Final Report

Application of Stratified Aquifer Sampler to Three Gulf Coast Public Water Systems for Arsenic Violations

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Executive Summary

This is a final report on the multilevel sampling results to date. Field tests on four wells in three PWS systems have been performed, including one well operated by the City of Kenedy (PWS 1280002) in Karnes County, one well operated by the Victoria County WCID #1 (PWS 2350001) located in Bloomington, and two wells operated by the Texas Department of Criminal Justice (TDCJ) Wallace Pack Unit near Navasota in Grimes County. Analytical results and recommendations for all three systems are presented in this report.

Stratification sampling was conducted on the City of Kenedy well 9, which is a non-drinking water well used primarily to irrigate city public spaces. This well was selected for testing as it produces water having an arsenic concentration of 42 μg/L based on a screening water sample collected for this study, has multiple production horizons, and testing had minimal impact on system operations. Current City of Kenedy PWS system wells produce water with arsenic concentrations as high as ~90 μg/L. Results of this study indicate that there is significant stratification in both water quantity, with different strata producing from 5% to 50% of total production and water quality with arsenic concentrations varying from 33 to 42 μg/L between production horizons for well 9, though none of the tested intervals produced water with arsenic concentration below the MCL of 10 μg/L. However, results indicate that selective production from lower-concentration strata could reduce arsenic concentrations to approximately 33 mg/L, representing a 21% reduction of current values at a cost of a reduced production rate of 50% of current values. It is recommended that other system wells having construction configurations similar to well 9 also be tested for stratification.

Tests were also conducted on Victoria County WCID #1 well 5, which was initially in very poor condition due to heavy corrosion and scale build-up within the well, as verified by video survey, and the well had been off-line for several months due to a leaking ground storage tank. Following scraping and jetting of the well, the shallowest screen interval was found to be compliant with respect to arsenic concentrations. The well has historically produced water in the range of 16 to 22 μg/L arsenic. During initial testing, the shallowest screen interval produced water representing approximately 32% of total production with an arsenic concentration of 3.2 μg/L. (This is similar to concentrations in well 4 (4 to 7 μg/L), which is the PWS other water source.) A well-head sample from well 3 had an arsenic concentration of 29 μg/L while samples from below the shallowest screen ranged from 41 to 48 μg/L. A follow-up test was conducted three months after the initial test to verify initial results. This test revealed that production from the targeted screen was reduced to 3–5% of total production for reasons not determined. During follow-up testing, well 5 was producing water with arsenic concentrations of 36 μg/L at the well-head and 37 μg/L from below the screen. The reason for the loss of production should be investigated to determine whether rehabilitation/modification of well 5 is feasible or whether replacement with a new well that targets only the shallow production horizon is required.

Finally, two wells operated by the TDCJ Wallace Pack Unit were tested. Results indicate that well 3, which is the deeper of the two wells (720 ft) and has a single screen interval open to depths greater than well 4, does not have any horizons that are compliant with the arsenic MCL concentration. The well-head sample had 43 μg/L arsenic and concentrations from different depths within the screen ranged from 40 to 43 μg/L.

However, results for well 4 indicate that the shallowest of three screen intervals produced water with an arsenic concentration of 4.7 mg/L representing 43% of well discharge. The well-head sample had 14 μg/L arsenic and concentrations from depths below the shallowest screen ranged from 21 to 26 μg/L. A follow-up test performed on well 4 conducted two months after the original tests confirmed the initial results. The shallowest screen interval produced water with an arsenic concentration of 2.5 mg/L representing 38% of well discharge. The well-head sample had 16 μg/L arsenic and the net concentration from depths below the shallowest screen was 25 μg/L. Velocity profile tests for the shallowest screen were performed at three different pump rates, with results indicating that the shallow screen accounts for 38% to 43% of total production. Modification of well 4 to exclude production from depths below screen 1 (>455 ft) is indicated. Alternatively, well 4 could be replaced by or supplemented with one or more wells (depending on production requirements) installed nearby that target the shallow, low arsenic zone.

Introduction

Many small public water supply systems that obtain all or part of their water supply from the Gulf Coast aquifer system are currently producing water that is not in compliance with US EPA and State of Texas water quality regulations. The most wide-spread contaminant in produced Gulf Coast groundwater is arsenic, which commonly exceeds the maximum contaminant level (MCL) concentration of 10 μg/L. The Gulf Coast aquifer system is comprised of three major aquifers; the Jasper, Evangeline, and Chicot aquifers, that range in age from Pliocene to Quaternary. The aquifers are typical of coastal plain aquifers and consist of inter-bedded sands, silts, and clays deposited in a fluvial-deltaic environment. The aquifer strata have relatively narrow outcrop area recharge zones that dip downward towards the coast line, transitioning from unconfined to confined hydraulic conditions.

This study was designed to characterize water quality stratification between or within different production strata in groundwater wells using a stratified aquifer sampling system. Results provide valuable guidance that may potentially reduce or eliminate production of non-compliant water through well modification or replacement.

Materials and Methods

The stratified aquifer sampler is a mobile test system designed to characterize water quality stratification in actively pumping groundwater wells. The system consists of two major subsystems:

1. A dye-tracer injection and monitoring system.
2. A discrete depth sampling system.

The system is designed to characterize the quantity and quality of groundwater produced from specific depth intervals and is based on a design originally developed by the U.S. Geological Survey (Izbicki et al., 1999, Izbicki, 2004), with several enhancements and modifications.

The dye-tracer injection and monitoring system measures the average flow velocity between tested depths, from which estimates of the cumulative well discharge and interval average aquifer discharge are calculated. A small volume (~ 10mL) of Rhodamine WT dye solution (~200 – 400 ppm) is injected into the pumping well and the dye concentration is monitored at the well head in the produced water. Dye concentrations are recorded at 1-second intervals using a data logger and are typically < 100 ppb.

The discrete depth sampling system obtains water samples withdrawn from the flowing well stream at specific depths within the well. Data processing of stratification test data integrates the well velocity/discharge results with the constituent concentration analysis results from discrete-depth water samples.

The total mass of dye, D^T, recovered during a tracer test is determined by integrating the total well discharge, Q^T, and tracer concentration, C^T, over time, t. Assuming that both Q^T and the concentration measurement time interval, Δt, are constant during the test period:

$$D^T = \int Q^T C^T dt = Q^T \int C^T dt = Q^T \Delta t \sum C^T \qquad \text{(Eq. 1)}$$

The value of D^T is useful in examining consistency between tracer test injection volumes, and assumes that the injected mass of dye is conserved.

