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Piezometer Effectiveness Evaluation Criterion #3

Southeast County Landfill
Lithia, Florida

Prepared for

Hillsborough County Public Works Department
Solid Waste Management Division
332 N. Falkenburg Road
Tampa, Florida 33619

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Executive Summary

Significant field work and assessment related to liquid levels in the Southeast County Landfill (SCLF) have been completed by the Hillsborough County Public Works Department, Solid Waste Management Division (SWMD) and SCS Engineers. Pelz Environmental Services, Inc. (PES) has reviewed pressure transducer data, water level readings, monthly progress reports and other relevant information provided by SCS Engineers to assist in our analysis of piezometer effectiveness. If liquid levels in piezometers (PZ) installed in the landfill are to be an appropriate metric to measure compliance with the Corrective Action Plan, the piezometers must effectively respond to the implemented corrective actions.

Based on our review of data from drawdown/recharge, pump and slug tests and other relevant information, the following conclusions can be made:

1. The water levels recorded in the piezometers vary based on location, and exhibit variable responses to dewatering activities.

2. Dewatering with pumps installed in each PZ generally achieved drawdown of liquids to depths between 2 and 3 feet, but is not likely a feasible long term solution given field and operational constraints.

3. Large dewatering wells (such as DW 1 and DW 2) have some effect on nearby piezometers. Although SB-29 is 11 feet from DW 1 and responds fairly well to pumping in DW 1, SB-30 that is 10 feet away from DW 2 shows only minimal effects from DW 2.

4. Recharge rates are significantly slower than drawdown rates. Based on the observed recharge rates, reduction of the liquid levels in the landfill may only be discernable in the PZ in the long term (e.g., years instead of months), see Table 4.

5. The piezometers appear to have a "steady state" water level. Since this "steady state" level may be a result of the landfill design (e.g., leachate collection spacing) or other uncontrollable factors (e.g., uneven clay settlement), reducing the liquids to below this level may not be possible using reasonably available methods.

6. Based on equipment limitations, PZ locations with liquid levels near or below two-foot (SB-17D, SB-18D, SB-20D, SB-21D, SB-22D, SB-23D and SB-24D) are not considered to be useful monitoring points.

Background

As required by Florida Department of Environmental Protection (FDEP) Consent Agreement #17-0058 (July 28, 2017), Hillsborough County Public Works Department, Solid Waste Management Division (SWMD) has completed several corrective actions and evaluations regarding leachate management at the Southeast County Landfill (SCLF).

As previously discussed in Pelz Environmental Services' (PES') Memorandum Report dated May 1, 2018, for piezometer (PZ) liquid level readings to be an appropriate indicator of Corrective Action Plan (CAP) compliance, the following questions must be answered affirmatively for each PZ that is proposed to be part of the monitoring system:

Criterion 1. Is the liquid level reading accurate and repeatable?
Criterion 2. Can liquid move into and out of the PZ?
Criterion 3. Can the PZ, or its location relative to a specific extraction point, effectively detect changes in liquid levels due to leachate removal (i.e., pumping)?

That report concluded that the electronic water level tape measurements are a reasonably accurate and repeatable method to determine the liquid level in the PZ (Criterion 1); and although there is variability in the responsiveness of each PZ, liquids can/do move into and out of each PZ (Criterion 2).

This report describes the actions completed to evaluate the existing (primarily Series 2) piezometers and dewatering locations specifically with respect to Criterion 3. Series 2 PZ include: SB-15D, SB-16D, SB-17D, SB-18D, SB-19D, SB-20D, SB-21D, SB-22D, SB-23D, SB-24D, and SB-28D.

Pressure transducer data, water level readings, monthly progress reports and other relevant information was provided by SCS Engineers and Hillsborough County SWMD for PES' review.

1. Field Activities

Field investigations conducted by the SWMD and SCS Engineers since late 2016 have produced an abundance of data that are useful to evaluate the dewatering actions at the SCLF. Field work most relevant to Criteria 3 is discussed briefly.[1] These activities generally consisted of removing liquids from various locations in the landfill and then observing the piezometer recharge responses.

[1] A detailed list of field activities is included in **Appendix B** of *the Corrective Action Plan,* dated May 2, 2018, prepared by SCS Engineers.

1.1. November 2016, Drawdown/Recharge tests

Liquid Assessment Findings Report, dated December 13, 2016, prepared by SCS Engineers. This report details drawdown/recharge tests conducted on landfill gas extraction wells (EW) and piezometers (SB) that existed at that time.

Locations included: EW-32, EW-39, EW-40, EW-44, EW-46, EW-48, EW-70, SB-01, SB-02, SB-03, and SB-05.

Summary: Pressure transducers and temporary submersible pumps were installed in each LFG EW and piezometer. Pumps removed liquids and the liquid levels were monitored with transducers and in-line data loggers that provided one-minute level measurements during drawdown and recovery periods. Testing was performed over approximately fifteen days.[2]

1.2. May 2017, Drawdown/Recharge tests

Locations included: SB-15D, SB-16D, SB-17D, SB-18D, SB-25D, SB-28D, SB-01, SB-29, and SB-30.

Summary: Pressure transducers were installed in each piezometer. Temporary submersible pumps placed in each piezometer were used to dewater the liquid. Liquid levels were monitored with transducers that provided level measurements (one-second intervals) during drawdown and recovery periods. Data was collected over approximately three days.

1.3. July 2017, Pump tests

Locations included: DW 1 and SB-29 (SB-29 is the PZ closest to DW 1).

Summary: After installation of dewatering wells (DW 1 and DW 2), initial field tests were conducted (DW 1 only) to ensure proper operation. Two permanent pumps were installed for normal operation in each DW. For the July 2017 test, one of the pumps was temporarily removed and a pressure transducer was installed. The other permanent pump was used to remove liquid. Liquid levels were monitored with temporary transducers installed in DW 1 and SB-29 that provided level measurements (one-second intervals) during drawdown and recovery periods. Data was collected for approximately five hours. As a result of this test, pump installation was adjusted to improve its operation.

1.4. March 2018, Pump tests

Locations included: DW 1, SB-29, DW 2, and SB-30.

Summary: For this test, one of the permanent pumps was removed from both DW 1 and DW 2, leaving one pump in each DW to remove liquid. Liquid levels were monitored with

[2] *Liquid Assessment Findings Report*, dated December 13, 2016, Section 2.3.2.

temporary transducers installed in each DW and adjacent piezometer (SB-29 for DW 1, SB-30 for DW 2). Level measurements (one-minute intervals) were recorded during drawdown and recovery periods. Data was collected over approximately fifteen days.

1.5. March/April 2018, Slug tests

"Piezometer Effectiveness Evaluation," dated May 1, 2018, prepared by Pelz Environmental Services, Inc. [Appendix C of *Corrective Action Plan,* dated May 2, 2018, prepared by SCS Engineers]. This report details slug tests conducted on Series 2 piezometers in March/April 2018.

Locations included: SB-15D, SB-16D, SB-17D, SB-18D, SB-19D, SB-20D, SB-21D, SB-22D, SB-23D, SB-24D and SB-28D.

Summary: Pressure transducers were installed in each piezometer. Clean water was pumped into each PZ. Liquid levels were recorded by the transducers (fifteen-second intervals) during liquid addition and while the added liquids dissipated through the PZ screen into the adjacent materials. Data was collected over approximately six days.

