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OPERATION AND ANALYSIS OF THE BEHIVS SYSTEM AT EDWARDS AIR FORCE BASE

FINAL REPORT

by

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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

List of Acronyms, Unit Abbreviations, and Chemical Compound Names

AFB	Air Force Base
ASAP	Automated Sampling and Analysis Platform
AW	ratio of air to water flow rates (dimensionless)
BEHIVS	Bioenhanced In-Well Vapor Stripping
BIOFEM	computer simulation model used to analyze BEHIVS system
BIO1	well designated as SU44-BIO1 or biotreatment well 1
BIO2	well designated as SU44-BIO2 or biotreatment well 2
BT	biotreatment
cDCE	cis-1,2-dichloroethene
DO4	vapor-stripping well designation, (L) lower monitoring depth and (U) upper monitoring depth (the 4th vapor stripper demonstration well on Site 19)
FID	flame ionization detector
gpm	gallons per minute
IWVS	vapor stripping well (in-well vapor stripper)
MCL	Maximum Contaminant Level
µg/L	micrograms per liter
mg/L	milligram per liter
MW21	pre-existing monitoring well number designations (MW21, MW22, MW23)
N01-N20	BEHIVS project monitoring well numbers, each has an upper (U) and lower (L) sampling elevation
Phases 1-4	BEHIVS construction, demonstration, post-demonstration monitoring, and analysis periods
PID	photo ionization detector
scfm	standard cubic feet per minute
SERDP	Strategic Environmental Research and Development Program
SR	stripping ratio, or in-well single-pass concentration reduction
TCE	trichloroethene
VOC	volatile organic compound
1,1-DCE	1,1-dichloroethene

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1.0 BACKGROUND

The bioenhanced in-well vapor stripping (BEHIVS) system involved two innovative technologies in combination, cometabolic bioremediation and in-well vapor stripping, for treatment of a source of trichloroethene (TCE) contamination in groundwater. This system concept evolved from former demonstrations of each technology alone at Edwards Air Force Base (AFB). A realization of the potential of using these two technologies in combination to treat a high-concentration source of TCE arose from the successful results of each of these processes for in-situ treatment of a lower concentration TCE groundwater plume at Edwards Air Force Base Site 19 (McCarty et al., 1998; Gorelick and Pinto, 1997.) Funding was subsequently received from the Strategic Environmental Research and Development Program (SERDP) of the Department of Defense for construction of a BEHIVS system to treat the TCE source at Site 19, where TCE concentrations as high as 8 mg/L occur. SERDP also provided funds for the construction of an extensive monitoring system so that the BEHIVS performance could be thoroughly evaluated. The construction of the BEHIVS and associated monitoring systems neared completion at the end of December 2000, with additional support from Edwards AFB through their contractor, Earth Tech, Inc. Funds for operation and evaluation of the system were then requested from Edwards AFB, and a subcontract for this purpose was received on June 27, 2001, by Stanford University from Earth Tech, Inc. This final report summarizes the results of operation of the BEHIVS system at Edwards Air Force Base, numerical modeling analysis of the results, study conclusions, and recommendations for application of the BEHIVS system elsewhere as well as for remediation of the chlorinated solvent contamination at Site 19.

2.0 BEHIVS SYSTEM DESCRIPTION

The BEHIVS system involved three treatment wells; an upgradient vapor stripping well to reduce the TCE source concentrations (ranging from 6 to 10 mg/L) to levels that enable two biotreatment wells, located about 8 m downgradient to remove TCE to near regulatory levels with no need to pump contaminated groundwater to the surface for treatment. A schematic diagram of the system is illustrated in Figure 1. Groundwater was air-lift pumped through the vapor stripping well in an upward direction and mechanically pumped downward through the biotreatment wells, causing horizontal circulation between the vapor stripping and biotreatment wells. Air injection into the vapor stripping well caused groundwater to move in an upward direction through air-lift action, and at the same time, TCE was air stripped from the liquid to the gaseous phase. The air and water were separated at the surface, the partially treated groundwater returning to the aquifer and the TCE-contaminated air were passed through an activated carbon canister for removal of TCE. At the biotreatment wells, toluene, oxygen, and hydrogen peroxide were injected into groundwater entering the upper screens and the mixture was pumped downward to return to the aquifer through lower screens. Toluene-utilizing bacteria in the lower aquifer consumed toluene and oxygen while cometabolically biodegrading TCE. The TCE removal that resulted was monitored using an automated system (Automated Sampling and Analysis Platform, ASAP) that could collect and analyze samples around the clock at 61 points, providing shallow and deep coverage over an area of approximately 50 m by 60 m. A plan view showing the location of the monitoring and treatment wells at Site 19 is provided in Figure 2. A more detailed description of the treatment system construction appears in Appendix A.

3.0 PHASES OF EVALUATION

The evaluation proceeded in four phases. Phase one, final construction of the BEHIVS and monitoring systems and systems testing, was completed by August 12, 2001. The second phase, which began August 13, 2001, lasted about five months. This is represented by days 0 to 167 of operation. Initial operation of the vapor stripping well began at groundwater flow rates of about 30 liters/min (7.9 gpm) with the biotreatment wells pumping at 7.6 liters/min (2 gpm), but without toluene injection. The objective was to reduce TCE concentrations at the biotreatment wells to below a non-inhibitory level of 1 mg/L. This was achieved early in October 2001. From then through January 26, 2002, toluene, oxygen, and hydrogen peroxide were added into the lower aquifer to create bioactive zones of TCE degradation. During November, the biotreatment wells pumped at increased flows of 15 liters/min (4 gpm), toluene was increased gradually to about 12 mg/L, and hydrogen peroxide addition began. The operation of the in-well vapor stripping well was stopped on January 7, 2002 after nearly five months of operation. However, the biotreatment wells were operated through most of January in order to conduct a final bromide tracer study at biotreatment well two. Toluene addition was stopped at both wells on January 26, and the addition of oxygen and hydrogen peroxide was stopped two days later on January 28. At this time the pump operation was also stopped. This was the official end of phase two and beginning of phase three.

The purpose of phase three, which began January 28, 2002, (day 168) was to determine the rate, extent, and location of a possible rebound in the TCE concentrations in an effort to characterize sources of contamination at Site 19. Phase three lasted through June 20, 2002 (day 311). During this phase, the BEHIVS system was not operated, but samples were collected periodically at the various sampling locations to detect changes in TCE concentrations.

During phase two of system operation, a series of bromide tracer tests were conducted to help define the recirculatory flow system. During November, the first bromide study was carried out by adding approximately 400 mg/L bromide to the water passing up through the air stripping well. A bromide study was conducted at biotreatment well one (designated as SU44-BIO1 and referred to conveniently as Bio1) in December, and another at biotreatment well two (designated as SU44-BIO2 and referred to conveniently as Bio2) was conducted in January 2002.

Phase four was the development of a three-dimensional numerical model of the BEHIVS technology. The model was calibrated using data from the bromide tracer study and the extensive amount of data collected during the first three phases of system operation. It was used to evaluate system performance and to learn more about aquifer characteristics and the location of TCE sources at Site 19.