The dye-tracer center-of-mass arrival time is used to determine the average flow velocity between tested depths. The first-arrival time of dye is identified as the first data record at which a consistent increase above background concentration occurs. The cumulative sum of concentration measurements is calculated beginning at the first-arrival record and across all subsequent records until values return to background concentrations. Under the same assumptions of constant Q^T and Δt, the center-of-mass arrival time, t^m, is the elapsed test time at which the cumulative sum represents 50% of the total cumulative sum:

$$t^m = \frac{\sum C^T}{\sum C^T_{total}} = 0.50 \qquad \text{(Eq. 2)}$$

The average flow velocity, v^a, over a given depth interval, i, is the absolute difference between the bounding test interval depths z_1 (closest to the pump) and z_2 (farthest from the pump) divided by the difference between the respective center-of-mass arrival times:

$$\upsilon_i^a = \frac{|z_2 - z_1|}{t_2^m - t_1^m} \qquad \text{(Eq. 3)}$$

Cumulative well discharge, Q^c, is estimated as an average over interval *i,* from the interval average flow velocity and the well cross-sectional area:

$$Q_i^c = v_i^a \pi r_i^2 \qquad \text{(Eq. 4)}$$

Note that Equation 4 provides an actual discharge value for tested well depth intervals that are not open to and aquifer rather that an average discharge as for screened depth intervals. Finally, the cross-sectional area, πr_i^2, within the well casing radius, r_c, must be adjusted for displacement resulting from the sum of obstructions, r_o, due to riser pipes, electrical cables, etc., that may be present between the injection depths:

$$r_i^2 = r_c^2 - \sum r_o^2 \qquad \text{(Eq. 5)}$$

The interval average aquifer discharge, Q^a, is estimated as the difference between the cumulative well discharges for the interval i and the interval i-1 next farthest from the pump:

$$Q_i^a = Q_i^c - Q_{i-1}^c \qquad \text{(Eq. 6)}$$

Discrete depth samples provide a constituent flux concentration, C^f, in the flow stream at a given depth, z. The constituent average aquifer concentration, C^a, flowing into the well over the depth interval i between depths z_1 (closest to the pump) and z_2 (farthest from the pump) is estimated as:

$$C_i^a = \frac{Q_i^c C_{z_1}^f - Q_{i-1}^c C_{z_2}^f}{Q_i^a} \qquad \text{(Eq. 7)}$$

The units of discharge cancel out in eq. 7. Thus, aquifer concentration calculations may be performed by substituting average discharge with either average velocity or percentage of total average velocity measurements, provided that the cross-sectional flow area remains constant between the tested depth intervals.

Uncertainty

Uncertainty in analytical results arises due to measurement errors, which propagate through the calculations. Errors are associated with both measurement systems; the velocity profile tests and the sample chemical constituent analyses. Sources of error in the velocity profile tests are related to accuracy of positioning of the equipment in the well at pre-specified depths and to the accuracy of the dye injection and monitoring system. Depth positioning errors are estimated to be no greater than about 0.17 ft (2 in), as fixed depth reference points are used in the process. The accuracy of the dye injection and monitoring system is quantified by repeated testing at a given depth, which indicates that dye arrival times are generally repeatable to within about 1 second. Sources of error in the sample chemical analyses are minimized by employing stringent quality control standards on the sampling and analytical process. Analysis of major constituent anion and cation concentrations generally result in sample charge balance values within 5% of neutral, and usually within ~2%. Spiked matrix samples generally result in 95 to 105% recovery, and usually range from 98 to 102% recovery.

Errors were propagated for both the discharge and the stratified chemistry values and used both assumed and measured variance values as described above, including depth positioning error, measured dye center-of-mass arrival time variance, sample ionic charge balance, and spiked sample recoveries. Further confidence in discharge calculations is obtained by comparison of calculated discharge rates with well flow meter measurements (assuming the well flow meter is reasonably accurate). Also, results from velocity profile tests conducted over different depth intervals are compared for consistency within non-screened well sections.

Results and Discussion

<u>City of Kenedy (PWS 1280002)</u>

The City of Kenedy has a population of approximately 3,300 residents and is located in Karnes County, Texas, near the up-dip limits of the Gulf Coast Aquifer system. The city is serviced by a public water supply system with approximately 1,560 metered connections and relies solely on local groundwater resources. All groundwater is produced from the Catahoula Tuff and the Goliad Sand members of the Jasper aquifer, which are regionally associated with elevated arsenic concentrations and represent the lower-most strata within the Gulf Coast Aquifer system.

The PWS currently has five operational wells that range in depth from 153 to 650 ft (Table 1). Most operational wells currently produce water with arsenic concentrations that exceed the MCL (10 μg/L). Total dissolved solids (TDS) concentrations generally range between 1,200 and 2,000 mg/L, exceeding the secondary standard (500 mg/L). In general, higher arsenic concentrations are correlated with greater well depth (log As vs. well depth, r=0.69). Correlation between TDS concentrations and well depth is lower (log TDS vs. well depth, r=0.49). All produced drinking water is currently treated using reverse osmosis (RO) technology prior to distribution. Prior to implementing treatment, PWS entry point arsenic concentrations generally ranged from 20 – 42 μg/L.

Table 1. City of Kenedy PWS well identification, depths, status, and arsenic and TDS concentrations.

TCEQ Water Source ID	*TWDB Well ID*	*City of Kenedy Well ID*	*Depth (ft)*	*Status*	*Arsenic (μg/L)*	*TDS (mg/L)*
G1280002A	7910405	3	399	Abandoned	-	1,190
G1280002B	7910404	4	747	Abandoned	89.3	2,000
G1280002C	7910406	5	407	Abandoned	-	1,250
G1280002D	7910402	6	428	Abandoned	30	2,190
G1280002E	7910403	8	650	Operational	70	1,350
G1280002F	-	9	600	Non-drinking	42.4	2,000
G1280002G	7910408	10	545	Operational	92.3	1,230
G1280002H	7910807	11	329	Operational	-	1,130
G1280002I	7910808	12	153	Plugged	-	-
G1280002J	-	13	153	Operational	-	-
G1280002K	-	14	645	Operational	-	-

Arsenic and TDS concentrations are from the Texas Water Development Board water quality database.

Of the 11 system wells that are not plugged, one of the abandoned wells (well 4), two of the operational wells (wells 8 and 11), and the non-drinking water well (well 9) were completed with multiple screened sections and are thus most suitable for stratification analysis. Well 9 was selected for initial testing as it is used exclusively for irrigation and other non-potable uses and thus testing procedures would have minimal impact on system operations. Well 9 has three widely separated screen interval depths (Table 2).

Table 2. Surface casing and screen depth intervals for City of Kenedy well 9.

Description	*Top Depth (ft)*	*Bottom Depth (ft)*	*Length (ft)*	*Diameter (in)*
Surface Casing	0	282	282	14
Screen 1	292	350	58	8
Screen 2	430	456	26	8
Screen 3	540	586	46	8

Tests on well 9 were conducted June 8-10, 2009 following installation of an access tube that provided unobstructed access for the test equipment to depths below the pump. Tests were conducted on three subintervals of screen 1. Planned tests on screen 3 subintervals could not be conducted due to debris in the bottom of the well that prevented access to depths below 569 ft. All discharge from screen 3 was assumed to originate from the exposed screen interval (540 – 569 ft).