2. Results

For liquid levels measured in the PZ to be a reasonable metric for monitoring dewatering efforts, they must reflect changes within a reasonable timeframe. Drawdown rates are largely determined by pump selection and are expected to be significantly faster than recharge rates which are controlled by the characteristics of the porous media through which the liquid flows. Consequently, we focused our analysis on PZ recharge as the limiting factor.

Recharge rates estimated for the pump and drawdown/recharge tests are summarized in Table 1. The November 2016 results are as presented in SCS Engineers' report.[3] Recharge rates for the May 2017 drawdown/recharge tests and July 2017 pump tests are based on PES' review of the pressure transducer data.

The May 2017 tests generally included multiple drawdown/recharge cycles for each PZ, except for SB-01, SB-25D and SB-30 which exhibited only a single or partial recharge cycle. Figure 1 and Figure 2 illustrate a typical drawdown/recharge curve for the May 2017 tests. The rates listed in Table 1 for the May 2017 tests were determined by first graphing the data from each of the PZ. Peaks and low points that distinctly indicate pump on/pump off conditions were identified. Then for each cycle (pump on/pump off), starting and ending times, and depths were used to estimate the change in liquid depth per unit time (rate per drawdown/recharge cycle), assuming a linear relationship between liquid depth and time. Based on the average drawdown and recharge

[3] *Liquid Assessment Findings Report*, dated December 13, 2016, Table 1

times, a theoretical maximum number of cycles per day was calculated. Recharge rates based on those cycles are listed in Table 1 and Table 2.

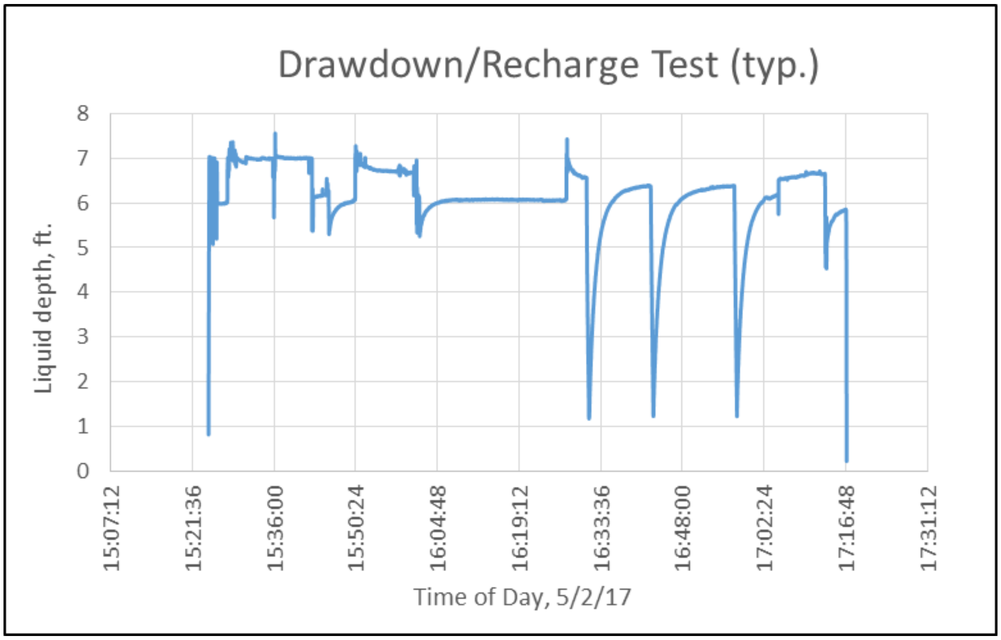

Figure 1 - May 2017 Drawdown/Recharge Test

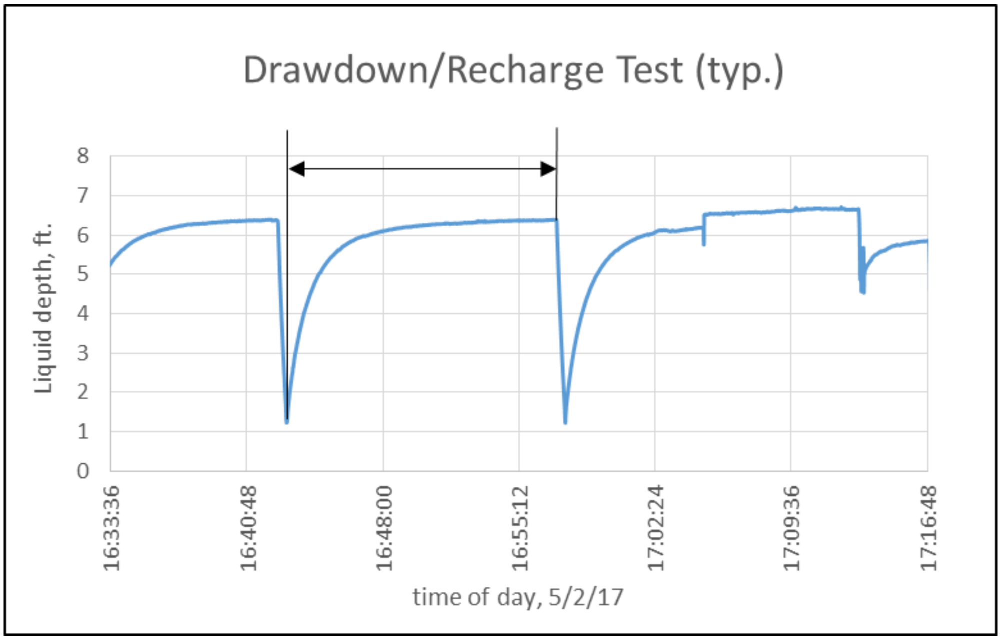

Figure 2 - May 2017 Drawdown/Recharge Test Detail

Table 1: Recharge Rate Summary			
	Nov-16 gal/day	May-17 gal/day	Jul-17 gal/day
SB-01	5	13	
SB-02	332		
SB-03	15		
SB-05	31		
SB-15D		436	
SB-16D		327	
SB-17D		111	
SB-18D		23	
SB-25D		*	
SB-28D		114	
SB-29		146	6
SB-30		230	
DW 1			1880
EW-32	419		
EW-39	83		
EW-40	180		
EW-44	828		
EW-46	161		
EW-48	735		
EW-70	154		
*	SB-25D abandoned in September 2017		

The July 2017 pump test included two cycles (two drawdowns, one recharge) for the DW 1/SB-29 locations. The March 2018 test allowed a direct comparison of SB-29 and SB-30 responses to pumping and showed that SB-29 responded more distinctly to pumping at DW 1 than SB-30 responded to pumping at DW 2. Since the March 2018 test only included one cycle (one drawdown, but incomplete recharge), recharge rates could not be accurately estimated for that test.

