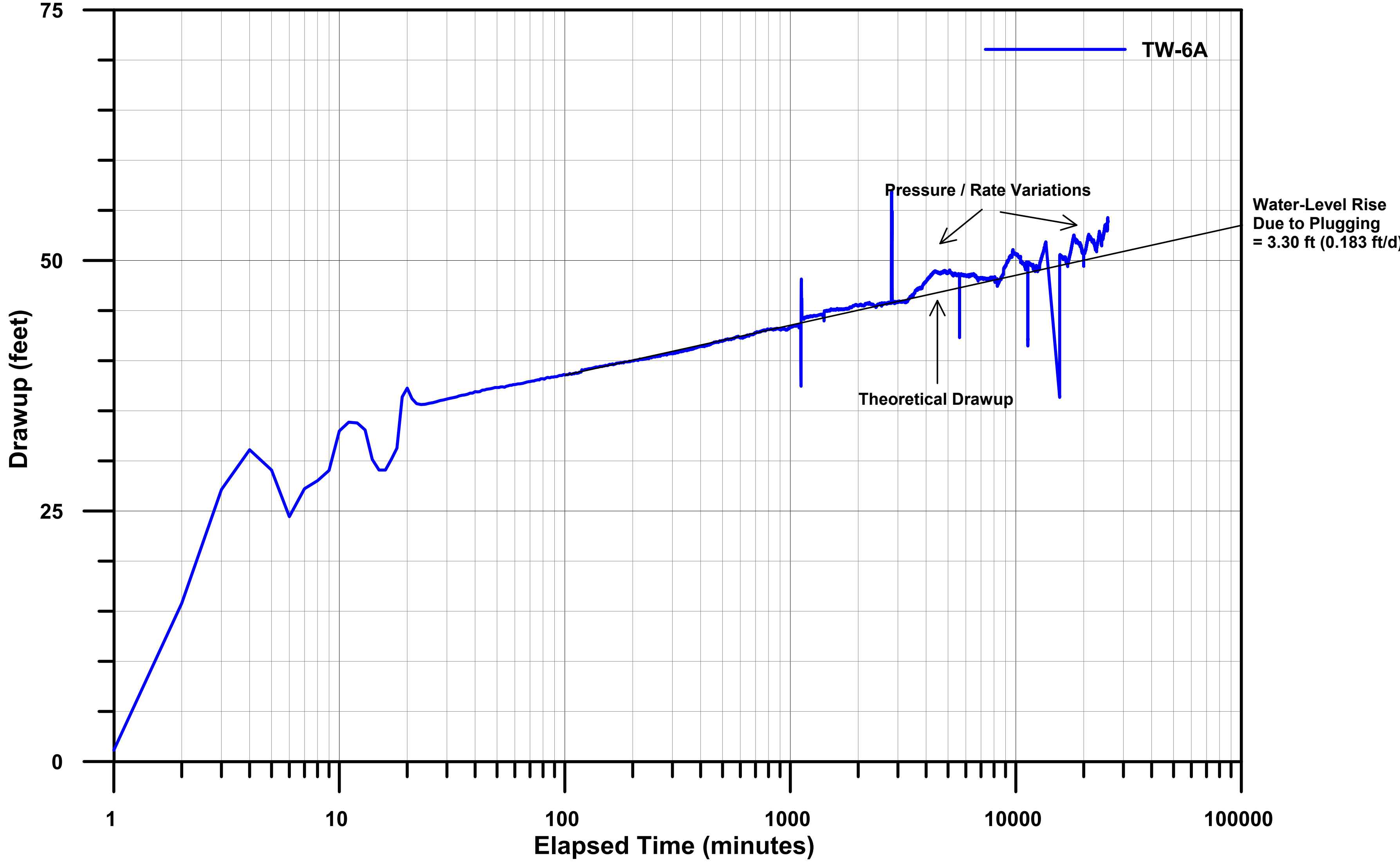
PUEBLO water resources

FIGURE 12. 10-MINUTE SPECIFIC CAPACITY DATA
Sonoma TW-6A ASR Pilot Test Project
GEI Consultants, Inc. / Sonoma County Water Agency