Total discharge calculated from the shallowest dye-tracer test (76.7 gpm) agreed very well with the inline meter that was used to independently monitor the flow rate during testing (76 gpm), increasing confidence in the flow results. Results of the velocity profile tests indicate large differences in discharge between the screened intervals, with 45%, 5%, and 50% of total well production originating from screens 1, 2, and 3, respectively (Table 3, Figure 1a). Subinterval tests conducted on screen 1 indicate that 38% of total production originated from intervals 1A and 1C, while only 5% of total production originated from interval 1B. However, uncertainty values for the discharge and chemical analysis of screen 1 subintervals are relatively large. Screen 1 data were combined for further analysis.

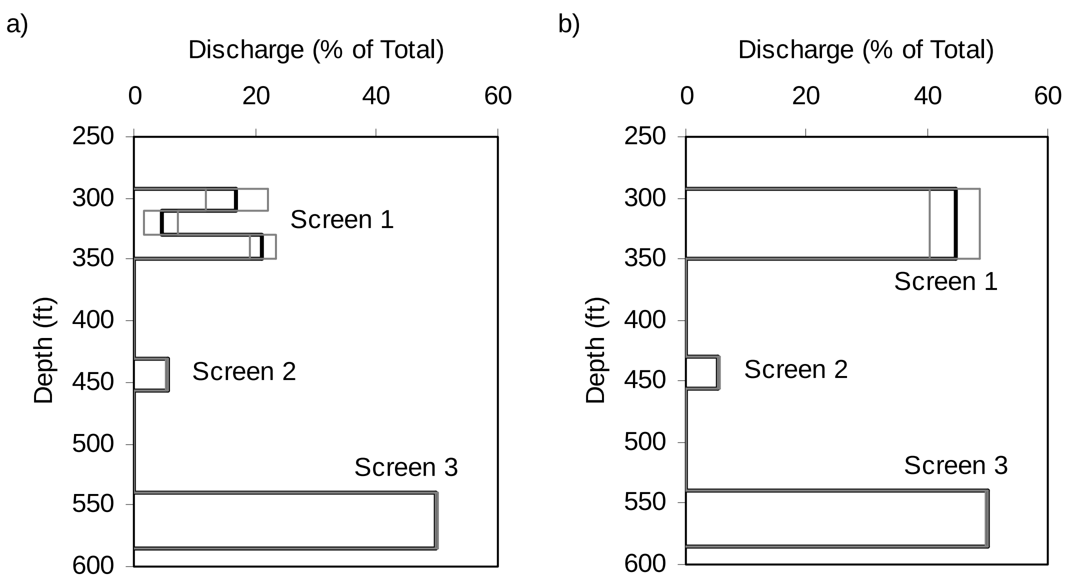

Figure 1. City of Kenedy well 9 discharge profile expressed as a) a percentage of total discharge and b) interval mean discharge normalized by interval thickness.

Though arsenic concentrations for all sampled intervals were greater than the MCL, analytical results for the water quality samples indicate large differences in most solutes within and between screened intervals (Tables 4 and 5). The average arsenic concentration in the well-head water was 42 μg/L. Arsenic concentrations were highest in water produced from screen 1 (51 μg/L) and from screen 2 (58 μg/L). Arsenic concentrations are lowest in screen 3 (33 mg/L). General water quality, indicated by TDS concentrations, does not vary significantly between the tested intervals.

Table 3. City of Kenedy well 9 velocity/discharge profile results. Values not associated with a screen represent results for blank sections of well casing above and between screen intervals and indicate actual flow rates. Flow rates for subintervals of screen 1 represent average values.

Screen		*Top (ft)*	*Bottom (ft)*	*Length (ft)*	Δt *(sec)*	v^a *(ft/min)*	Q^c *(gpm)*	Q^a *(gpm)*	Q^a *(gpm/ft)*	*Q (%)*
-		282	292	10	20	29.4	76.7	-	-	
1	A	292	310	18	44	24.4	63.7	13.0	0.72	17 ± 5
	B	310	330	20	52	23.1	60.3	3.5	0.17	5 ± 3
	C	330	350	20	71	16.8	44.0	16.3	0.81	21 ± 2
1		292	350	58	168	20.8	54.3	34.2	0.59	45 ± 4
-		350	430	80	295	16.3	42.5	-	-	
2		430	456	26	103	15.2	39.6	4.2	0.16	5 ± 0.3
-		456	540	84	344	14.7	38.3	-	-	
3		540	569	29	-	-	-	38.3	1.32	50 ± 0.2

Top: test interval top depth, *Bottom*: test interval bottom depth, *Length*: test interval length, Δt: difference in arrival time between top and bottom depth dye-tracer injections (Eq. 2), v^a: average discharge velocity in tested interval (Eq. 3), Q^c: cumulative total well discharge (Eq. 4), Q^a: average or actual interval discharge and discharge normalized by tested interval length (Eq. 6), *Q*: percentage of total well discharge.

The results for well 9 indicate the presence of significant stratification of both water quantity and water quality between local groundwater production horizons in the vicinity of Kenedy. While none of the tested intervals in well 9 produced water with arsenic concentrations below the MCL, that may not be true for other wells in the PWS system. Well 9 is not used to produce drinking water but other system wells produce water with much higher arsenic concentrations (e.g., well 8: 70 μg/L, Table 1).

Table 4. City of Kenedy well 9 water quality profile test results for arsenic and major anion concentrations. Total represents well-head sample.

Screen	*Top (ft)*	*Bottom (ft)*	*As μg/L*	*Cl mg/L*	HCO_3 *mg/L*	SO_4 *mg/L*	NO_3*-N mg/L*	*F mg/L*
Total	-	-	42.4	777	398	228	2.8	0.75
1	292	350	51 ± 7	747 ± 110	428 ± 59	216 ± 32	2.6 ± 0.4	0.82 ± 0.11
2	430	456	58 ± 10	1,051 ± 226	239 ± 107	351 ± 67	4.8 ± 0.8	0.40 ± 0.20
3	540	569	33 ± 1	773 ± 15	388 ± 7.8	226 ± 4.5	2.8 ± 0.1	0.73 ± 0.01

Table 5. City of Kenedy well 9 water quality profile test results for TDS and major cations. Total represents well-head sample.