Table 2: Recharge Rate Calculation								
		[A]	[B]	[C]	[D]	[E]	[F]	[G]
		recharge, min/cycle	drawdown, min/cycle	Total time, min/cycle	potential cycles per 24 hour day	ave recharge depth, ft/cycle	ave recharge volume, gal/cycle	ave recharge volume, gal/day
May-17	SB-01	79	0.30	79	18	0.50	0.74	13
	SB-15D	22	1.16	24	61	4.88	7.17	436
	SB-16D	27	0.37	27	53	4.19	6.16	327
	SB-17D	30	8.17	38	38	1.98	2.90	111
	SB-18D	20	8.80	29	50	0.31	0.46	23
	SB-25D	*	*	*	*	*	*	*
	SB-28D	18	13.50	31	46	1.69	2.48	114
	SB-29	36	4.23	40	36	2.79	4.09	146
	SB-30	30	4.95	35	41	3.83	5.62	230
Jul-17								
Cycle 1	SB-29	74	32	106	13	0.31	0.45	6
	DW 1	76	29	105	13	2.73	144.60	1880
Cycle 2[1]	SB-29	95	41	137	11	0.51	0.75	8
	DW 1	109	42	151	10	2.90	153.45	1461

Note 1	Recharge during July 2017 2nd cycle was incomplete.		
SB	6-inch dia. Borehole	1.469	gal/ft height
DW	36-inch dia. Borehole	52.873	gal/ft height
*	SB-25D abandoned in September 2017		

Table 2, cont'd

[A], [B]=	May 2017 average based on identified cycles; July 2017 based on single cycle
[C]=	recharge time + drawdown time
[D]=	(60*24)/[C]
[E]=	May 2017 average based on identified cycles; July 2017 based on single cycle
[F]=	[E]*1.469 for SB, [E]*52.873 for DW
[G]=	[F]*[D]

Reported Quantities	DW 1-1			DW 1-2		
	gal pumped	days	gal/day	gal pumped	days	gal/day
Jul-17	18,259	25	730	12,681	23	551
Aug-17	23,288	31	751	7,839	29	270
Sep-17	9,645	11	877	15,939	16	996
Oct-17	2,822	1	2,822	8,580	9	953
Nov-17	35,956	30	1,199	0	0	0
Dec-17	37,376	31	1,206	0	0	0
Jan-18	30,828	30	1,028	0	0	0
Feb-18	28,499	26	1,096	0	0	0
Mar-18	23,772	25	951	6,836	15	456
Apr-18	14,203	18	789	5,252	14	375
May-18	18,003	20	900	20,603	27	763
total	242,651	248		77,730	133	
	average gal/day		1,123		average gal/day	624
	DW 1 total	1,746	average, gal/day			

Table 3: Pump Test Cycles						
	Jul-17					Mar-18
	Cycle 1			Cycle 2		Cycle 1
	Cycle time					
	Drawdown, min.	Recharge, min.	Ratio, Recharge/Drawdown	Drawdown, min.	Recharge[1], min.	Drawdown, min.
SB-29	32	74	2.32	41	95	775
DW 1	29	76	2.61	42	109	777
Ratio, SB-29/DW 1	1.09	0.97		0.98	0.87	1.00
SB-30						926
DW 2						848
Ratio, SB-30/DW 2						1.09
	Change in Liquid Depth					
	Drawdown, ft.	Recharge, ft.	Ratio, Recharge/Drawdown	Drawdown, ft.	Recharge[1], ft.	Drawdown, ft.
SB-29	0.40	0.31	0.77	0.66	0.51	3.05
DW 1	2.81	2.73	0.97	2.99	2.90	5.69
Ratio, SB-29/DW 1	0.14	0.11		0.22	0.17	0.54
SB-30						0.59
DW 2						3.17
Ratio, SB-30/DW 2						0.19
Note 1	Recharge during 2nd cycle was incomplete.					
	Values listed are calculated based on observed drawdown and ratio of recharge/drawdown.					

Figure 3 and Figure 4 show the July 2017 and March 2018 pump test results. Similar to the May 2017 drawdown tests, recharge rates were estimated for the July 2017 test and are included on Table 1 and Table 2.

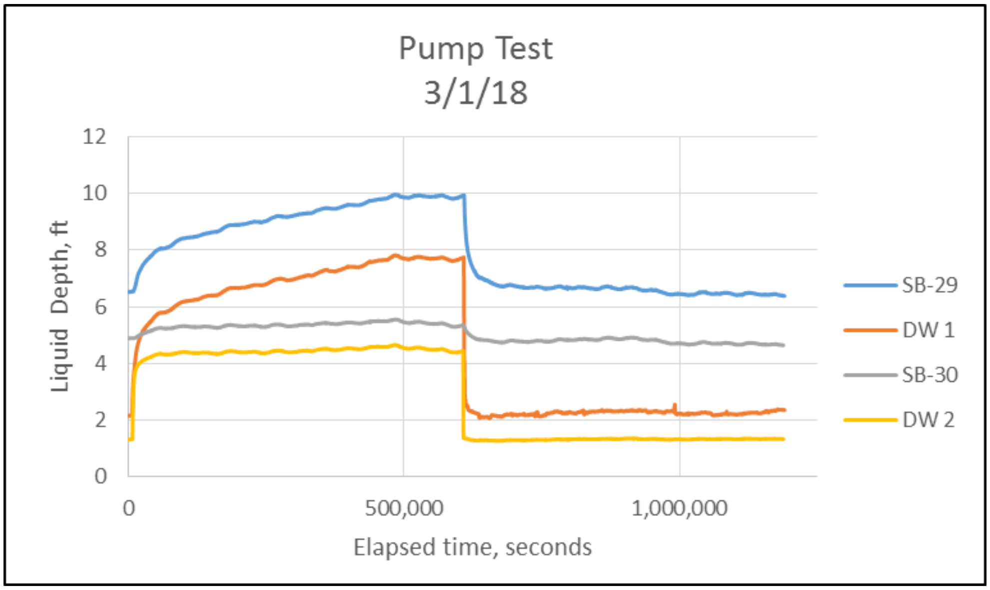

Figure 3 - March 2018 Pump Tests

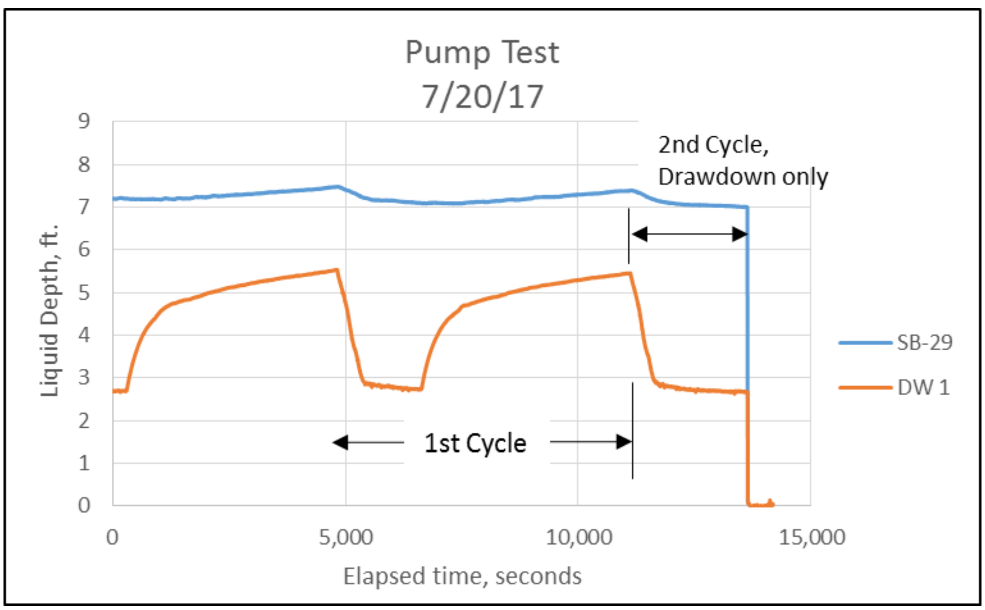

Figure 4 - July 2017 Pump Test

The March/April 2018 slug test data generally show an initial "steady state" water level, followed by a peak ("slug") and then a logarithmic decline in water level approaching a similar "steady state." Each of the PZs, except for SB-28D (discussed below) exhibited this behavior. Figure 5 shows a typical slug test curve for the March/April 2018 tests. The maximum liquid depth recorded (approximately 32 feet) is due to transducer limitations. During the test, each PZ was filled to the top of the casing. Consequently, some PZs experienced as much as 90 feet of water pressure during the slug test.