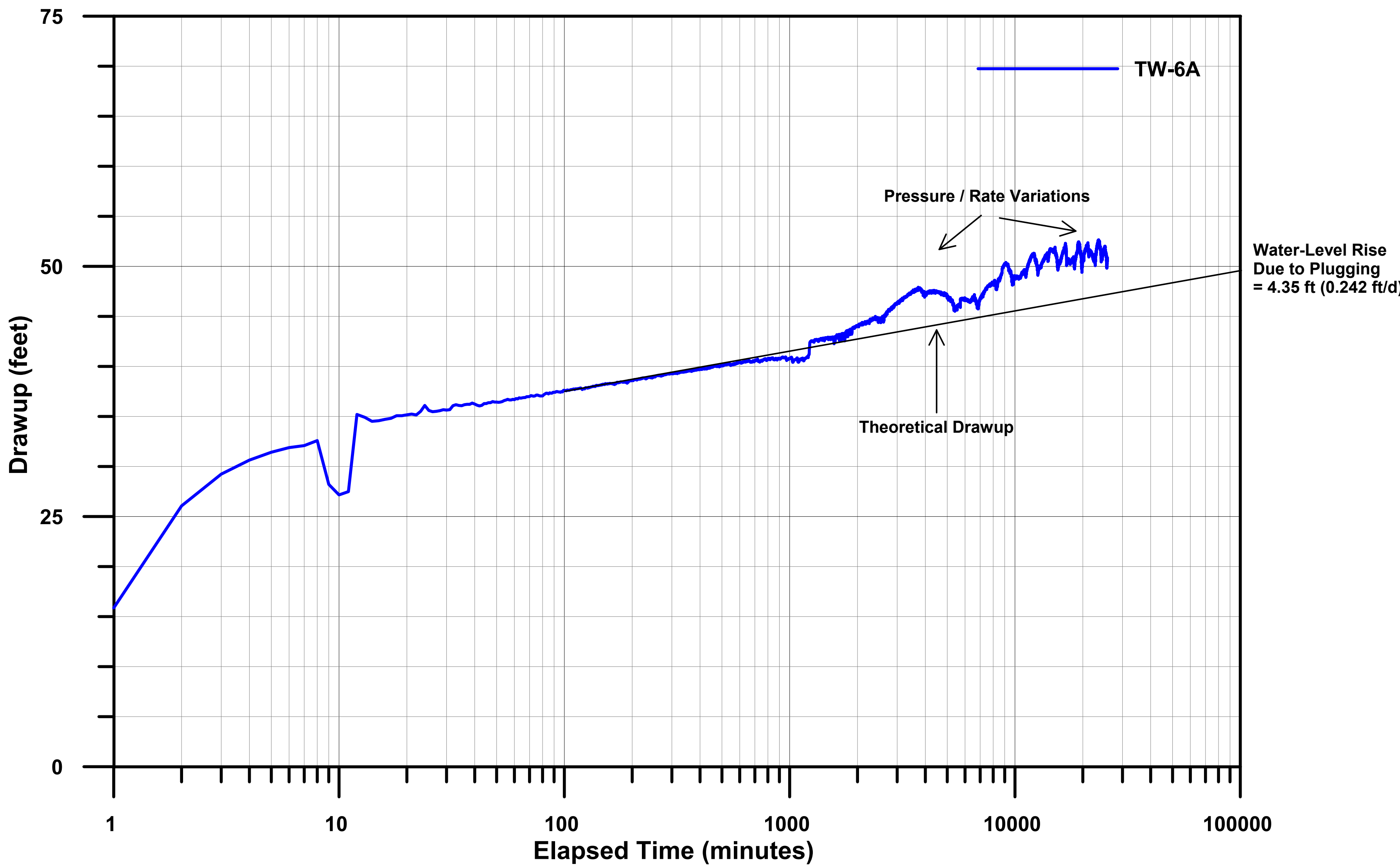
PUEBLO water resources

**FIGURE 13. ASR CYCLE 1 - INJECTION PLUGGING RATE ANALYSIS
OBSERVED VS. THEORETICAL DRAWUP METHOD
Sonoma TW-6A ASR Pilot Test Project
GEI Consultants, Inc. / Sonoma County Water Agency**