4.0 SYSTEM OPERATION AND RESULTS

4.1 Operational Schedule

The schedule of operation for the BEHIVS system is outlined in Table 1, which shows phase two operations and phase three post-demonstration monitoring. Day zero on the schedule is taken to be the day that full-time operation of the pumps at the biotreatment wells commenced on August 13, 2001. The remainder of this report will always use this convention for "day zero." However, the groundwater monitoring system was placed into operation 320 days before that time, and so an extensive database of groundwater quality was obtained over about a 10-month period prior to starting the BEHIVS system. This 320-day period is termed the pre-operational period.

Table 1: Operational schedule for the BEHIVS system at Site 19, Edwards Air Force Base.

			Vapor Stripper (IWVS)		BioTreatment (BT)		
Phase and Date	Day	Description	Air Flow, L/min	Water Flow, L/min	Bio-Well Nos.	Wwater Flow, L/min	Toluene Added, mg/L
Phase 2							
9/27/00	-320	Monitoring begins	0	0		0	0
7/15/01	-29	Testing of IWVS	0	0		0	0
8/13/01	0	BT - pumping begins	0	0	1&2	7.6	0
8/21/01	8	Begin IWVS operation	2,200	30	1&2	7.6	0
9/16/01	34	IWVS off, O_2 inject begins	0	0	1&2	7.6	0
9/25/01	43	Toluene pulse addition	0	0	1&2	7.6	10
9/26/01	44	IWVS on	2,200	30	1&2	7.6	0
10/03/01	51	Toluene pulse addition	2,200	30	1&2	7.6	3.8
10/05/01	51	IWVS off	0	0	1&2	7.6	3.8
10/06/01	55	BEHIVS stopped	0	0	1&2	0	0
10/18/01	66	Toluene continuous addition begins	0	0	1&2	7.6	5.7
10/26/01	74	IWVS on	2,200	30	1&2	7.6	5.7
11/07/01	86	BT flow doubled	2,000	27	1&2	15	6.4
11/17/01	96	Toluene increased	2,000	27	1&2	15	12
12/07/01	116	IWVS off	0	0	1&2	15	12
12/16/01	125	IWVS on	1,800	23	1&2	15	12
12/31/01	140	BIO1 toluene off	1,800	22	1	15	0
12/31/01	140	BIO2 remains on	1,800	20	2	15	12
1/05/02	145	IWVS off	0	0	2	15	12
1/07/02	147	BIO1 toluene on	0	0	1&2	15	10
Phase 3							
1/27/02	168	Rebound study begins	0	0		0	0
6/20/02	311	Rebound study ends	0	0		0	0

Testing of the BEHIVS system began one month before operation of the system was started on day zero. On day 8, the vapor stripping system was officially started and was operated for one month with the biotreatment wells pumping, but with no toluene injection. On day 34, the vapor stripper was turned off to begin the toluene injection phase at the biotreatment wells. From days 34 to 43, oxygen was mixed with the water circulating through the biotreatment wells in order to insure a sufficient supply was present in the aquifer before toluene injection. Toluene injection began as a pulse feed of toluene, sufficient to result in an injection concentration of 10 mg/L over a one-day injection period. After this injection, the biotreatment well pumps were also stopped to wait for toluene consumption and the build-up of a toluene consuming bacterial population. The toluene concentration injected was higher than desired and so the vapor stripper pumps were started on day 44 to draw out excess toluene in the event that toluene degradation did not occur rapidly enough. However, the biological population responded well, and reduced the concentration throughout the system. A second toluene pulse was made on day 51, this time at a concentration of about 3.8 mg/L over a one-day period, and the vapor stripper was turned off on day 51. All pumps were turned off on day 55 to wait for toluene to disappear. This occurred rapidly (within 10 days), the system was then considered ready for continuous toluene injection.

Continuous toluene injection began on day 66 at 5.7 mg/L, which was delivered in pulses throughout the day. Vapor stripper operation began again on day 74, bringing the system to full operation. On day 86, the biotreatment well pumping rate was doubled to 15 liters per minute (4 gpm), resulting in a total flow for the two wells of 30 liters per minute. On day 96 the toluene concentration was increased to 12 mg/L, and the BEHIVS system was operated at the maximum rate that had been planned.

On day 116, the vapor stripper was turned off to increase the height of the upper portion of the well casing because of apparent clogging of the infiltration gallery above the water table. Despite a 15% decline in water pumping rates (6.8 gpm by the end of November), water air-lift pumped from the IWVS lower screen was overflowing the casing top. With the increased casing height, the vapor stripper was again started. The pumping rate was reduced to 5 gpm. It is noteworthy that we discovered a design/construction detail that was critical. Namely, there was no direct connection between the vapor stripping well casing and the three radiating infiltration galleries. These channels were designed to receive the water pumped from the vapor stripper for percolation back into the aquifer. This design/construction flaw should be corrected in future efforts to prevent such a clogging problem. Successful infiltration galleries (without clogging) have been designed and constructed at two other locations at Site 19 where in-well vapor stripping was used.

On day 140, toluene delivery at biotreatment well one was discontinued for a short period to correct a problem with blockage in the oxygen injection line. Toluene delivery at biotreatment well one restarted on day 147; during this time the well remained pumping. Vapor stripper operation was terminated on day 145. However, the biotreatment wells were operated until day 167 in order to conduct a bromide tracer study at biotreatment well two. At the end of phase two on day 167, all pumping was stopped, and the third phase rebound study was begun. Samples were collected periodically from all monitoring locations until the end of phase three at day 311, a period of 140 days. The purpose of this study was to determine where increases in TCE concentrations occurred as a means of characterizing sources of TCE contamination. The gathering of field data was completed on day 311.

4.2 Pre-Operational Chemical Characteristics

The ASAP analytical system became operational at the end of September 2000. By the time the BEHIVS system started in August there were 2,330 samples collected, providing a sound background database. This was of considerable value for evaluating system effectiveness. Besides TCE, the other VOCs present at Site 19 with significant, although much lower, concentrations are 1,1-dichloroethene (1,1-DCE) and cis-1,2-dichloroethene (cDCE). Selected inorganic constituents were also measured, namely chloride and sulfate. Dissolved oxygen concentrations and pH were also monitored.

Summary results for the BEHIVS pre-operational period (September 30, 2000, through July 31, 2001), are given in Tables B1 to B10 in Appendix B. Tables B1 to B9 present data for dual-screened monitoring locations. Table B10 contains results for other wells in the area that were present before the BEHIVS system was constructed. The tables indicate the number of samples analyzed for a given constituent during the ten-month pre-startup period and the average (mean) concentration at each location. Also listed are the standard deviations and the coefficients of variation, which is the ratio of the standard deviation to the mean.