The slug tests were "slug-in" (i.e., water was added, not removed) so "recharge" rates were not determined. However, since the rate of water dissipation out of each PZ is also an indication of its ability to reflect changes in liquid levels, this response rate was estimated. Overall response rates for the slug tests are significantly influenced by the hydraulic pressure in each PZ. Since it is neither likely, nor desirable, to have the excessive hydraulic pressure (i.e., greater than 30 feet) experienced in the slug tests during normal operation, the response rate was estimated based on the linear (trailing) portion of the curve (instead of the entire curve) as more representative of long-term operation. These rates are summarized in Table 4.

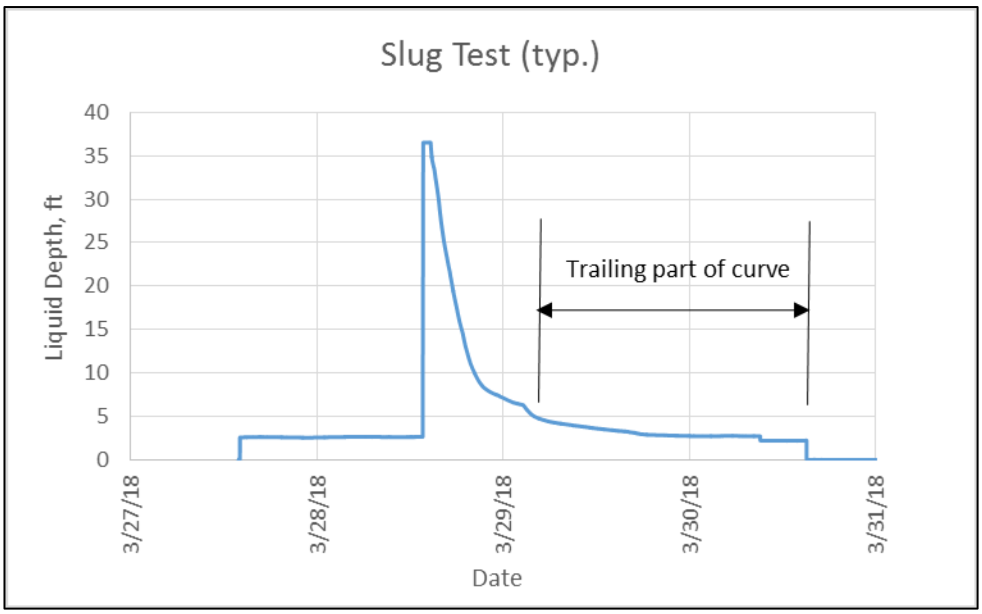

Figure 5 - Typical Slug Test Results

Table 4: Slug Test Response Rate								
	start depth (ft)	end depth (ft)	depth change (ft)	elapsed time (days)	dY/dX estimated rate (ft/day)	m	b	est. time to reach 2 ft (days)
SB-15D	8.004	6.858	1.147	0.83	-0.205	-0.17	8.2474	9.12E+15
SB-16D	6.498	6.414	0.084	2.04	-0.035	-0.07	6.422	1.12E+27
SB-17D	1.797	1.300	0.497	2.06	-0.037	-0.08	1.6598	n/a
SB-18D	2.393	2.010	0.384	2.06	-0.023	-0.05	2.2586	n/a
SB-19D	2.989	2.246	0.743	1.78	-0.414	-0.74	3.0781	n/a
SB-20D	2.302	2.049	0.253	2.05	-0.078	-0.16	2.0961	n/a
SB-21D	2.201	1.446	0.755	1.98	-0.378	-0.75	1.7641	n/a
SB-22D	2.204	1.998	0.206	2.03	-0.061	-0.12	2.0438	n/a
SB-23D	0.997	0.530	0.467	1.97	-0.012	-0.02	0.4871	n/a
SB-24D	7.000	5.778	1.222	2.06	-0.051	-0.11	5.7865	3.26E+15
SB-28D	5.999	5.381	0.618	0.11	-4.431	-0.49	4.2636	101

n/a levels were at or below 2 feet at end of test

3. Discussion

Volume estimations assume that the 2-inch PZs were constructed with 6-inch boreholes and dewatering wells (DW 1 and DW 2) were constructed with 36-inch boreholes. The formula for the volume is:

$$V = \pi r^2 h \qquad \text{[Eqn. 1]}$$

where,

V = volume (gal.)
h = liquid depth (ft.), and
r = radius of borehole (ft.).
$\frac{V}{h}$, the volume per foot of depth for each PZ is 1.469 gal/ft. Similarly, the volume per foot of depth in the DWs is 52.873 gal/ft.

3.1. May 2017 Drawdown/Recharge tests

In these tests, a small pump was placed in each PZ and liquids were removed and allowed to recharge for multiple cycles. Although the pumps were small, drawdown rates were (as expected) higher than recharge rates. The ratio of recharge time vs. drawdown time ranged from 72 (SB-16D) to 2 (SB-18D) minutes. In other words, depending on the PZ, for one minute of drawdown time, it took between 2 and 72 minutes for liquids to recharge the PZ sufficiently to begin the next drawdown cycle. SB-25D data was erratic, showing a single drawdown of 1.5 feet in 0.02 min., likely due to a transducer error. Consequently SB-25D results for this test are not included in our analysis.

The data also showed that the maximum recharge depth per cycle tended to slightly decrease over time. However, it is likely that these decreases are a result of field constraints (e.g., not enough time for levels to recharge fully) and not an indication of overall liquids reduction during the test. These tests were relatively short, ranging from 63 minutes (SB-18D) to 259 minutes (SB-15D). Some pumping cycles did not fully drawdown the PZ (i.e., the "pump off" liquid depth varied) possibly due to equipment issues such as pump overheating. As shown in Table 2, the average predicted recharge rates range from 13 gal/day (SB-01) to 436 gal/day (SB-15D). These results also suggest that SB-15D, SB-16D, SB-29 and SB-30 are relatively "productive" locations (recharge depths ranging from approximately 3 to 5 ft. per cycle) that could potentially be used for liquid extraction and/or monitoring.

These results are subject to notable limitations. Pump selection is limited due to the size of the PZ casing (2-inch dia.). Although the tests were conducted over a relatively short time, some of the pumps experienced operational issues such as overheating. Also, the extensive infrastructure (e.g., electrical power and liquid discharge piping) required for PZs to be used as extraction points would be difficult to protect and maintain in an operating landfill.

3.2. July 2017 and March 2018 Pump tests

The July 2017 and March 2018 pump tests were conducted using similar methodologies (discussed in Sections 1.2 and 1.3 above), and yielded similar results. Since these tests show the relationship between a dewatering location (DW 1, DW 2) and a nearby PZ (SB-29, SB-30), the effects, if any, of pumping can be more directly identified.