Screen	*Top (ft)*	*Bottom (ft)*	*TDS mg/L*	*Na mg/L*	*K mg/L*	*Ca mg/L*	*Mg mg/L*
Total	-	-	1,996	722	28	24	0.49
1	292	350	1,948 ± 283	714 ± 103	26 ± 3.9	16 ± 3.0	0.02 ± 0.06
2	430	456	2,552 ± 575	843 ± 206	41 ± 8.1	109 ± 9.2	6.7 ± 0.39
3	540	569	1,977 ± 40	717 ± 14	27 ± 0.5	23.1 ± 0.4	0.24 ± 0.01

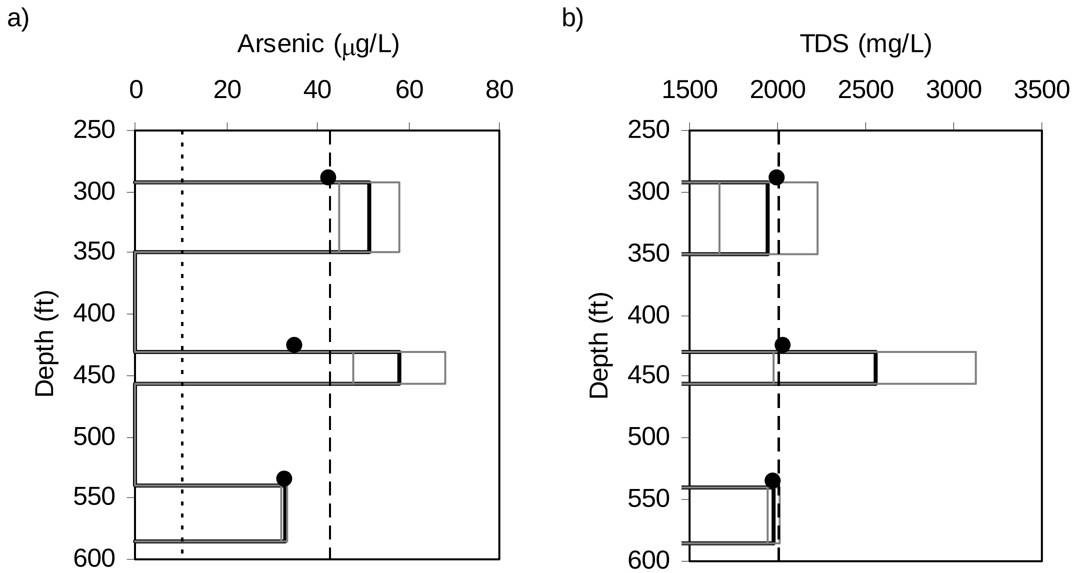

Figure 2. City of Kenedy well 9 profiles for a) arsenic and b) TDS concentrations. TDS was estimated as the sum total of major anion and cation concentrations (Tables 4 and 5). Charge balance for major constituents is within ~4% for all samples. Gray lines represent analysis uncertainty. Vertical short-dash line in (a) represents the MCL for arsenic (10 μg/L). Vertical long-dash lines represent concentrations for As (42 μg/L) and TDS (1,996 mg/L) in well-head samples. Points represent concentrations and depth locations of samples.

The results for well 9 can be used to demonstrate a possible well-modification scenario that could be employed to reduce arsenic concentrations currently entering the PWS system RO plant and thereby potentially reduce operational expenses. Eliminating production from screens 1 and 2 would result in a 50% reduction in capacity and a 21% reduction in arsenic concentrations from 42 μg/L to 33 μg/L. These results are unique to well 9 and may not reflect conditions in other system wells.

It is recommended that further stratification testing be conducted on City of Kenedy system wells, particularly well 4 (currently abandoned) and possibly also wells 8 and 11, all of which have multiple screened intervals (Table 6). Of these, the screened intervals in well 4 are the most widely separated (by 43 and 193 ft) while the intervals in wells 8 and 11 are separated by only 2 to 6 ft and may not be completed in separate producing strata.

Table 6. Candidate City of Kenedy PWS wells for future stratification testing.

City of Kenedy Well ID	*Screen*	*Top Depth (ft)*	*Bottom Depth (ft)*	*Length (ft)*	*Diameter (in)*
4	1	432	477	45	7
	2	520	530	10	7
	3	723	743	20	7
8	1	564	589	25	8
	2	594	634	40	8
10	1	232	262	30	10
	2	268	288	20	10
	3	290	310	20	10

Victoria County WCID #1 (PWS 2350001)

The Victoria County WCID #1 serves the City of Bloomington, which has a population of approximately 2,800 residents and is located in Victoria County, Texas. The PWS system has approximately 780 metered connections and relies solely on local groundwater resources. All groundwater is produced from the Evangeline aquifer.

The PWS currently has two operational wells. Well 4 is completed to a depth of 1001 ft and well 5 to a depth of 1010 ft (Table 7). Archival water quality sample data indicate that well 4 has consistently produced water with arsenic concentrations below the MCL (10 μg/L) while well 5 has consistently produced water with arsenic concentrations above the MCL. (Note: results for samples collected from both wells in March, 2006 were apparently switched and are herein treated as such.) TDS concentrations have also remained very consistent for both wells at about 840 mg/L. The PWS system currently does not treat produced water for arsenic.

Table 7. Victoria County WCID #1 well identification, depths, status, and arsenic and TDS concentrations. Ranges of arsenic and TDS concentrations are shown and median concentrations are given in parenthesis.

TCEQ Water Source ID	*TWDB Well ID*	*WCID Well ID*	*Depth (ft)*	*Status*	*Arsenic[1] (μg/L)*	*TDS[2] (mg/L)*
G2350001A	8017904	4	1,001	Operational	4.4-7.2 (5.1)	827-888 (837)
G2350001B	8017905	5	1,010	Operational[3]	13.5-22.1 (17.9)	823-856 (837)

[1] source: TCEQ and TWDB; well 4: 8 samples 2005-2006, well 5: 8 samples 1997-2008.
[2] source: TWDB; well 4: 4 samples 1969-1981, well 5: 4 samples 1981 and 2005.
[3] temporarily off-line due to leaking ground storage tank.

Field work began on well 5 on July 28, 2009. At that time, Well 5 had been off-line for several months due to a leaking ground storage tank. No information regarding the pump setting depth was available. The pump was pulled (set at 150 ft below the top of casing) and a video survey was conducted to verify construction records regarding screen interval depths. The video revealed that much of the well was heavily corroded to the point that screen intervals were not recognizable. Several days of physical scraping and jetting were required to remove the corrosion. A follow-up video survey was conducted on August 5 that revealed clean conditions, though many of the screen openings appeared to be restricted by deposits which the scraping process used was unable to remove. The video also revealed that the screen depths listed on the well construction record were within 1 ft of those viewed (Table 8). Additionally, a split in the casing between screens 2 and 3 with gas bubbles entering the well was observed. The pump was subsequently reset at the original depth and an access tube was installed to a depth of 147 ft below TOC that provided unobstructed access for the test equipment. A gate valve was also installed and located downstream from the existing flow meter to provide flow control during testing.

Stratification testing was conducted on well 5 August 12-13, 2009. Velocity profile measurements between the pump and the top of the shallowest screen interval resulted in a total well discharge value of 160 gpm, agreeing very well with the rate indicated by the system flow meter (155 gpm). Subintervals of individual screens were not tested and screens 3 and 4 were tested as one interval due to the short distance between the top of screen 3 and the bottom of screen 4 (15 ft). A supplemental test was conducted at 913 ft to determine if, in addition to the observed gas bubbles, water was also entering the well at that depth.