Table B1 contains information on TCE, the constituent that the BEHIVS system is designed to remove, obtained using a flame ionization detector (FID). Concentrations in the upper and lower aquifers were significantly different. The average pre-operational concentration in the upper aquifer based upon 985 samples was 1,270 µg/L while in the lower aquifer the average concentration was 4,570 µg/L, based upon 970 samples. The range of average concentrations in the upper aquifer was 460 to 2,930 µg/L, while in the lower aquifer, the range was between 2,480 and 8,270 µg/L. These values are all well above EPA's drinking water maximum contaminant level (MCL) of 5 µg/L. An interesting aspect of the TCE data is the relatively low coefficient of variation at any given location, averaging 0.22 in the upper aquifer and 0.17 in the lower aquifer. The coefficient of variation is a measure of the spread of data at a given location and reflects not only true variations in water quality with time at a given location, but also measurement errors. During the 10 month period of sample collection and analysis, concentrations at given locations did not change radically.

Tables B2 and B3 contain summaries of cDCE and 1,1-DCE data, respectively. Average cDCE concentrations were well below EPA's drinking water MCL concentration of 70 µg/L. However, they are above the California MCL for cDCE of 6 µg/L, which is the cleanup goal for Edwards AFB projects. For 1,1-DCE, the average concentrations were below the EPA MCL of 7 and California MCL of 6 µg/L in the upper aquifer, but somewhat above these values in the lower aquifer at some locations. Table B4 provides a comparison between cDCE and TCE concentrations. The cDCE concentration was about 0.9% of the TCE concentration in both the upper and lower aquifers, and this percentage was similar throughout the aquifer, varying between about 0.7% and 1.1% at most locations.

Table B5 is another summary of TCE results, but using a photo ionization detector (PID), rather than the FID used for Table B1. Two detectors were used for each sample to provide a check on the analysis, and also to provide backup data in case one of the detectors failed during the study.

The coefficients of variation were essentially the same for both detectors, meaning that the precision of each was about the same. However, on average, the concentrations recorded by the PID detector were about 94% of the values recorded by the FID detector. This may have been a result of the PID detector not having as good a linear response as the FID detector. Thus, for reporting and monitoring, the FID detector results were used, with the PID results being used to catch errors and serve as a backup system for volatile organic chemical analyses.

Tables B6 and B7 contain information on pre-operational chloride and sulfate concentrations, respectively, and Table B8 lists the ratio of sulfate to chloride concentrations at different locations. Based upon the latter table, the sulfate concentrations in the upper aquifer were somewhat higher on a relative basis, about 66% of the chloride concentrations in the upper aquifer compared with 57% in the lower aquifer. Based upon Table B6 values, the sulfate concentrations were about the same in both aquifer locations, 1,310 mg/L in the upper aquifer and 1,410 mg/L in the lower aquifer. The chloride concentrations in the two aquifers displayed a greater difference, 1,990 mg/L in the upper aquifer and 2,480 mg/L in the lower aquifer, a 25% difference.

One interesting observation is that the sulfate and chloride concentrations in the lower aquifer of the northern monitoring wells, N6, and N15, were significantly lower than the average values. These concentrations are also less than those found in the upper aquifer.

The pre-operational dissolved oxygen concentrations throughout the aquifer generally were quite low, especially in the lower aquifer. This changed significantly when the BEHIVS system was started--since both aeration by in-well vapor stripping and oxygen and peroxide additions at the biotreatment wells represented significant oxygen inputs to the system.

Table B10 is a summary of the pre-operational data obtained from other monitoring wells that were present in the BEHIVS study area before system construction. These results are presented only for information about the aquifer. They were outside of the planned study area and so were not monitored during BEHIVS operation.

4.3 In-well Vapor Stripper (IWVS) Operation

The IWVS began continuous pumping on August 21, 2001 (day 8), and completed operation on January 5, 2002 (day 145). Figure 3 shows the air and water pumping rates at the IWVS. During this time period the well was actually pumping for a total of 92 days. The airflow to the vapor stripper (Table 2) varied between 1,530 and 2,300 liters/min (54-81 standard cubic feet per minute). Carbon dioxide was added at a rate of approximately 0.9 L/min to the air entering the vapor stripper to maintain pH in the water exiting the vapor stripper at about 7.0 in order to avoid $CaCO_3$ precipitation. The resulting groundwater flow rate through the vapor stripper (Tables 2 and 3) was 12-33 liters/min (3.3-8.8 gallons per minute). . The resulting dimensionless air to water flow ratio (Table 2) varied between 46 and 128. The vapor stripper was not operated between days 34and 44 and again between days 51 and 74 to allow startup of the biotreatment system (Table 1). As mentioned in section 4.1, the vapor stripper was operated from days 44 to 51 to remove an unintentionally high toluene injection.

During the period of operation, a total groundwater volume of 3,680 m^3 was treated by vapor stripping (Figure 4). Figure 5 shows influent (DO4-L) and effluent (DO4-U) TCE concentrations from the air stripper since August 15, 2001. The concentration scale is logarithmic so that the effluent concentrations can be seen more clearly. With time, the influent concentration dropped from an average pre-operational concentration of 4,960 µg/L to and average 1,479 µg/L in December. The total TCE removal by air stripping (Figure 6) was 7.1 kg. Much greater mass removal occurred when the influent concentration was higher. Table 2 presents calculated stripping ratios (SR) for TCE based on measured BEHIVS air to water flow rates (AW). These ratios are calculated as:

$$SR = 1 - \left[\frac{1}{\left(1 + AW * K_h\right)} \right]$$

Table 2: Air flow rates and calculated theoretical stripping ratios for TCE at the IWVS.

Date	**Day**	**Air Flow (scfm)**	**Water Flow (gpm)**	**Dimensionless Air:Water Ratio**	**Stripping Ratio**
13-Aug-01	0.0	54.4	8.75	46.50	94.2%
15-Aug-01	2.2	78.5	6.6	88.97	96.9%
15-Aug-01	2.2	91.6	6.6	103.81	97.3%
15-Aug-01	2.2	113	6.6	128.07	97.8%
21-Aug-01	8.0	74.10	7.66	72.36	96.2%
22-Aug-01	9.0	76.60	7.66	74.80	96.3%
23-Aug-01	10.0	80.70	7.62	79.22	96.5%
24-Aug-01	10.9	79.60	7.60	78.34	96.5%
26-Aug-01	12.9	79.60	7.59	78.45	96.5%
29-Aug-01	15.9	76.30	7.77	73.45	96.3%
8-Sep-01	26.0	78.50	7.94	73.95	96.3%
14-Sep-01	31.9	77.40	7.96	72.73	96.2%
26-Sep-01	44.0	80.70	7.72	78.19	96.5%
26-Oct-01	74.1	74.10	7.66	72.36	96.2%
27-Oct-01	74.9	65.40	7.66	63.86	95.7%
31-Oct-01	78.9	58.90	7.36	59.86	95.4%
1-Dec-01	110.1	65.40	8.11	60.32	95.5%
6-Dec-01	115.0	75.14	6.19	90.80	96.9%
17-Dec-01	126.2	60.11	6.08	73.95	96.3%
18-Dec-01	127.1	62.26	6.26	74.39	96.3%

The stripping ratio is a function of the air to water ratio (AW) and the Henry's Law constant (K_h) for the particular VOC. The Henry's Law constant (dimensionless) used for this calculation is 0.35. The calculated stripping ratios range from 94.2% to 97.8%, with an average of 96.3%. For comparison, stripping ratios estimated from influent and effluent TCE concentrations are given in Table 3. These estimates range from 87.6% to 99.1%. In-well concentrations for the entire period indicate an average in-well concentration reduction of 95.4%.