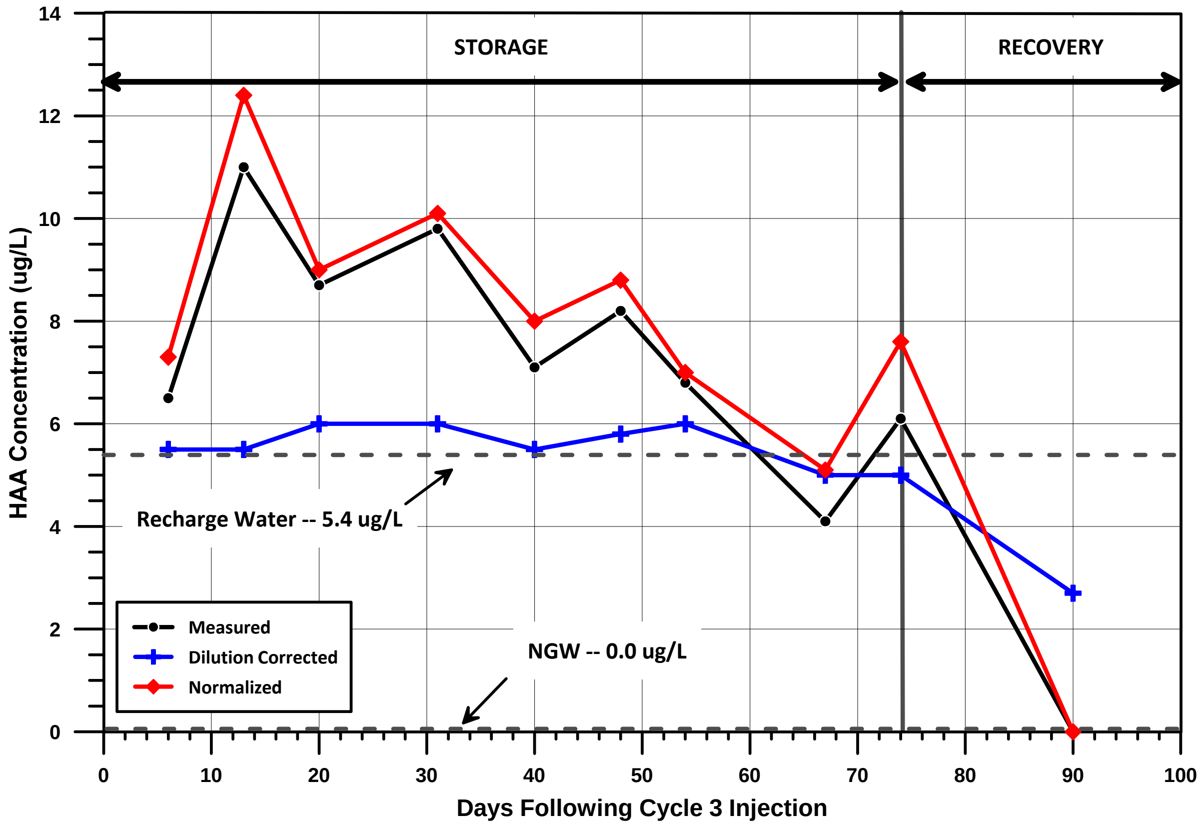
PUEBLO water resources

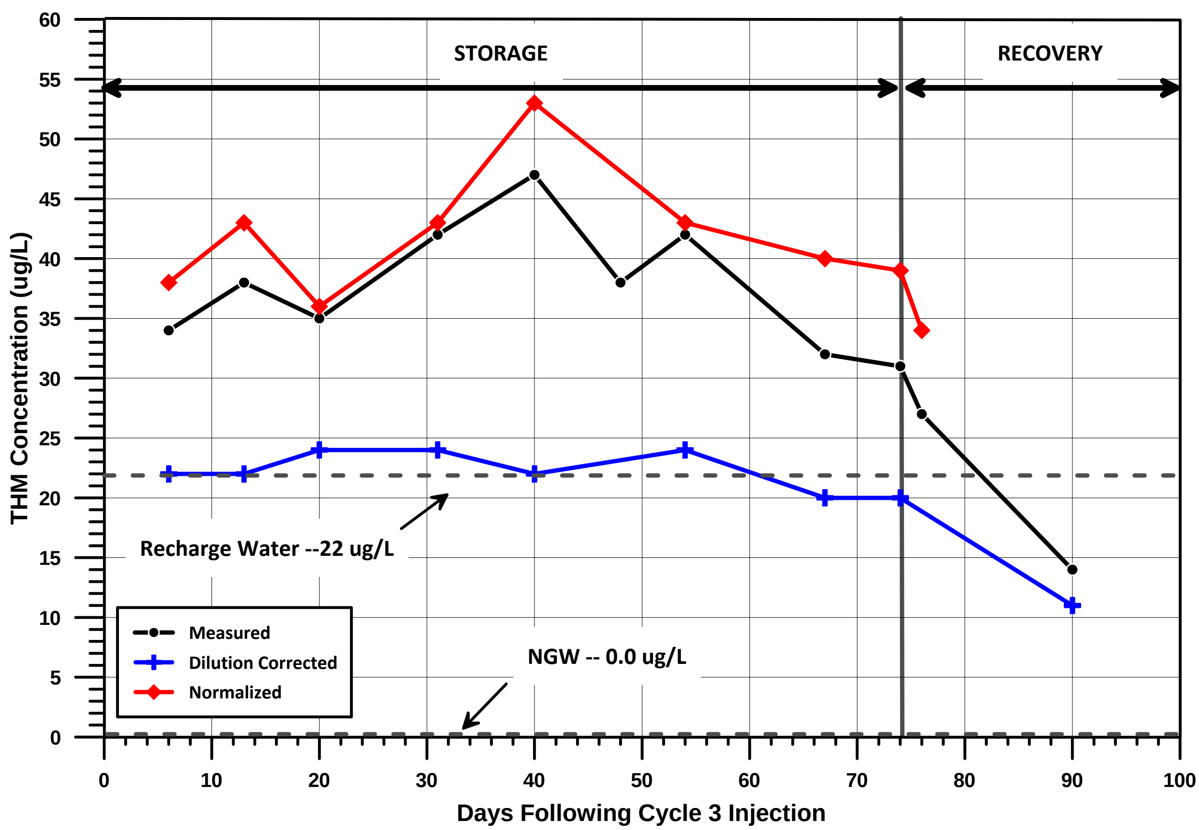
FIGURE 14. ASR CYCLE 2 - INJECTION PLUGGING RATE ANALYSIS OBSERVED VS. THEORETICAL DRAWUP METHOD
Sonoma TW-6A ASR Pilot Test Project
GEI Consultants, Inc. / Sonoma County Water Agency



PUEBLO water resources