Table 8. Surface casing and screen depth intervals for Victoria County WCID #1 Well 5. Depth values are relative to top of casing (TOC). Swage from 10" to 8" casing located at 769 ft depth. TD viewed at 1004 ft.

Description	*Top Depth (ft)*	*Bottom Depth (ft)*	*Length (ft)*	*Diameter(s) (in)*
Casing	0	783	783	10, 8
Screen 1 openings	783	823	40	8
Screen 2 openings	871	889	18	8
Casing Split	913	-	-	-
Screen 3 openings	941	946	5	8
Screen 4 openings	954	959	5	8
Screen 5 openings	973	995	22	8

Table 9. Victoria County WCID #1 well 5 velocity profile test results. Values not associated with a screen represent results for blank sections of well casing above and between the screen intervals and indicate actual flow rates rather than average flow rates.

Screen	*Top (ft)*	*Bottom (ft)*	*Length (ft)*	Δt *(sec)*	v^a *(ft/min)*	Q^c *(gpm)*	Q^a *(gpm)*	Q^a *(gpm/ft)*	*Q (%)*
-	155	769	614	938	39.3	160	-	-	-
1	784	824	40	53.1	45.2	118	50.5	1.26	32 ± 4
-	824	872	48	68.6	42.0	110	-	-	-
2	872	890	18	28.5	37.9	99.0	13.1	0.73	8 ± 2
split	890	913	23	37.3	37.0	96.6	4.4	4.4	3 ± 3
-	913	942	29	49.3	35.3	92.2	-	-	-
3 – 4	942	960	18	32.5	33.2	86.8	10.4	1.04	6 ± 3
-	960	973	13	24.9	31.3	81.8	81.8	-	-
2 – 4	872	960	88	147.6	35.8	93.4	27.9	1.00	17 ± 3
5	973	995	22	-	-	81.8	81.8	3.72	51 ± 3

Top: test interval top depth, *Bottom*: test interval bottom depth, *Length*: test interval length, Δt: difference in arrival time between top and bottom depth dye-tracer injections (Eq. 2), v^a: average discharge velocity in tested interval (Eq. 3), Q^c: cumulative total well discharge (Eq. 4), Q^a: average or actual interval discharge and discharge normalized by tested interval screen length (Eq. 6), *Q*: percentage of total well discharge ± uncertainty.

Results of the velocity profile measurements indicate significant differences in discharge between the screened intervals (Table 9, Figure 3). The main productive intervals are screen 1 (32%) and screen 5 (51%). Screens 2 through 4 and the casing split at 913 ft together produce the remaining 17%. The small discharge percentages originating individually from screens 2 through 4 and the casing split result in large uncertainties in the chemical constituent analysis for samples within this zone. Therefore, this entire zone was combined into one for further analysis.

The arsenic concentration in the well-head water was 29 μg/L. Analytical results for the water quality samples indicate large differences in arsenic concentrations between screened intervals (Tables 10 and 11). The arsenic concentration was 3.2 μg/L in water produced from screen 1, well below the MCL (10 μg/L) and similar to concentrations produced from well 4. Arsenic concentrations in water produced from deeper sections were greater and increased with depth, with and average of 20 μg/L produced from the combined screen 2-4 zone and 48 μg/L from screen 5. General water quality, reflected by TDS and other constituents, does not vary significantly between the screen sections.

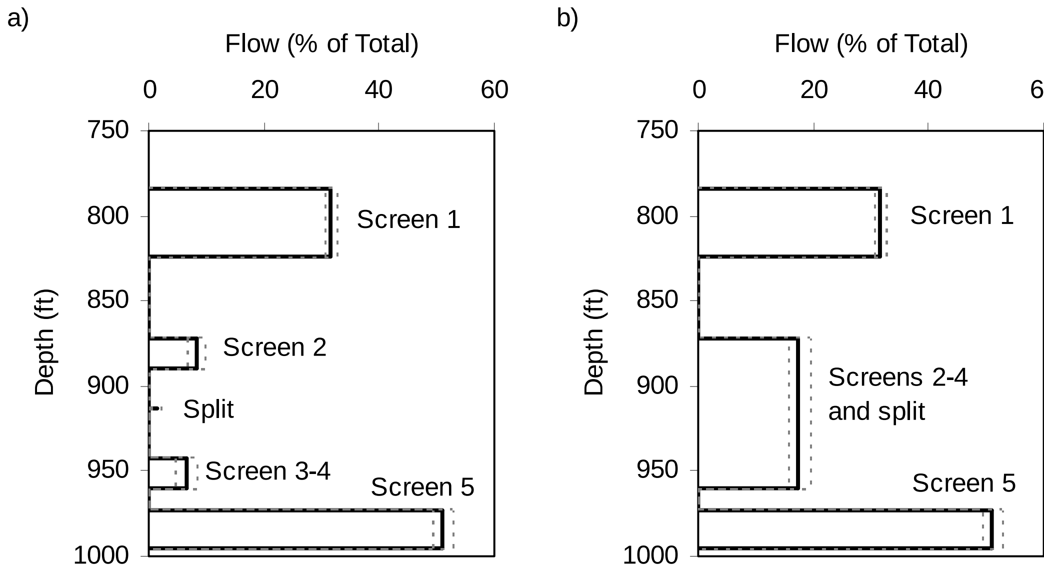

Figure 3. Victoria County WCID #1 Well 5 discharge profile showing the percentage of total well production originating from a) all screens, including the casing split at 913 ft and b) screens 1 and 5 with all other screens and the casing split combined.

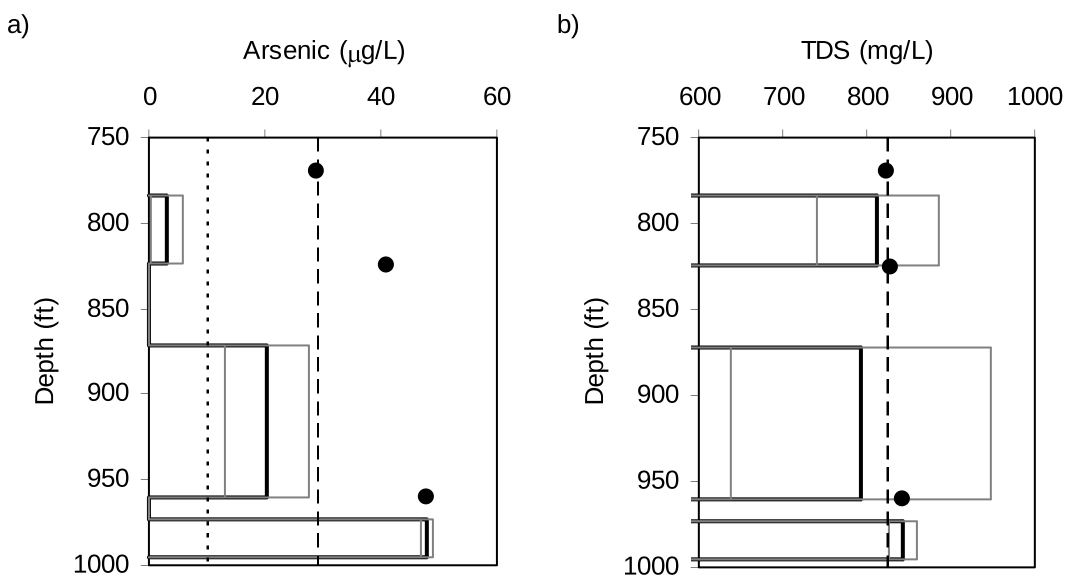

Figure 4. Victoria County WCID #1 well 5 profiles for a) arsenic and b) TDS concentrations. TDS was estimated as the sum total of major anion and cation concentrations (Tables 10 and 11). Charge balance for major constituents is within ~2% for all samples. Gray lines represent analysis uncertainty. Vertical short-dash line in (a) represents the MCL for arsenic (10 μg/L). Vertical long-dash lines represent concentrations for As (29 μg/L) and TDS (824 mg/L) in well-head samples. Points represent concentrations and depth locations of samples.