4.4 Biotreatment Well Operation

The biotreatment wells began pumping on August 13, 2001 and ceased operation on January 27, 2002, a total of 167 days. Figure 7 shows the pumping rates at both biotreatment wells during system operation. TCE mass removal by the biotreatment wells is provided in Figure 8. A total of about 1.0 kg was removed by the two biotreatment wells. Figure 9 indicates TCE removal

Table 3: TCE stripping ratios estimated from influent and effluent concentrations at the vapor-stripping well.

Date	IWVS Pumping (gpm)	Stripping Ratio	continued Date	IWVS Pumping (gpm)	Stripping Ratio	continued Date	IWVS Pumping (gpm)	Stripping Ratio
21-Aug-01	7.6	96.7	01-Oct-01	7.3	96.8	24-Nov-01	6.8	94.7
22-Aug-01	7.7	96.4	02-Oct-01	7.5	98.2	25-Nov-01	6.8	94.9
23-Aug-01	7.6	96.2	03-Oct-01	7.4	98.7	26-Nov-01	6.7	94.3
24-Aug-01	7.6	96.5	26-Oct-01	7.6	98.3	27-Nov-01	6.7	94.0
25-Aug-01	7.6	96.6	27-Oct-01	7.7	98.1	28-Nov-01	6.7	93.7
26-Aug-01	7.6	96.6	28-Oct-01	7.6	98.1	29-Nov-01	6.7	93.5
27-Aug-01	7.6	96.5	29-Oct-01	7.5	98.2	30-Nov-01	7.3	94.3
28-Aug-01	7.8	97.1	30-Oct-01	7.8	98.2	01-Dec-01	8.1	94.6
29-Aug-01	7.8	96.8	31-Oct-01	7.4	98.5	02-Dec-01	6.7	94.5
30-Aug-01	7.8	96.8	01-Nov-01	7.5	98.8	03-Dec-01	5.7	93.8
31-Aug-01	7.8	96.6	02-Nov-01	7.4	99.1	04-Dec-01	7.4	93.0
01-Sep-01	7.7	98.4	03-Nov-01	7.4	96.6	05-Dec-01	6.5	92.3
02-Sep-01	7.7	93.6	04-Nov-01	7.2	94.3	06-Dec-01	6.2	92.3
03-Sep-01	7.7	92.6	05-Nov-01	7.2	94.5	08-Dec-01	12.5	92.3
04-Sep-01	7.8	94.0	06-Nov-01	7.0	94.6	09-Dec-01	0.3	92.3
05-Sep-01	7.7	97.2	07-Nov-01	7.1	94.7	16-Dec-01	0.1	95.4
06-Sep-01	7.8	97.8	08-Nov-01	7.3	94.8	17-Dec-01	6.1	95.3
07-Sep-01	7.7	91.1	09-Nov-01	7.3	94.9	18-Dec-01	6.3	95.7
08-Sep-01	7.9	94.3	10-Nov-01	7.3	94.8	19-Dec-01	6.3	95.3
09-Sep-01	8.0	92.6	11-Nov-01	7.3	94.8	20-Dec-01	6.2	96.2
10-Sep-01	7.9	91.1	12-Nov-01	7.3	94.8	22-Dec-01	6.9	96.6
11-Sep-01	8.0	93.8	13-Nov-01	7.4	94.6	24-Dec-01	3.2	96.4
12-Sep-01	7.9	92.5	14-Nov-01	7.1	94.7	26-Dec-01	2.4	97.2
13-Sep-01	7.9	91.0	15-Nov-01	7.2	95.0	27-Dec-01	5.6	97.9
14-Sep-01	8.0	91.4	16-Nov-01	7.1	95.7	28-Dec-01	5.4	98.5
15-Sep-01	7.9	87.6	17-Nov-01	7.2	96.6	29-Dec-01	5.7	95.4
16-Sep-01	8.0	96.6	18-Nov-01	7.1	95.1	31-Dec-01	5.2	95.8
27-Sep-01	7.6	94.8	19-Nov-01	7.0	94.6	01-Jan-02	10.5	95.9
28-Sep-01	7.5	95.5	20-Nov-01	7.0	94.1	02-Jan-02	7.4	96.0
29-Sep-01	7.7	96.3	21-Nov-01	7.0	94.0	03-Jan-02	5.7	96.1
30-Sep-01	7.6	96.5	22-Nov-01	6.9	94.4	04-Jan-02	5.0	96.3
--	--	--	23-Nov-01	6.9	94.6	05-Jan-02	5.3	96.3

efficiency by biotreatment. At biotreatment well one, the removal efficiency is represented by the difference in TCE concentrations between the biotreatment well and nearby monitoring well N07. At biotreatment well two, the TCE concentration difference between the treatment well and monitoring well N11 is used. The bromide tracer study revealed little dispersion/dilution between these locations, indicating that reduction in TCE concentration is due to bioactivity.

The lower removal efficiency indicated initially is partly the result of the low biomass initially present. TCE sources (desorbed from aquifer material) also artificially lower the calculated removal efficiency as this mass was not included. The true removal efficiency is probably indicated by steady state operation after 90 days for biotreatment well one and after 120 days at biotreatment well two.

Maximum measured TCE removal by biological treatment was about 70 percent. At biotreatment well one, toluene addition was stopped temporarily on day 140, which corresponds to a precipitous drop in TCE removal efficiency. Removal efficiency increased to over 70 percent following the resumption of toluene addition on day 147. Removal efficiency at biotreatment well two began to decrease on day 145 following shut off of the vapor stripping well. A similar decrease is not evident at biotreatment well one until about day 160. The decreasing efficiencies at the two biotreatment wells at the latter part of the study are not due to a decrease in biological activity, but to an increase in the TCE concentration reaching the biotreatment wells following the stoppage of the vapor stripper operation, as discussed below.

Biotreatment well treatment efficiency is a function of vapor stripper operation because it controls the concentration of TCE reaching the biotreatment wells. Figures 10 and 11 provide a useful picture of TCE removal by biological treatment. Figure 10 shows TCE removal in µg/L for the biotreatment wells. For biotreatment well one, the values shown equal the difference between measured concentrations at Bio1-L and N7-L, the monitoring well used to evaluate removal efficiency. For biotreatment well two, the values shown are the difference between TCE concentrations at Bio2-L and N11-L. We see that TCE removal increased to a high of 300 to 500 µg/L near day 125. These highs correspond to the time when higher TCE concentrations of 400 to 500 µg/L were arriving at the biotreatment wells as indicated in Figure 11. The TCE removal then decreased from day 130 to 145, which corresponds to lower TCE concentrations (200 to 300 µg/L) arriving at the biotreatment wells. A lower TCE removal is also shown for biotreatment well one from day 140 to 147, when no toluene was being added here. Following day 160, the TCE removals once again increased to the 400 to 500 µg/L range. This correlates with an increased TCE concentration arriving at the biotreatment wells (up to 800 µg/L). The variations in TCE concentration arriving at the biotreatment wells shown in Figure 11 are a result of vapor stripper operation. When the vapor stripper was off, TCE concentrations at the biotreatment wells rose as there was no vapor stripped water to dilute the groundwater being drawn into the biotreatment wells.