FIGURE 15. ASR CYCLE 3 - INJECTION PLUGGING RATE ANALYSIS OBSERVED VS. THEORETICAL DRAWUP METHOD
Sonoma TW-6A ASR Pilot Test Project
GEI Consultants, Inc. / Sonoma County Water Agency



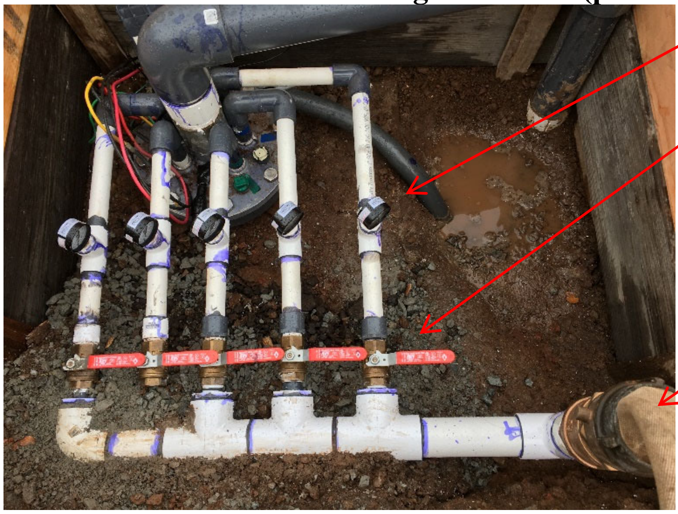


PUEBLO water resources

FIGURE 16. ASR CYCLE 3 DISINFECTION BY PRODUCTS
Sonoma TW-6A ASR Pilot Test Project
GEI Consultants, Inc. / Sonoma County Water Agency