Table 10. Victoria County WCID #1 Well 5 water quality profile test results for arsenic and major anion concentrations. Total represents well-head sample.

Screen	*Top (ft)*	*Bottom (ft)*	*As μg/L*	*Cl mg/L*	*HCO_3 mg/L*	*SO_4 mg/L*	*NO_3-N mg/L*	*F mg/L*
Total	-	-	29	263	372	54	<0.01	0.53
1	784	824	3.2 ± 2.8	243 ± 23	403 ± 33	52 ± 4.8	<0.01	0.69 ± 0.05
2 – 4	872	960	20 ± 7.2	245 ± 50	371 ± 68	52 ± 10	<0.01	0.32 ± 0.08
5	973	995	48 ± 1.0	282 ± 6	351 ± 7	55 ± 1.1	<0.01	0.51 ± 0.01

Table 11. Victoria County WCID #1 Well 5 water quality profile test results for TDS and major cations. Total represents well-head sample.

Screen	*Top (ft)*	*Bottom (ft)*	*TDS mg/L*	*Na mg/L*	*K mg/L*	*Ca mg/L*	*Mg mg/L*
Total	-	-	824	277	5.0	24	16
1	784	824	812 ± 73	263 ± 25	8.3 ± 0.4	23 ± 2.1	18 ± 1.4
2 – 4	872	960	792 ± 155	263 ± 53	3.7 ± 0.7	28 ± 4.8	18 ± 3.0
5	973	995	842 ± 17	290 ± 6	3.4 ± 0.1	23 ± 0.5	14 ± 0.3

Follow-up stratification sampling was conducted on well 5 during November 16-17, 2009 that focused only on screen 1 to verify the results described. The well had not been operated since the original testing phase in August. Velocity profile tests indicated that the percentage of water produced from screen 1 had decreased to approximately 3% to 5% of total well production. Two water quality samples, one above and one below screen 1, were analyzed for arsenic and resulted in 36.2 and 37.6 μg/L, respectively. The difference in concentrations indicates marginal dilution (as with the original test), but analytical uncertainty and the uncertainty associated with the very small discharge contribution from screen 1 prevent these results from verifying the original findings. The cause of the decrease in discharge from screen 1 was not determined and is beyond the scope of this work.

TDCJ Wallace Pack Unit (PWS 0930034)

The Texas Department of Criminal Justice (TDCJ) Wallace Pack Unit PWS system serves a population of approximately 1,800 staff and inmates located near Navasota in Grimes County, Texas. The system relies solely on local groundwater resources, which are produced from the Jasper aquifer.

The PWS currently has two operational wells. Well 3 is completed to a depth of 720 ft and Well 4 to a depth of 582 ft (Table 12). Archival water quality data indicate that 12 of 15 entry point samples analyzed between 2000 and 2008 and representing a mix of water from both wells exceeded the MCL by a median 25.6 μg/L.

Testing of wells 3 and 4 occurred September 14-18, 2009. Access tubes were installed to a depth of 420 ft below TOC in well 3 and 340 ft below TOC in well 4 that provided unobstructed access for the test equipment. Well 3 has only one screen interval while well 4 has three screen intervals (Table 13).

Table 12. TDCJ Wallace Pack Unit well identification, depths, status, and arsenic and TDS concentrations. Ranges of arsenic and TDS concentrations are shown and median concentrations are given in parenthesis.

TCEQ Water Source ID	*TWDB Well ID*	*WCID Well ID*	*Depth (ft)*	*Status*	*Arsenic[1] (μg/L)*	*TDS[2] (mg/L)*
G0930034C	5948408	3	720	Operational	< 2.0-36.5 (25.6)	648-929 (691)
G0930034D		4	586	Operational		

[1] source: TCEQ; 15 entry point samples 2000-2008
[2] source: TCEQ; 3 entry point samples 2000-2006

Table 13. Surface casing and screen depth intervals for TDCJ Wallace Pack Unit wells 3 and 4. Depth values are relative to top of casing (TOC). Well 3 swage from 14” to 8” casing located at 530 ft depth. Well 4 swage from 16” to 8” casing located at 315 ft depth.

Well	*Description*	*Top Depth (ft)*	*Bottom Depth (ft)*	*Length (ft)*	*Diameter(s) (in)*
3	Casing	0	628	628	14, 8
	Screen openings	621	691	70	8
4	Casing	0	415	18	16, 8
	Screen 1 openings	415	455	40	8
	Screen 2 openings	477	500	23	8
	Screen 3 openings	535	562	27	8

Well 3

Velocity profile tests for well 3 were performed at a measured pump rate of 352 gpm. The system flow meter showed poor agreement (225 gpm) and is considered unreliable. Prior to testing the screen interval, multiple tests were performed over different non-screened sections of the well and results were consistent. Most production from the well originated from the shallowest 14 ft of the screened interval (64%) and production decreased rapidly with increasing depth (Figure 5, Table 14). Arsenic concentrations were high throughout the profile, ranging from 40 to 43 μg/L, and no intervals were identified that had arsenic concentrations compliant with the MCL (Figure 6, Tables 15 and 16). General water chemistry did not vary significantly throughout the profile, with TDS generally consistent at about 1,300 mg/L.

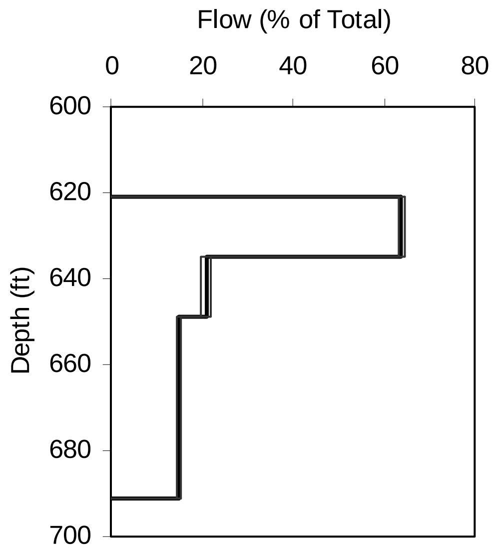

Figure 5. TDCJ Wallace Pack Unit well 3 discharge profile showing the percentage of total well production originating from the single screen.