The data show the maximum TCE removal that can be obtained by the biotreatment system at Edwards AFB. This is a function of the toluene concentration added. Maximum TCE mass removal per unit mass of toluene added is termed the transformation yield (T_y) of the microorganisms. Assuming TCE removal of 500 µg/L represents this maximum, which was obtained with addition of 12 mg/L of toluene, T_y would equal 0.5/12 or 0.04 g TCE/g toluene. This is similar to the maximum T_y of 0.06 g TCE per gram of phenol, a similar compound, found in early studies on cometabolism at Moffett Field (Hopkins, et al., 1993). In the previous Edwards AFB bioremediation study, a maximum TCE removal of 89% was found (McCarty, et al., 1998), but this was after 200 days of operation when good steady-state removal was obtained. At that time, the TCE concentrations being treated were approximately 254 µg/L. After 150 days of operation, removal efficiencies of 85 percent were obtained. The current study differs in that the time was short to reach steady-state operation. More importantly, the TCE concentrations being treated were much higher than in the previous study so that TCE removal was near the maximum value as governed by T_y.

4.5 Overall System Results

The overall removals effected during the BEHIVS operation between August 13, 2001 and December 31, 2001, a period of four and one-half months, are shown in Table 4. The monitored region was approximately 48 m by 56 m. The monitoring-well layout was designed to collect data both within and outside the treatment area. The active treatment area was approximately 32 m by 42 m, and contained 14 monitoring wells that provided 28 locations with data for the upper and lower aquifer zones. Figure 12 shows the active treatment area. Within the BEHIVS treatment area, the average TCE concentration reduction in the lower aquifer zone was 91 percent, with a reduction of 94 to 97 percent at 10 of the 14 monitoring wells. Average TCE removals in the treatment area exceeded 56% in the upper aquifer zone, with 3 monitoring wells showing a reduction of 92% or more. Overall for the entire study area, including that area outside the treatment area, average TCE removals were 70 percent in the lower aquifer zone and 38 percent in the upper aquifer zone. The total TCE mass removal was 8.1 kg, 7.1 kg of which resulted from vapor stripping and 1.0 kg from biotreatment. Average TCE concentrations for each month of system operation are given in Appendix C.

The removal of cDCE and 1,1-DCE by the BEHIVS system was not the major focus of this study. However, concentrations for December 2001 indicate significant removals were obtained during BEHIVS operation. Comparisons with initial values are contained in Appendix C, Tables C10 (cDCE) and C12 (1,1-DCE). These results indicate that in the treatment zone, average cDCE and 1,1-DCE concentrations in December were at or below the California MCL of 6 µg/L for both cDCE and 1,1-DCE. Table C11 shows cDCE concentrations during June 2002, and indicates that concentrations increased during the rebound period.

5.0 NUMERICAL MODELING AND ANALYSIS

Modeling of the BEHIVS site utilized a finite element code developed specifically for recirculating well systems, BIOFEM. The code includes groundwater flow, contaminant transport, and biological processes—details may be found in Gandhi (2001). The original BEHIVS model, used for design purposes, consisted of two homogeneous layers, each five meters thick. The upper layer of material corresponded to the more highly conductive alluvium and the lower layer to the less conductive weathered bedrock. Initial data collection at the site indicated that local flow conditions could not be adequately represented with a model consisting of simple homogeneous layers.

The non-pumping head measurements taken within the lower aquifer (see Figure 13) suggest two differing local gradient directions. One is a northwest to southeast gradient in the northern portion of the treatment area and the other is a slight southeast to northwest gradient in the southern portion. Some sort of preferred flow “channel” in the lower layer would be necessary to recreate this flow pattern with the model. The tracer test data further confirmed the need to include aquifer heterogeneity. The development of a new conceptual model of the BEHIVS site was an iterative process, incorporating new data as it became available. This task entailed hundreds of model runs exploring the effects of various changes to the model before the final conceptual model was adopted. The final BEHIVS model is described in the following subsections.

Table 4. Average TCE concentrations measured at various sampling locations showing comparisons between pre-operational (average Initial) TCE concentrations and those during December 2001. Note: **Bold values** are monitoring locations within the treatment zone.

	Upper Aquifer Zone				Lower Aquifer Zone			
	December		Initial		December		Initial	
		Average	Average	Change		Average	Average	Change
Well	n	(µg/L)	(µg/L)	(Percent)	n	(µg/L)	(µg/L)	(Percent)
D04-B	**5**	**933**	**2,193**	**-57%**				
D04-C					**7**	**1,479**	**4,960**	**-70%**
Bio1	**22**	**495**	**659**	**-25%**	**28**	**432**	**6,862**	**-94%**
Bio2	**11**	**311**	**608**	**-49%**	**13**	**320**	**4,982**	**-94%**
N-01	6	658	815	-19%	9	4,613	6,955	-34%
N-02	8	193	797	-76%	9	2,217	2,475	-10%
N-03	6	450	927	-51%	8	2,756	3,352	-18%
N-04	**11**	**347**	**1,712**	**-80%**	**57**	**2,125**	**8,273**	**-74%**
N-05	**8**	**742**	**1,000**	**-26%**	**7**	**191**	**6,056**	**-97%**
N-06	9	859	1,323	-35%	14	2,768	3,450	-20%
N-07	**11**	**66**	**808**	**-92%**	**27**	**142**	**4,574**	**-97%**
N-08	**12**	**60**	**2,932**	**-98%**	**9**	**184**	**5,637**	**-97%**
N-09	**12**	**56**	**810**	**-93%**	**14**	**488**	**4,209**	**-88%**
N-10	**6**	**442**	**1,109**	**-60%**	**25**	**208**	**3,718**	**-94%**
N-11	**5**	**443**	**1,051**	**-58%**	**10**	**192**	**3,823**	**-95%**
N-12	**5**	**927**	**2,317**	**-60%**	**7**	**203**	**3,684**	**-94%**
N-13	5	287	459	-37%	15	2,669	4,169	-36%
N-14	**5**	**1,658**	**1,136**	**46%**	**13**	**751**	**5,117**	**-85%**
N-15	6	1,556	690	126%	5	2,911	5,001	-42%
N-16	7	528	932	-43%	10	2,552	4,677	-45%
N-17	6	610	775	-21%	12	2,083	3,694	-44%
N-18	6	2,048	1,568	31%	11	1,141	4,959	-77%
N-19	7	1,900	2,178	-13%	7	1,244	3,516	-65%
N-20	6	2,134	2,256	-5%	8	2,689	3,090	-13%
MW21	**10**	**67**	**616**	**-89%**	**23**	**241**	**4,278**	**-94%**
MW22	5	1,460	1,533	-5%	7	1,460	3,305	-56%
MW23	**6**	**532**	**919**	**-42%**	**25**	**297**	**5,075**	**-94%**
Average for Treatment Zone		**506**	**1,276**	**-56%**		**518**	**5,089**	**-91%**
Average for Monitored Area		760	1,236	-36%		1,398	4,611	-66%

5.1 Model grid geometry

The BEHIVS model covers a domain of 200 by 200 meters, which is larger than the coverage of the monitoring system but was needed to account for boundary effects. In the vertical, the modeled region is 20 m and extends from the water table surface (approximately 685 meters) to the bottom of the vapor stripping well lower screen (665 meters). The final model mesh consists of 26,726 nodes and 49,205 elements over 13 vertical layers. Mesh discretization is highest near the treatment/pumping wells and coarsest approaching the boundaries. The BEHIVS model grid is shown in Figure 14.