Figure 3 and Figure 4 show the responses of SB-29 and SB-30 to the pumping at DW 1 and DW 2. Although the magnitude is different, effects from pumping in DW 1 can be seen in SB-29 for both the July 2017 and March 2018 tests. As shown in Table 2, a drawdown of 2.81 ft. and 2.99 ft. in

DW 1 resulted in 0.40 ft. and 0.66 ft. drawdown in SB-29 in the July 2017 test. The March 2018 response was greater, with 5.67 ft. drawdown in DW 1 resulting in 3.05 ft. reduction in SB-29 water level.

In the July 2017 test, the initial increase seen in the graph appears similar to the recharge part of the cycle. However, since the pump on/off status and liquid level prior to data collection were unknown, it was not considered to be a recharge cycle. In other words, for the initial rise in depth to be "recharge," the pump would have to be off and the liquid level would have to be at a minimum prior to data collection. These conditions were not known. Thus, the first cycle begins with the first recorded pump "on" (decline in liquid levels) condition and ends just before then next pump "on" condition.

The cycle time for the initial cycle in July 2017 for SB-29 and DW 1 were approximately equal (between 105 and 106 minutes), potentially resulting in approximately 13 cycles per day. As expected, since the pump was located in DW 1, the liquid level decreased 2.73 ft. in DW 1, but only 0.31 ft. in SB-29 in the first cycle. Accounting for differences in the well sizes, the recharge rates were 0.45 gal/day for SB-29, and 144.60 gal/day for DW 1.

The second cycle included full drawdown, but only partial (if any) recharge. The drawdown for the second cycle was greater than the first cycle, and may be due to initial flushing of the dewatering well or other field adjustments.

Recharge data for the second cycle was not recorded. However, it is reasonable to expect that the recharge/drawdown characteristics for the second cycle would be similar to the first cycle. Assuming the ratio of recharge time to drawdown time (recharge/drawdown) is the same as the first cycle, the second cycle time and volume was estimated (see Table 2 and Table 3). Based on time recorded for Cycle 1, 13 cycles (drawdown and recharge) per day could be achieved, resulting in 1,880 gallons/day of liquid removal. Estimates for Cycle 2 were 10 to 11 cycles per day resulting in approximately 1,461 gal/day of liquid removal. As summarized in Table 2, liquid removal reported for DW 1 from July 2017 through May 2018 averaged 1,746 gal/day, which correlates reasonably well with our analysis.

In the March 2018 pump tests, the pumps in DW 1 and DW 2 were turned off and rising liquid levels were recorded for several days. The pumps were turned back on and drawdown data was recorded. The transducers were removed and normal automatic pumping operation resumed. Consequently, recharge data for the March 2018 tests is not available. Since it was necessary to allow liquids to accumulate over several days, daily cycle times could not be accurately estimated for this test.

As shown in Figure 2, SB-29 responded to DW 1 similar to its response in the July 2017 test. SB-30 showed a small response to DW 2 in the March 2018 test. Although the tests were conducted concurrently, initial liquid levels in SB-29 and DW 1 increased at a faster rate than SB-30 and DW 2. The liquid depths in SB-29 and DW 1 were also greater than in SB-30 and DW 2. This suggests that liquids flow to and are extracted more readily in the vicinity of SB-29/DW 1 than in the area of SB-30/DW 2. These results are confirmed by the monthly progress reports that consistently show more liquid is removed from DW 1 than from DW 2.

Although recharge behavior is the limiting factor in evaluating the PZs effectiveness, recharge data for March 2018 is not available. Examination of the drawdown data (see Table 3) shows that the time required to drawdown SB-30/DW 2 is slightly longer than SB-29/DW 1, but the difference in liquid depth drawdown is notable. The liquid level response for SB-29 to DW 1 was 0.54 ft./ft. In other words, for every foot of drawdown in DW 1, liquid depth in SB-29 decreased by approximately 0.54 ft. The response for SB-30 and DW 2 was significantly lower, at 0.19 ft./ft. Assuming the liquid level during drawdown has a linear relationship with respect to time, the rate (drawdown depth divided by time) in SB-29 is estimated to be 0.00394 ft./min and SB-30 is 0.00064 ft./min. Since recharge times may be conservatively estimated to be two to three times slower than drawdown times, the rate during recharge is estimated to be one-half to one-third the drawdown rate. Thus, SB-29 recharge could range between 0.00131 ft./min. [0.00394/3] and 0.00197 ft./min., and SB-30 recharge could range between 0.00021 ft./min. and 0.00032 ft./min. It should be noted that since the data show that dewatering activities typically follow logarithmic/exponential relationships, these values suggest faster recharge than would actually occur.

In the March 2018 test, the liquid level in SB-29 decreased 3.05 ft. in response to a decrease of 5.67 ft. in DW 1. This ratio, 0.54 indicates a much more significant influence on SB-29 from pumping than in the July 2017 test, but may be a result of the duration of the data collection (fifteen days in March 2018 vs. four hours in July 2017). A similar ratio for SB-30/DW 2 for March 2018 is 0.19. Based on the results from these pump tests, dewatering efforts in DW 2 may be minimally detected in SB-30, but DW 1 pumping is more easily identified in SB-29.

In both pump tests (July 2017 and March 2018), pumping reduced liquid levels until an apparent "steady state" level was achieved. As shown in Figure 4, the "steady state" (pump off) level for DW 1 and DW 2 is approximately two feet based on pump operational constraints. Consequently, liquid levels are not expected to fall below that level in DW 1 or DW 2. Based on Figure 4, the levels to which SB-29 and SB-30 appear to rebound, are approximately liquid depths of seven feet (SB-29) and five feet (SB-30). This apparent "steady state" liquid level is discussed in more detail in Section 4.4 below.

3.3. April/March 2018 Slug tests

Figure 4 shows a typical slug test curve. The rates are similar for all PZs except SB-28D. Due to a pressure transducer malfunction in the March test in SB-28D, the test was re-run on April 4th. During the April event, a slug of water was introduced into the PZ multiple times instead of only once as in the March tests. Figure 6 shows the results of the April re-test of SB-28D. Data was recorded the same as the March tests.