Appendix B. Photographs

Test Well TW-6A with recharge manifold (pressure gauges, valves, and pump-to-waste hose)

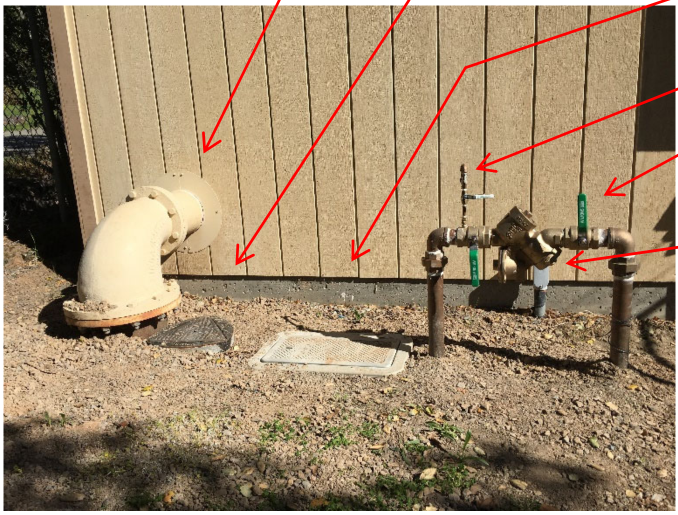


Recharge (injection) tube with ¾-inch orifice

Installation of injection tubes with orifices and sounding tubes around pump column.

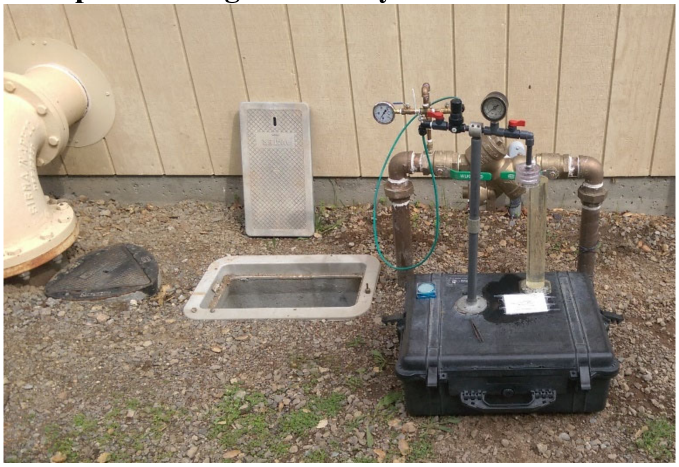
TW-6A enclosure

Sonoma Water pipeline, connection valve box, vault for flow, sampling port, valves, and backflow preventor



Flow meter at connection with Sonoma Water pipeline

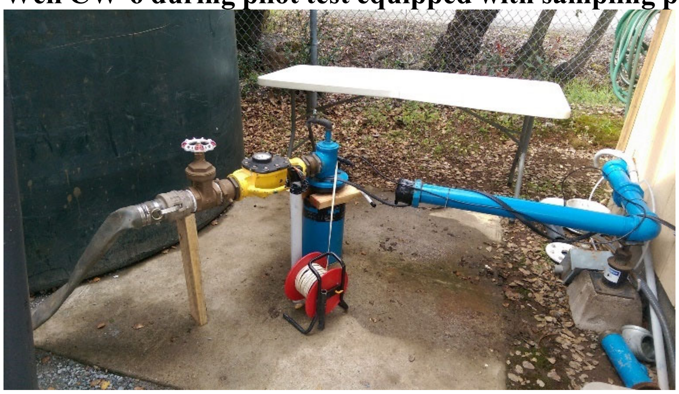
Set-up for testing silt density index



Set-up for testing water quality

Well CW-6 before pilot test

Well CW-6 during pilot test equipped with sampling pump, flow meter, water level gauge, and storage tanks



Recovery (extraction meter between TW-6A and temporary storage tanks

Appendix C. Groundwater and Temperature Data (transducer) on flash drive

Appendix D. Laboratory Reports on flash drive