Well boring logs from the 36 wells in the treatment area as well as those of 13 additional wells just outside of the area were examined to determine the location of the competent bedrock (CBr) and the interface between the weathered bedrock (WBr) and the upper alluvium. The distribution of these boreholes is shown in Figure 15. These data were kriged onto the model grid and used to create new material zones. The elevation of the competent bedrock/aquifer bottom is shown in Figure 16. The elevation of the interface between the weathered bedrock and this extremely low conductivity material varies from 678 to 675 meters within the BEHIVS treatment area, increasing in elevation toward the north and south of the site. The result is a bathtub-like shape with the BEHIVS treatment wells located in the center of the tub.

The elevation of the contact between the weathered bedrock and the alluvium (the upper and lower aquifer materials) is also variable throughout the treatment domain. This interface varies by approximately three meters in the vertical. Thus the thickness of both the alluvium and weathered bedrock is quite variable. Figure 17 shows the elevation of the top of the weathered bedrock material in the model. The alluvium/upper aquifer is actually composed of many small layers of sands and clays. This material is considered to be highly anisotropic in the vertical, with horizontal to vertical anisotropy ratios near 100. Both the weathered bedrock and all other materials of the lower aquifer are isotropic.

Another feature in our site model of the BEHIVS system is a set of low conductivity zones in the weathered bedrock. Despite numerous attempts at calibrating the model without these zones, they appear to be necessary to recreate bromide arrival at the monitoring wells as well as measured heads. The final configuration of these zones was the result of many permutations. The low conductivity zones lie in the northeast (around wells N05, N06, N12, N15, and N20) and southeast (around wells N13, N16, and N17) corners of the treatment area. There is an additional low conductivity zone in the southern upgradient portion of the site, around wells N02, N03, and MW21.

The final significant feature of the BEHIVS site model is a high conductivity zone within the weathered bedrock that runs northwest/southeast from biotreatment well two to monitoring well N05. This region likely represents a fracture zone that serves to decrease travel times to N05. The lower aquifer material types/zones are shown in Figure 18.

5.2 Model Initial and Boundary Conditions

The BEHIVS model requires initial conditions for all modeled constituents. These include bromide, dissolved oxygen, toluene, and TCE. Prior to the beginning of the first tracer injection, bromide measurements were taken at all but a handful of monitoring wells. Due to high levels of chloride present in the aquifer, bromide measurements are thought to be accurate to +/- 50 mg/L. The initial mean bromide concentration was 17 mg/L, ranging from a low of less than 1 mg/L to a high of 47 mg/L. Since the spatial coverage of this data is not complete, a single initial value of 17 mg/L for bromide is used at all model locations.

For dissolved oxygen and TCE, many measurements were available allowing for spatially variable initial conditions. Measurements of each taken in the week prior to system startup (i.e., the first week of August) were kriged onto the model grid creating initial condition maps. Figure 19 shows the initial TCE concentration used for the upper and lower aquifers, respectively. In the deep aquifer, hotspots are present around monitoring well N04 and between biotreatment well one and N07. Figure 20 shows the initial dissolved oxygen concentrations used in the upper and lower aquifers, respectively. As would be expected, dissolved oxygen levels in the weathered bedrock are significantly lower than those in the alluvium.

The model domain was purposely made large to minimize the effects of boundary conditions on flow and transport processes within the BEHIVS treatment area. The east and west border of the model domain are constant head (type I) boundaries and the north and south borders are zero-gradient or no-flow (type II) boundaries. The heads used for the constant head boundaries were developed from the initial conditions (e.g., July 27, 2001) observed in the BEHIVS head field. The transport boundary conditions are zero concentraction gradient or "advective flux only" across the model boundaries.

5.3 Modeling of Well Operations

The recirculating wells are represented in the model as pairs of connected well screens. Each of the three treatment wells has one injection and one pumping well screen, each with its own flowrate. The model approximates changing flow conditions as a succession of 34 different steady-state flow fields corresponding to the differing pumping conditions that occurred from August 13 through January 27.

An additional source of water that was accounted for in the model was the sampling return flow from the ASAP that was injected into the treatment wells. This return flow reached a maximum of about 5 gpm during the tracer test. Sampling return flow is shown in Figure 21. From the beginning of operations through January 9, 2002, this water was injected equally into the biotreatment wells. After January 9, this water was added to the infiltration originating from the vapor stripping well. Consequently, the pumping rates measured within the wells reflect a combination of the pumped water and the sampling return water. The flowrates modeled at the pumping screens are less than that at the injection screens, by the amount of the return flow. The pumping regimes and the corresponding pumping rates used in the model are given in Table 5.

Although flowmeter readings at the bioremediation wells measured constant flow rates from November 14 through January 27, evidence from head and tracer data suggests that effective pumping rates were significantly less at certain times. In particular, the bromide injections at the biotreatment wells produce concentrations that are inconsistent with the total mass injected using the measured pumping rates. Furthermore, at both respective bioremediation wells, bromide appeared at the non-injection well screen almost immediately after each test began, implying some short-circuiting of flow at the wells. Estimations of the effective pumping rates at these wells were calculated based both on balancing the total bromide mass injected with the measured

Table 5: Steady state pumping regimes for BEHIVS treatment system.