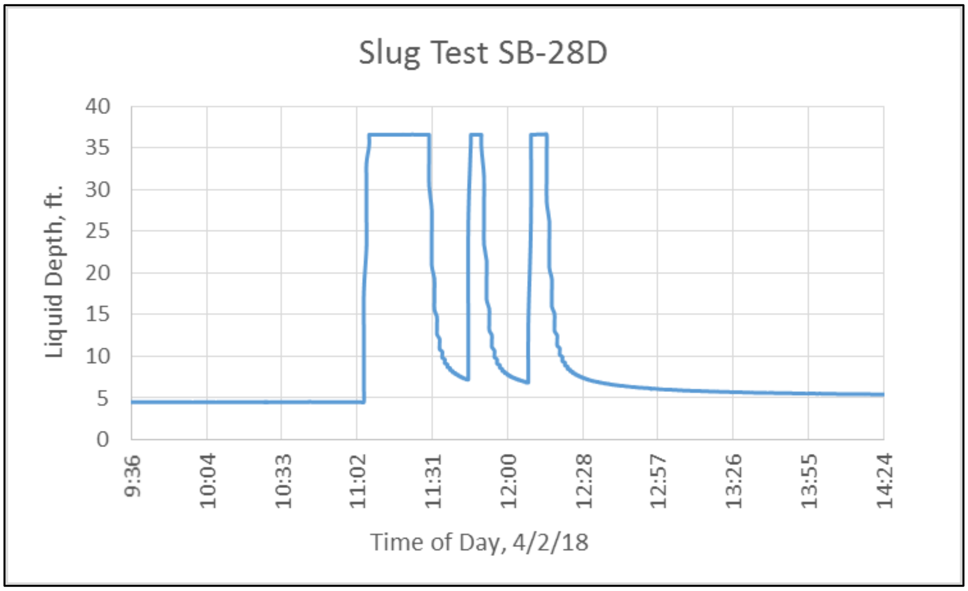

Figure 6 - SB-28D Slug Re-test

Each of the PZs generally responded to the slug with a logarithmic decline in liquid depth vs. time. The data for each test was graphed, and a best equation for the long-term decline was determined. The equations were of the form:

$$y_{slug} = m\ ln(x) + b \qquad \text{[Eqn. 2]}$$

where

y_{slug} = liquid depth (ft.)

x = elapsed time (days)

m, b = constants steepness of the curve and intercept.

Rearranging equation [2],

$$y_{slug} - b = m\,ln(x) \qquad \text{[Eqn. 3]}$$

The derivative of the equation represents the instantaneous slope of the function at a given selected point. In this case, the rate of depth change with respect to time. Taking the derivative of liquid depth with respect to *x* (time), the equation can be rewritten as,

$$\frac{d}{dx} y_{slug} - \frac{d}{dx} b = m * \frac{d}{dx}(ln(x)) \qquad \text{[Eqn. 4]}$$

Since *b* is a constant its derivative equals 0, leaving

$$\frac{d}{dx}(y_{slug}) = m * (\frac{d}{dx}\ln(x))$$

Since $\frac{d}{dx}\ln(x) = \frac{1}{x}$, the rate of change of liquid depth can be expressed as:

$$\frac{d}{dx}(y_{slug}) = \frac{m}{x} \qquad \text{[Eqn. 5]}$$

Example:

For SB-15D, the best fit equation (R^2=0.9485), b=8.2474, m=-0.17 and x=0.83 days, so the long-term rate of liquid decline is,

$$y_{slug} = -0.17\,ln(x) + 8.2474$$

$$y_{slug} - 8.2474 = -0.17\,ln(x)$$

$$\frac{d}{dx} y_{slug} - \frac{d}{dx} 8.2474 = -0.17 * \frac{d}{dx}(ln(x))$$

$$\frac{d}{dx}(y_{slug}) = \frac{-0.17}{0.83} = -0.205\,ft/day$$

Table 4 includes the calculated response rates and constants, *m* and *b*. The calculated rates represent the rate at the end of the slug test. Since the retest in SB-28D included multiple slugs, the time elapsed for each slug was relatively short resulting in the calculated rate for SB-28D being significantly skewed. The data show that liquid depths continue to decline logarithmically with time, approaching a horizontal asymptote. This "steady state" liquid level is discussed in Section 4.4 below.

4. Predicting Piezometer Liquid Levels

4.1. Darcy's Law

Assuming that the assumptions for Darcy's law are true for flow within the landfill drainage sand, the liquid levels in the PZ can be estimated. Darcy's law is the basis for fluid flow in a porous media, and is expressed as:

$$Q = kiA \quad \text{[Eqn. 6]}$$

with

$$i = \frac{h_1 - h_2}{L} \quad \text{[Eqn. 7]}$$

where,

Q = flow through porous media ($ft.^3/s$),
k = hydraulic conductivity of the porous media (ft./s),
i = hydraulic gradient (dimensionless)
h_1 = depth of liquid, location 1 (ft.)
h_2 = depth of liquid, location 2 (ft.)
L = distance between locations 1 and 2 (ft.), and
A = cross-sectional area of porous media perpendicular to flow (ft^2).

The flow velocity (also called the Darcy flux), $\frac{Q}{A}$ (ft./s) can be determined between locations, and travel time can be estimated. Based on surveyed locations, SB-29 is approximately 11 feet away from DW 1 and SB-30 is approximately 10 feet away from DW 2.[4] Recent tests[5] of the landfill drainage sand indicate that the hydraulic conductivity of the sand currently ranges from 3.5 x 10^{-3} cm/s (1.15 x 10^{-4} ft./s) to 5.8 x 10^{-3} cm/s (1.90 x 10^{-4} ft./s).

[4] Boring-Piezometer construction data provided and confirmed by SCS Engineers in April/May 2018
[5] Data provided by SWMD via email July 12, 2018

In the July 2017 pump test, recharge began at Cycle 1 “pump off.” The liquid depth in SB-29 at this “pump off” time was 7.08 ft., and the depth in DW 1 was 2.72 ft. Since the distance between these locations is 11 ft., the gradient was 0.3969 [(7.08-2.72)/11]. Using an average (1.50×10^{-4} ft./s) of hydraulic conductivities noted above, *Q/A* is 3.57×10^{-3} ft./min. It would take approximately 2 days for liquid to travel from SB-29 to DW 1 (at gradient=0.3969) based on gravity drainage only and assuming no other influences (i.e., rainfall). Since the operating minimum liquid level in DW 1 is approximately two feet, the estimated time assumes the pumps are operating normally. Table 5 shows that based on the July 2017 and March 2018 pump tests, SB-29/DW 1 travel time is also estimated to be two days.

4.2. Radius of Influence

For the effects of liquid removal to be observable in the PZ, the pumping location must be within a certain distance of the PZ. This distance, the radius of influence (R_0), is the distance at which the drawdown from the pumping location is effectively zero. For our analysis, since the leachate collection system operation is based on flow through a porous media (i.e., drainage sand), fluids in the landfill are assumed to behave similarly, and were modelled using equations for flow in an unconfined aquifer. It is important to note that the radius of influence calculation is based only on the hydraulic conductivity of the porous media and the difference in the liquid levels at the points of interest. Time is not a factor.

To estimate the radius of influence, R_0, Sichardt's[6] equation provides a reasonable approximation.

$$R_0 = 3000\,(H_0 - h_w)\sqrt{k} \qquad \text{[Eqn. 8]}$$

where,
R_0 = Radius of influence (m)
H_0 = Liquid depth at R_0 (m)
h_w = Liquid depth at theoretical pumping location (m), and
k = hydraulic conductivity of the porous media (m/s).