Table 14. TDCJ Wallace Pack Unit well 3 velocity profile test results. Values not associated with a screen represent results for blank sections of well casing above and between the screen intervals and indicate actual flow rates rather than average flow rates.

Screen	*Top* (ft)	*Bottom* (ft)	*Length* (ft)	Δt (sec)	ν^a (ft/min)	Q^c (gpm)	Q^a (gpm)	Q^a (gpm/ft)	*Q* (%)
-	541	621	80	35.6	135	352	-	-	-
1A	621	635	14	14.1	59.4	155	225	16.1	64 ± 1.0
1B	635	649	14	22.2	37.8	99	74	5.3	21 ± 1.0
1C	649	691	42	39.4	24.4	64	64	1.5	15 ± 1.0

Top: test interval top depth, *Bottom*: test interval bottom depth, *Length*: test interval length, Δt: difference in arrival time between top and bottom depth dye-tracer injections (Eq. 2), ν^a: average discharge velocity in tested interval (Eq. 3), Q^c: cumulative total well discharge (Eq. 4), Q^a: average or actual interval discharge and discharge normalized by tested interval screen length (Eq. 6), *Q*: percentage of total well discharge ± uncertainty.

Table 15. TDCJ Wallace Pack Unit well 3 water quality profile test results for arsenic and major anion concentrations. Total represents well-head sample.

Screen	*Top* (ft)	*Bottom* (ft)	*As* μg/L	*Cl* mg/L	HCO_3 mg/L	SO_4 mg/L	NO_3-N mg/L	*F* mg/L
Total	-	-	43	112	810	< 0.1	<0.01	0.40
1A	621	635	42 ± 3.2	119 ± 4	813 ± 26	< 0.1	<0.01	0.41 ± 0.01
1B	635	649	41 ± 4.8	93 ± 7	796 ± 60	< 0.1	<0.01	0.38 ± 0.03
1C	649	691	40 ± 2.5	105 ± 4	781 ± 32	< 0.1	<0.01	0.37 ± 0.02

Table 16. TDCJ Wallace Pack Unit well 3 water quality profile test results for TDS and major cations. Total represents well-head sample.

Screen	*Top (ft)*	*Bottom (ft)*	*TDS mg/L*	*Na mg/L*	*K mg/L*	*Ca mg/L*	*Mg mg/L*
Total	-	-	1,309	335	15	34	1.7
1A	621	635	1,311 ± 43	333 ± 11	15 ± 0.5	35 ± 1.1	1.9 ± 0.06
1B	635	649	1,299 ± 98	338 ± 25	15 ± 1.1	34 ± 2.5	1.5 ± 0.11
1C	649	691	1,286 ± 52	340 ± 14	15 ± 0.6	33 ± 1.4	1.4 ± 0.06

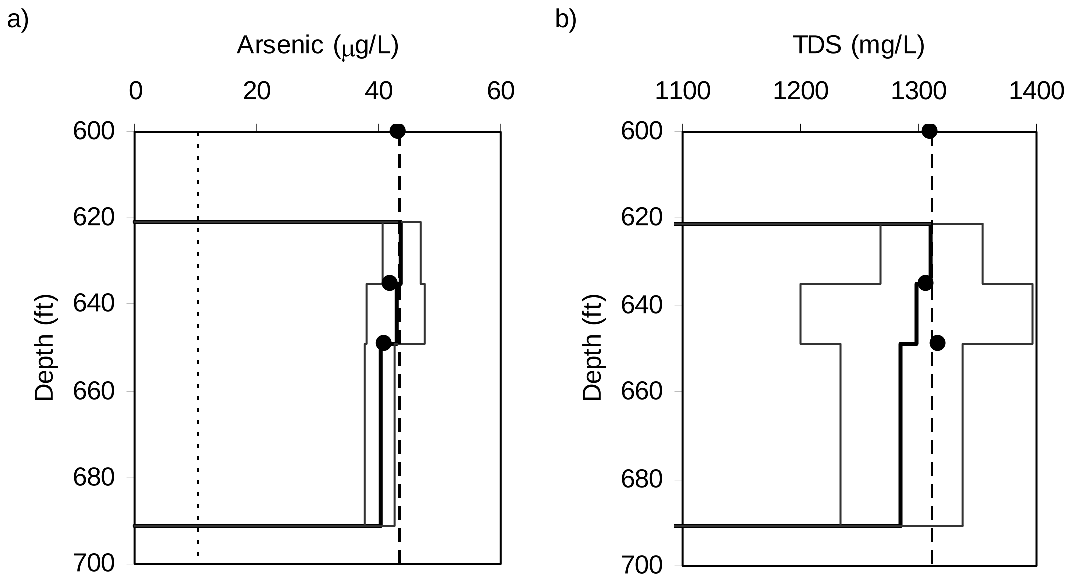

Figure 6. TDCJ Wallace Pack Unit well 3 profiles for a) arsenic and b) TDS concentrations. TDS was estimated as the sum total of major anion and cation concentrations (Tables 15 and 16). Charge balance for major constituents is within ~3% for all samples. Gray lines represent analysis uncertainty. Vertical short-dash line in (a) represents the MCL for arsenic (10 μg/L). Vertical long-dash lines represent concentrations for As (43 μg/L) and TDS (1309 mg/L) in well-head samples. Points represent concentrations and depth locations of samples.

Well 4

Velocity profile tests performed over different non-screened sections of the well were consistent at 224 gpm and were in near perfect agreement with the well flow meter (223 gpm). Results of the velocity profile tests indicate large differences in discharge between the screened intervals, with 43%, 8%, and 49% of total well production originating from screens 1, 2, and 3, respectively (Table 17, Figure 7).

The arsenic concentration in the well-head water was 14 μg/L. Analytical results for the water quality samples indicate large differences in arsenic and other solute concentrations between screened intervals (Tables 18 and 19, Figure 8). The arsenic concentration was 4.7 μg/L in water produced from screen 1, well below the MCL (10 μg/L). Arsenic concentrations in water produced from deeper sections were greater and increased with depth, with an average of 19 μg/L produced from screen 2 and 23 μg/L from screen 3. General water quality, reflected by TDS, followed the same pattern and increased from ~600 mg/L in screen 1 to ~800 mg/L in screen 3. Among ionic constituents, the most notable changes occurred for both sodium and bicarbonate, for which concentrations also both increased with increased depth (Tables 18 and 19).