DAY	RETURN FLOW GPM	BIO1 TOP GPM	BIO1 BOTTOM GPM	BIO2 TOP GPM	BIO2 BOTTOM GPM	IWVS TOP GPM	IWVS BOTTOM GPM
0.0	0.28	2.36	2.50	2.36	2.50	8.75	8.75
0.1	0.28	2.36	2.50	2.36	2.50	0.00	0.00
2.2	0.28	1.86	2.00	1.86	2.00	6.50	6.50
2.2	0.28	1.86	2.00	1.86	2.00	0.00	0.00
3.1	0.28	2.16	2.30	2.16	2.30	6.60	6.60
4.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8.0	0.28	1.86	2.00	1.86	2.00	7.70	7.70
29.0	0.28	1.86	2.00	1.86	2.00	0.00	0.00
30.9	0.28	1.86	2.00	1.86	2.00	7.93	7.93
34.0	0.28	1.86	2.00	1.86	2.00	0.00	0.00
44.0	0.27	0.00	0.14	0.00	0.14	0.00	0.00
44.8	0.30	0.00	0.15	0.00	0.15	7.72	7.72
46.0	0.31	1.85	2.00	0.00	0.15	7.54	7.54
46.2	0.31	0.00	0.15	0.00	0.15	7.54	7.54
48.0	0.30	1.85	2.00	0.00	0.15	7.58	7.58
48.2	0.30	0.00	0.15	0.00	0.15	7.45	7.45
51.0	0.33	1.84	2.00	1.84	2.00	0.00	0.00
55.0	0.30	0.00	0.15	0.00	0.15	0.00	0.00
66.0	0.29	1.85	2.00	1.85	2.00	0.00	0.00
74.0	0.25	1.87	2.00	1.87	2.00	7.77	7.77
78.9	0.39	1.80	2.00	1.80	2.00	7.26	7.26
85.9	0.45	3.78	4.00	3.78	4.00	7.26	7.26
92.9	0.37	3.82	4.00	3.82	4.00	7.18	7.18
99.9	0.39	3.81	4.00	3.81	4.00	6.80	6.80
107.2	0.45	3.78	4.00	3.78	4.00	6.83	6.83
115.5	0.28	3.86	4.00	3.86	4.00	0.00	0.00
125.1	0.40	3.80	4.00	3.80	4.00	6.40	6.40
130.8	0.29	3.85	4.00	3.85	4.00	3.30	3.30
134.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
135.0	0.41	3.79	4.00	3.79	4.00	3.30	3.30
135.9	0.31	3.85	4.00	3.85	4.00	5.40	5.40
140.0	0.34	3.83	4.00	3.83	4.00	5.20	5.20
145.0	0.36	4.00	4.00	4.00	4.00	0.36	0.00
167.1	0.44	0.00	0.00	0.00	0.00	0.44	0.00

concentrations and by matching the source to separate measurements of tracer remaining in the injection tank each day. Based on these methods, the effective pumping rate at bioremediation well one during the tracer test was 18% +/- 3% less than the measured pumping rate. At bioremediation well two, the effective pumping rate was likely 32% +/- 8% less during the tracer test. Similar short-circuiting occurred during the original bioremediation demonstration elsewhere on Site 19.

The relative effective pumping rates at the biotreatment wells (i.e., the rate of biotreatment well one as opposed to biotreatment well two) determine the location of stagnation points between them. Thus the local direction of flow is very much dependent on these rates. For example, monitoring wells N09, N14, and N18 receive tracer from bioremediation well two, but not from bioremediation well one.

Transducer data from the four biotreatment well screens are helpful in explaining the reduced pumping rates. As seen in Figure 22, the difference in pressure head from the upper to the lower screens reflects the difficulty in injecting at the well. The large increase in the head differential around day 86 marks the doubling of the pumping rate at the biotreatment wells. Around day 100, the head differential at biotreatment well one begins to increase, likely due to clogging of the aquifer by biomass accumulation. After day 120, the head difference stabilizes, only changing again on day 145 when the vapor stripper is turned off. At biotreatment well two, however, the clogging is more pronounced. Beginning at approximately day 120 the head differential in the well steadily increases until the system is shut down. On day 145 there is a large, 2 meter increase in the head differential. This behavior is represented in the model with a localized zone around the biotreatment wells (approximately 1 meter in diameter). Starting around day 120, the vertical conductivity in this zone is increased to allow more vertical flow right around the wells. At day 145, this same area surrounding the lower wellscreen of biotreatment well two is changed to a lower horizontal conductivity. This forces more water to move up rather than out, and reduces the “effective” pumping rate of the well. This pattern of behavior is consistent with the results seen from the bromide tracer test (discussed below) as well as the measured heads at the site (see Appendix D.)

5.4 Injection Schedules

Oxygen addition at the biotreatment wells began on September 16 and continued throughout well operation. In the model, this is included as a constant concentration of 35 mg/L of dissolved oxygen at the lower/injection screens of the biotreatment wells. Additionally, the water coming through the vapor stripper is oxygenated by exposure to air. In the model, all water entering the upper/injection screen of the vapor stripper has a constant concentration of oxygen of 10 mg/L.

Peroxide was injected at both biotreatment wells starting on November 7. The modeled concentration at the injection wellscreens is constant at 45 mg/L until January 27. At the vapor stripping well, peroxide addition began on November 30, modeled at a constant concentration of 45 mg/L through January 5.

Regular toluene injections began at the biotreatment wells on October 18. The initial schedule included one pulse to each well every two hours. On October 26, the delivery schedule was changed to one pulse to each well every twelve hours. From November 7 through the duration of biotreatment well operation, the delivery schedule was one pulse per well per day. The BEHIVS model averages toluene injections over one-day intervals. The toluene injection concentrations used in the model are shown in Table 6 and are based on the total mass delivered each day.

Table 6. Daily averaged toluene injection schedule used in BEHIVS model.

from day	to day	Bio1 mg/L	Bio2 mg/L	from day	to day	Bio1 mg/L	Bio2 mg/L
43	44	15.0	0.8	78	80	5.6	6.4
44	51	**NONE**	**NONE**	80	81	5.6	7.2
51	55	**NONE**	1.9	81	82	6.4	4.0
55	66	**NONE**	**NONE**	82	83	6.4	8.0
66	67	4.8	4.8	83	84	6.0	5.6
67	68	4.0	4.0	84	85	6.4	6.0
68	69	5.3	5.3	85	86	2.4	2.4
69	70	5.6	5.6	86	87	6.4	6.4
70	71	0.4	0.4	87	88	6.8	6.8
71	72	3.8	3.8	88	93	6.4	6.4
72	73	6.2	6.0	93	94	6.6	6.6
73	74	5.2	5.2	94	96	6.4	6.4
74	75	6.4	6.4	96	97	12.7	12.7
75	76	5.8	6.2	97	140	12.0	12.0
76	77	5.2	5.2	140	147	**NONE**	12.0
77	78	6.0	4.4	147	166	10.0	10.0

5.5 Bromide Fate and Transport

The bromide tracer test was critical to development of the BEHIVS model. In particular, heterogeneity in the lower aquifer and the variability in effective pumping rates at the biotreatment wells could not have been properly evaluated without the tracer data.

Tracer was injected at the vapor stripping well from day 87 through day 92, at an average concentration of 228 mg/L. The tracer injection at bioremediation well one lasted from day 126 though day 132. Over this six-day period the average bromide concentration was 229 mg/L. The final tracer injection at bioremediation well two started on day 151 and continued through day 160. The average bromide concentration over this time would have been 237 mg/L. In fact, the concentrations of tracer injected at each well varied over time. Figure 23 shows the bromide concentrations measured at the injection source for each tracer injection. In the model, the concentrations were mass averaged over one-day increments. The bromide concentrations used in the model are shown in Figure 23 as blue bars.

Data shown in Figure 24 suggests significant vertical flow at the biotreatment wells during the tracer tests. At biotreatment well one, bromide concentrations at the non-injection/non-source screen increase immediately and are approximately 20% of those at the injection screen. The effect is also seen at biotreatment well two, but the relative concentrations at the non-injection screen are higher, approximately 25% of the injection. The immediate transport of tracer from the injection to withdrawal screens in each of the biotreatment wells suggests short-circuiting in their respective near-well environments. Vertical short-circuiting at each of the biotreatment wells effectively reduces their injection rates. Consequently, the driving force for lateral transport is less than intended and less than the in-well measurements indicate. Therefore, the effective injection rates at each of the biotreatments must be estimated. An important goal during model calibration was determining the correct effective injection rates by replicating this short-circuiting behavior.