[6] Referenced in “EXHIBIT III, CALCULATION METHODS FOR RADIUS OF INFLUENCE AND DEWATERING FLOW RATE FROM AQUIFER TEST DATA,” Broward County Florida, Environmental Protection and Growth Management Department, Pollution Prevention, Remediation and Air Quality Division, found at [accessed May 17, 2018]: http://www.broward.org/Environment/ContaminatedSites/Documents/sopexhibitiii1209.pdf

Table 5: Travel Time Predictions

Based on pump tests

	Distance between L (ft)	Difference in depth H_0-h_w (ft)	Gradient i (-)	$\frac{Q}{A}=ki$ (ft/min)	Estimated time (days)	Difference in depth h_2-h_1 (ft)	Gradient i (-)	$\frac{Q}{A}=ki$ (ft/min)	Estimated time (days)
	July 2017 pump test					March 2018 pump test			
SB-29/DW 1	11								
Cycle 1		4.37	0.3969	3.57E-03	2	4.83	0.4394	3.95E-03	2
Cycle 2		4.26	0.3875	3.48E-03	2				
SB-30/DW 2	10					3.50	0.3501	3.15E-03	2

Based on radius of influence

Assume: Distance between PZ and pumping well, L = R_0

Liquid depth at theoretical pumping well (h_w) assumed to be 2 ft

Max. depth at PZ (H_0) based on monthly reporting for January through May 2018

k_{ave}= 4.57E-03 cm/s; 1.50E-04 ft/s; 8.99E-03 ft/min

	L (ft)	H_0 (ft)	H_0-h_w (ft)	i (-)	Q/A=ki (ft/min)	estimated time, L/ki (min)	estimated time, L/ki (days)
SB-15D	109	7.40	5.4	0.0493	4.44E-04	2.47E+05	171
SB-16D	93	6.60	4.6	0.0493	4.44E-04	2.10E+05	146
SB-17D	79	5.90	3.9	0.0493	4.44E-04	1.78E+05	124
SB-18D	18	2.90	0.9	0.0493	4.44E-04	4.11E+04	29
SB-19D	n/a, H_0 less than 2 ft						
SB-20D	32	3.60	1.6	0.0493	4.44E-04	7.31E+04	51
SB-21D	4	2.20	0.2	0.0493	4.44E-04	9.14E+03	6
SB-22D	4	2.20	0.2	0.0493	4.44E-04	9.14E+03	6
SB-23D	4	2.20	0.2	0.0493	4.44E-04	9.14E+03	6
SB-24D	77	5.80	3.8	0.0493	4.44E-04	1.74E+05	121
SB-28D	77	5.80	3.8	0.0493	4.44E-04	1.74E+05	121
SB-29	158	9.80	7.8	0.0493	4.44E-04	3.56E+05	248
SB-30	83	6.10	4.1	0.0493	4.44E-04	1.87E+05	130

Table 6: Radius of Influence

	H_0	h_w	H_0-h_w	H_0-h_w	R_0	R_0
	ft	ft	ft	m	m	ft
Pump test data:						
max. depth at PZ (H_0)						
min. depth at DW (h_w)						
Jul-17						
SB-29/DW 1						
Cycle 1	7.48	2.72	4.76	1.45	29	97
Cycle 2	7.39	2.47	4.92	1.50	30	100
Mar-18						
SB-29/DW 1	9.95	2.06	7.89	2.40	49	160
SB-30/DW 2	5.36	1.27	4.09	1.25	25	83

k= 4.57E-03 cm/s
k= 4.57E-05 m/s

Hypothetical Prediction:

Max. depth at PZ (H_0) based on monthly reporting for January through May 2018

Liquid depth (h_w) at theoretical pumping well (*DW_t*) assumed to be 2 ft

	H_0	h_w	H_0-h_w	H_0-h_w	R_0	R_0
	ft	ft	ft	m	m	ft
SB-15D	7.4	2	5.4	1.65	33.37	109
SB-16D	6.6	2	4.6	1.40	28.42	93
SB-17D	5.9	2	3.9	1.19	24.10	79
SB-18D	2.9	2	0.9	0.27	5.56	18
SB-19D	1.9	2	n/a, H_0 less than 2 ft			
SB-20D	3.6	2	1.6	0.49	9.89	32
SB-21D	2.2	2	0.2	0.06	1.24	4
SB-22D	2.2	2	0.2	0.06	1.24	4
SB-23D	2.2	2	0.2	0.06	1.24	4
SB-24D	5.8	2	3.8	1.16	23.48	77
SB-28D	5.8	2	3.8	1.16	23.48	77
SB-29	9.8	2	7.8	2.38	48.20	158
SB-30	6.1	2	4.1	1.25	25.33	83

Using this equation and the average hydraulic conductivity of the drainage sand ($k=4.57 \times 10^{-5}$ m/s), two conditions were examined. Table 6 includes the results of these calculations. First, using the July 2017 and March 2018 pump test data, R_0 for SB-29 and SB-30 were calculated. R_0

for SB-29 ranged from 97 to 160 ft., and SB-30 (only one data set) was estimated to be 83 ft. Although the data for SB-30 is limited, these results suggest that in order for SB-30 to effectively detect changes from pumping, it should be located no greater than 83 feet away from a dewatering well. Similarly, SB-29 may be located as much as 100 to 160 feet away from a dewatering well.

Next, the maximum distance (R_0) from a theoretical pumping well ("DW_t") to each piezometer was estimated. This calculation assumed the greatest liquid depth reported for each piezometer from January through May 2018 and that the pumping location would have a minimum of two feet of liquid based on pump intake constraints (such as in DW 1 and DW 2).

Not surprisingly, Table 6 shows that the R_0 for SB-29 and SB-30 based on maximum reported liquid depths are consistent with the R_0 calculated from the pump test data. Since the maximum liquid depths reported for SB-18, SB-19D, SB-21D, SB-22D and SB-23D are close to two feet (the minimum level in DW_t), those locations are not expected to provide meaningful information for measuring long-term compliance. SB-15D (109 ft.) and SB-16D (93 ft.) are within the range estimated for SB-29 and SB-30. SB-17D, SB-24D and SB-28D are similar and may respond to changes within 75-80 ft. of DW_t.

4.3. Time Considerations

The calculations presented in Table 6 suggest that certain PZs (SB-15D, SB-16D, SB-17D, SB-24D and SB-28D) may respond to pumping if DW_t is within a reasonable distance. However, when travel time is considered, the number of potentially useful locations is more limited.

Using the same assumptions as the radius of influence calculations (e.g., h_w=2 ft., H_0=max. reported liquid depth) and assuming that the distance between DW_t and the PZ is equal to R_0, the time for liquids to move between DW_t and the PZ were estimated and are shown in Table 5. Since R_0 and the gradient are based on differences in liquid depths and L is assumed to equal R_0, the gradient between each PZ and DW_t are all equal to 0.0493 ft./ft. The estimated times vary due to differences in R_0.

Based on pump tests, travel times between SB-29/DW 1 and SB-30/DW 2 are estimated to be two days. Based on radius of influence, the travel time between SB-29 and DW_t located 158 ft. away would be 248 days. Since the actual distances between these PZs and DWs are significantly less, the travel time is expected to be significantly less.

Travel times based on the slug test results were also estimated. These predictions assume the target liquid depth in the PZ is two feet (based on theoretical pump intake limitations), and that the liquid level follows a logarithmic decline with respect to time. Predictions were not necessary for the PZs for which liquid levels had already declined to two feet or less during the test. Table 4 shows that the estimated time for SB-28D was 101 days, and for all practical purposes, SB-15D, SB-16D and SB-24D cannot reach the two-foot level.

4.4. Apparent "Steady State"

Results of the each of the field investigations suggest that the liquid depths in the PZ have an apparent "steady state" level. To estimate this "steady state" level, several approaches were used.

First, for the slug tests, the starting (pre-slug) and ending liquid depths were compared for each of the piezometers. Although the depths were not the same for each PZ, the *differences* between the starting and ending depths were small (less than one foot) for all PZs except SB-15D (1.147 ft.) and SB-24D (1.222 ft.). This suggests that each PZ has a minimum liquid depth below which dewatering efforts would have limited success.