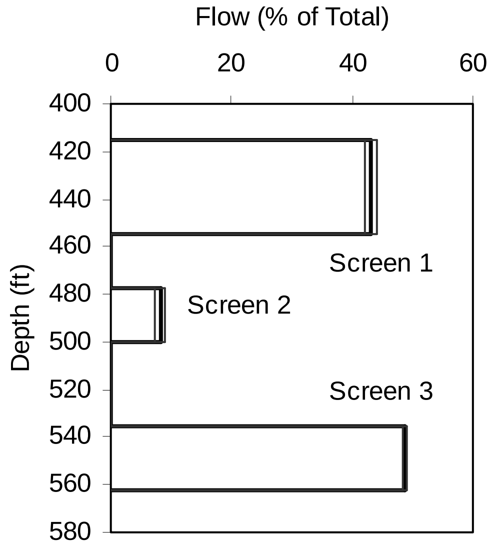

Figure 7. TDCJ Wallace Pack Unit well 4 discharge profile showing the percentage of total well production originating from all screens.

Table 17. TDCJ Wallace Pack Unit well 4 velocity profile test results. Values not associated with a screen represent results for blank sections of well casing above and between the screen intervals and indicate actual flow rates rather than average flow rates.

Screen	*Top (ft)*	*Bottom (ft)*	*Length (ft)*	Δt *(sec)*	ν^a *(ft/min)*	Q^c *(gpm)*	Q^a *(gpm)*	Q^a *(gpm/ft)*	*Q (%)*
-	350	410	60	42.0	85.6	224	-	-	-
1	415	455	40	34.9	68.7	180	97	2.41	43 ± 0.9
-	455	477	22	27.1	48.7	127	-	-	-
2	477	500	23	34.0	40.5	106	18	0.80	8 ± 0.9
-	500	535	35	50.5	41.6	109	-	-	-
3	535	562	27	-	-	-	109	4.02	49 ± 0.4

Top: test interval top depth, *Bottom*: test interval bottom depth, *Length*: test interval length, Δt: difference in arrival time between top and bottom depth dye-tracer injections (Eq. 2), ν^a: average discharge velocity in tested interval (Eq. 3), Q^c: cumulative total well discharge (Eq. 4), Q^a: average or actual interval discharge and discharge normalized by tested interval screen length (Eq. 6), *Q*: percentage of total well discharge ± uncertainty.

Table 18. TDCJ Wallace Pack Unit well 4 water quality profile test results for arsenic and major anion concentrations. Total represents well-head sample.

Screen	*Top (ft)*	*Bottom (ft)*	*As* $\mu g/L$	*Cl mg/L*	HCO_3 *mg/L*	SO_4 *mg/L*	NO_3*-N mg/L*	*F mg/L*
Total	-	-	14	95	622	< 0.1	< 0.01	0.57
1	415	455	4.7 ± 2.4	80 ± 6	532 ± 40	< 0.1	<0.01	0.73 ± 0.03
2	477	500	19 ± 18	105 ± 29	691 ± 187	< 0.1	<0.01	0.38 ± 0.16
3	535	542	23 ± 1.1	108 ± 2	708 ± 14	< 0.1	<0.01	0.45 ± 0.01

Table 19. TDCJ Wallace Pack Unit well 4 water quality profile test results for TDS and major cations. Total represents well-head sample.

Screen	*Top (ft)*	*Bottom (ft)*	*TDS mg/L*	*Na mg/L*	*K mg/L*	*Ca mg/L*	*Mg mg/L*
Total	-	-	704	258	11	32	2.3
1	415	455	597 ± 44	216 ± 16	9.0 ± 0.7	27 ± 2.0	2.4 ± 0.14
2	477	500	782 ± 211	288 ± 78	12 ± 3.3	35 ± 8.8	2.1 ± 0.40
3	535	542	803 ± 16	296 ± 6	13 ± 0.3	35 ± 0.7	2.0 ± 0.04

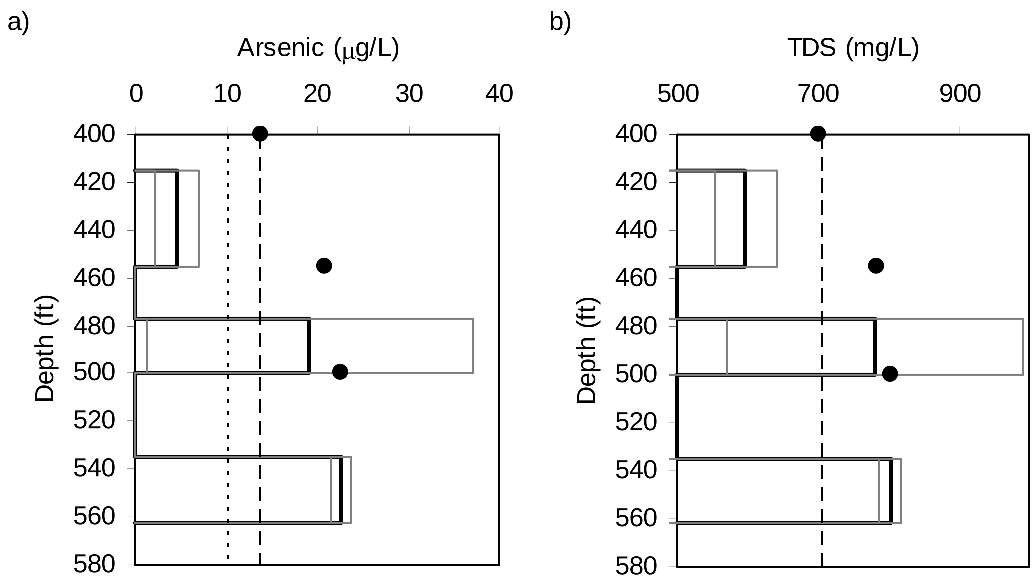

Figure 8. TDCJ Wallace Pack Unit well 4 profiles for a) arsenic and b) TDS concentrations. TDS was estimated as the sum total of major anion and cation concentrations (Tables 18 and 19). Charge balance for major constituents is within ~2% for all samples. Gray lines represent analysis uncertainty. Vertical short-dash line in (a) represents the MCL for arsenic (10 μg/L). Vertical long-dash lines represent concentrations for As (14 μg/L) and TDS (704 mg/L) in well-head samples. Points represent concentrations and depth locations of samples.

Follow-up velocity profile and water quality stratification sampling were conducted on well 4 during November 18-19, 2009 that focused only on screen 1 to verify the results described. During velocity profiling, well 4 was operated at three pumping rates to determine if there were any changes in the relative proportion of water produced from screen 1 under different pumping regimes. Results indicate that there is some variability, but no significant trend between pumping rate and relative proportion of water produced from screen 1. At pump rates between ~220 and ~425 gpm, screen 1 produced between 38 and 43% of total production (average 40%). The follow-up sampling also verified the very low arsenic concentration found during the initial test phase, with a concentration of 2.5 ± 3.0 μg/L.

These results indicate that well 4 is a candidate for possible well modification to exclude production from depths below screen 1. Alternatively, one or more new wells could be installed near well 4 that target the shallow horizon.

References

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Izbicki, J.A., 2004, A small-diameter sample pump for collection of depth-dependent samples from production wells under pumping conditions; U.S. Geological Survey Fact Sheet FS 2004-3096.