Next, examination of the data revealed that certain liquid depths (specific to the PZ) appear in the data much more frequently than other depths. Since these values could represent a "steady state," frequency distributions were created for each PZ for each of the tests (drawdown, pump, slug). Each data point was assigned to a "bin" based on the depth recorded at that point. The "bins" were in 0.1 ft. increments from 1.0 ft. through 11.9 ft. depths, and 1 foot increments from 12.0 ft. through 34 ft. depths. The "bin" with the most number of data points (i.e., highest frequency) is identified as the "steady state" based on this procedure. Table 7 shows that the apparent "steady state" for SB-17D, SB-18D, SB-19D, SB-20D, SB-21D, SB-22D and SB-23D is below 2 feet. In general, the other PZ show declining trends over time from May 2017 (drawdown) through April 2018 (pump and slug tests), except for SB-15D and SB-16D. When comparing the "steady state" predicted by the May 2017 pump tests and the March/April slug tests, a slight increase in "steady state" is seen for SB-15D and SB-16D. This may be due to the relatively short duration of the May 2017 test.

Table 7: Apparent "Steady State" Liquid Depths							
	Frequency of Data				Weekly Liquid Level Reporting, Averages		
	May 2017 Drawdown tests (ft.)	Pump tests July 2017 (ft.)	Pump tests Feb/March 2018 (ft.)	Slug tests March/April 2018 (ft.)	June 2016-May 2017 (ft.)	June 2017-June 2018 (ft.)	January 2018-June 2018 (ft.)
SB-01	11				10.39	10.08	9.34
SB-15D	6.1			6.8	8.26	7.20	6.85
SB-16D	6.1			6.4	7.20	6.35	6.24
SB-17D	4.5			1.6	5.08	5.21	4.27
SB-18D	3.3			2.2	3.30	3.00	2.14
SB-19D				2.6	1.60	1.97	1.69
SB-20D				2.0	2.07	2.67	3.14
SB-21D				1.3	2.10	2.13	1.94
SB-22D				2.0	1.64	1.89	1.77
SB-23D				<1.0	2.34	2.23	2.08
SB-24D				5.7	4.47	5.78	4.90
SB-25D	*	*	*	*	*	*	*
SB-28D	5.9			4.5	4.57	5.04	4.86
SB-29	9.6	7.1	6.6		12.26**	8.48	8.39
SB-30	5.2		4.8		6.85	6.10	5.73

Average liquid depths for three time periods (June 2016 through May 2017; June 2017 through June 2018; and January 2018 through June 2018) were also reviewed. The initial liquid level assessments and much of the field work was completed between June 2016 and May 2017. June 2017 through June 2018 reflects liquid level reduction progress for the first year. Comparison of average liquid levels initially (June 2016/May 2017) to current levels (January 2018/June 2018) illustrates that average liquid levels in the majority of the PZs have declined. Also, current averages suggest the levels in SB-16D, SB-18D, SB-19D, SB-22D and SB-24D are near or below the estimated “steady state” level. Consequently, the levels in these PZs are not expected to decline significantly from the current levels. Average liquid levels in SB-15D, SB-17D, SB-21D, SB-23D, SB-28D, SB-29 and SB-30 are currently above, but are generally declining toward, the estimated “steady state.” Although the average liquid levels in SB-20D appear to have increased from initial values, weekly readings (reported monthly to FDEP) show that the levels have been trending downward since March 2018 toward the "steady state" depth of two feet.

5. Conclusion

As proposed in our May 2018 memorandum, piezometer effectiveness (Criterion #3) has been evaluated with respect to the following:

1. What is the response rate for each PZ?
2. Which, if any, existing PZ respond to leachate removal by the existing system in a timeframe that would be reasonable for monitoring?
3. What dewatering system configuration is reasonable to meet the objectives of the CAP?

5.1. Response rate for each PZ

Drawdown/recharge, pump and slug test results show that liquid levels in the PZs respond variably to dewatering activities. Recharge occurs much slower than drawdown, and is therefore the controlling factor. SB-15D, SB-16D, SB-29 and SB-30 exhibited the highest recharge rates based on the May 2017 drawdown/recharge tests ranging from an average of 146 gal/day to 136 gal/day.

Pump tests showed that the SB-29 response to DW 1 pumping is more significant than the SB-30 response to DW 2 pumping. Radius of influence (R_0) was estimated for each PZ and a theoretical dewatering well. R_0 for SB-15D, SB-16D, SB-17D, SB-24D and SB-28D were estimated to be between 75 to 110 feet. The R_0 distances estimated for the other PZs were small.

Although the slug tests did not include "recharge," the rate of change of liquid dissipation was estimated. Based on the logarithmic decline of liquid depth with respect to time, the response rates ranged from -0.378 ft./day (SB-21D) to -0.012 ft./day (SB-23D).

5.2. Response timeframes

Response timeframes were estimated for each PZ. Generally, the time required for recharge is two to three times as long as the drawdown time. Assuming a linear relationship between the liquid depth and time, the drawdown/recharge tests show that SB-15D, SB-16D, SB-28D, SB-29 and SB-30 exhibit the highest number of potential drawdown/recharge cycles per day, ranging from 36 cycles (SB-29) to 61 (SB-15D) cycles per day. Theoretically, the greater the number of cycles, the more liquid can be removed. However, it is important to note that these results are based on small pumps placed in each PZ that would not likely achieve these high number of cycles. The pump test results indicate that 10 to 13 drawdown/recharge cycles may be completed per day.

Experience from existing dewatering wells has shown that removal of liquids less than two feet deep is impractical based on equipment limitations. Assuming liquids below two-foot depth cannot feasibly be removed, the slug test data was used to estimate the time necessary for the liquid depth to decline to two feet in each PZ. PZs that had reached two-foot or less at the end of the slug test were not included. Liquid in SB-28D was estimated to reach two feet depth is approximately 100 days. Based on the assumptions used, liquid levels in SB-15D, SB-16D and SB-24D are not expected to reach two-feet.

Based on hydraulic gradient, drainage sand hydraulic conductivity, and estimated R_0, travel times from each PZ to a theoretical dewatering well placed at/near the R_0 (between 75-110 ft. of the PZ) were calculated. The PZs with liquid depths approximately two-feet were not included. The travel times ranged from 29 days (SB-18D) to 171 days (SB-15D), and are based on no other external influences occurring, e.g., rainfall.

5.3. Proposed configuration

Based on equipment limitations, PZ locations with liquid levels near or below two-foot are not considered to be useful monitoring points. Based on our analysis, SB-17D, SB-18D, SB-20D, SB-21D, SB-22D, SB-23D and SB-24D are not likely to provide information necessary to confirm compliance with the Consent Agreement.

Although SB-15D and SB-16D theoretically could be used for monitoring, response times are expected to be relatively long. Additionally, since the liquid depths are near or approaching their apparent “steady state,” installation of an additional dewatering well is likely to have limited benefit.

Based on our analysis, while liquid levels in certain PZs respond in varying degrees to dewatering activities, the following significant limitations must be considered:

- The measurements may not reflect changes until extended periods of time have elapsed;
- It may not be reasonably feasible to remove liquids below a “steady state” level;
- The long-term monitoring and maintenance of the PZ may be difficult due to operational constraints (i.e., active landfilling); and
- The measurements may be subject to other factors (discussed by others).