5.6 Results of Model Calibration

The flow and conservative transport model was calibrated by matching simulated and observed head and concentration data from the tracer tests. The calibrated flow and transport parameters from modeling bromide transport are shown in Table 7.

Table 7: Flow and transport parameters used in bromide transport model.

Parameter	**Value**
K_alluvium (horizontal)	8 m/d
K_alluvium (vertical)	0.09 m/d
K_WBr	3 m/d
K_CBr	0.001 m/d
K_low conductivity zone	0.05 m/d
K_high conductivity channel	10 m/d
θ alluvium	0.20
θ WBr	0.05
θ CBr	0.01
θ low conductivity zone	0.08
θ high conductivity channel	0.05
Dispersivity	2 m / 0.2 m

Figures 25 and 26 show the results of the BEHIVS bromide transport model. In these figures, the model results are shown as a blue line, and bromide measurements are shown as red dots. The figures illustrate bromide concentration over time at most of the monitoring locations, spatially arranged in an approximation of reality. In the shallow model results (Figure 25), the model fit to the data is quite good at early times, with the exception of the large tracer peak at biotreatment well 2 (coming from the vapor stripping well). The model predicts the timing of this peak correctly, thus this quick arrival time suggests some sort of high conductivity feature in the upper alluvium material. The current model did not attempt to create such features in the upper zone. Likewise the modeled peak at MW21 is less than that measured, but the discrepancy is less. Note the second bromide peaks at both of the biotreatment wells. These occur simultaneously with bromide injection in the deep aquifer. The model replicates this behavior quite well with the change in conductivity around the biotreatment well deep screens as discussed earlier in this report.

The lower aquifer results (Figure 26) also show a quite reasonable match of the model to bromide data. The only peak that the model misses is the biotreatment well 1 bromide peak from the first tracer injection. This is the same peak that the model does not predict in the shallow zone. It is also seen at N11 as it moves downgradient from the biotreatment well. For the most part, the locations where the model fit to the data is the worst are all in the low conductivity zone (N04, N12, MW21). The model is extremely sensitive to the geometry of this zone.

The tracer test simulation match the pattern of tracer arrival from the bromide measurements taken from December through February. Both simulation results and the data show that no tracer is seen at downgradient wells N13, N15, N16, N17, N19, or N20, nor does any of the tracer reach upgradient deep wellscreens at N01, N02, N03 or N06. Furthermore, bromide from the tracer injection at bioremediation well one does not appear at any monitoring wells north of the vapor stripper. This is less surprising than the fact that none of this tracer injection shows up at wells N09, N14, and N18, which lie between the two bioremediation wells. These wells only register the later tracer injection at bioremediation well two. This somewhat unintuitive behavior is captured in the model.

Table 8 shows a comparison of tracer peak arrival times (days after the peak appears) with modeled peak arrival times. The comparison of the model data with the measured data is accompanied by the caveat that the measurements at any location may have missed the bromide peak. Likewise, the location of smaller peaks is not necessarily recognizable due to analytical measurement error on the order of 50 mg/L. Nonetheless, the model match to the tracer data is quite reasonable. Despite the asymmetries seen in the tracer data (e.g., the difference in peak arrival times from the vapor stripper to each of the biotreatment wells,) the model predicts the existence of tracer only where it occurs in the measurements. At most locations, the peak arrival time is within a day of that measured. This is within the expected margin of error considering that daily averaging was used in the model. The worst model fits are to the third tracer injection. At the time of this tracer injection, the velocities are much slower since the vapor stripping well is off. Thus travel times are longer in general (e.g., 8 days between biotreatment well 2 and N08), and the discrepancy in model to measured peak is exaggerated. Results are moderately good at all locations except N07 shallow and N12 and N18 deep. Given the overall fit to the data shown in Figures 25 and 26, these mismatches do not appear to be critical.

Table 8: Comparison of tracer peak arrival time and modeled peak arrival time. Note blanks indicate no discernable peak.

Tracer Peak Arrival Time: Days After Peak at Source						
Well	**First Injection**		**Second Injection**		**Third Injection**	
	Model (days)	**Measured (days)**	**Model (days)**	**Measured (days)**	**Model (days)**	**Measured (days)**
SHALLOW WELLSCREENS						
D04	source	Source	3	3	2	NA
Bio1	2	4	<1	<1	--	--
Bio2	2	1	--	--	<1	<1
N07	1	1	2	3	15	--
N08	1	<1	2	3	--	--
N09	1	1	7	11	--	--
N11	8	18	--	--	--	--
N14	9	--	--	--	--	--
MW21	2	2	10	16	--	--
MW23	--	--	--	--	--	--
DEEP WELLSCREENS						
D04	9	5	1	2	11	5
Bio1	3	2	source	source	--	--
Bio2	3	1	--	--	source	source
N04	--	--	--	--	15	10
N05	--	--	--	--	11	10
N07	3	2	<1	2	--	--
N08	3	1	--	--	8	10
N09	5	--	--	--	8	10
N10	7	2	1	2	--	--
N11	3	2	--	--	8	8
N12	--	--	--	--	11	37
N14	--	--	--	--	12	10
N18	--	--	--	--	33	12
MW21	--	--	4	2	--	--
MW23	3	16	<1	4	--	--

5.7 TCE Fate and Transport

The BEHIVS TCE model includes cometabolic bioremediation processes, vapor stripping removal, as well as local TCE sources in the BEHIVS treatment area. Biological parameters for the model are taken from those fit to data at the bioremediation demonstration site (Gandhi, 2002) and are shown in Table 9. Due to much higher TCE concentrations at this location, it is believed that TCE removal is primarily limited by the toluene concentrations. Thus a higher value of the transformation capacity (T_c = 1 kg/kg) was used for this model. At the bioremediation demonstration site, T_c = 0.05.

Table 9: Bioremediation parameters in BEHIVS model.

Parameter	**Description**	**Value**
k_{sTol}	toluene saturation constant	1.3×10^{-4} kg/m^3
X_i	Initial biomass concentration	1.9×10^{-3} kg/m^3
T_c	TCE transformation capacity	1 kg/kg
k_{per}	Hydrogen peroxide disproportionation rate constant	22 d^{-1}
k_{Iper}	Hydrogen peroxide inhibition constant	3.4×10^{-4} kg/m^3
k_T	Maximum TCE degradation rate constant	9.4 d^{-1}
Y	Yield coefficient	0.77 kg/kg
F	Mass ratio of oxygen to toluene for biomass growth	2.1 kg/kg
k_{sTCE}	TCE saturation constant	0.01 kg/m^3
k	Maximum toluene utilization rate constant	1.5 d^{-1}
k_{sOx}	Dissolved oxygen saturation constant	0.001 kg/m^3
b	Biomass decay constant	0.15 d^{-1}
f_d	Fraction of cell mass that is biodegradable	0.8
d_c	Biomass decay oxygen demand	1.42 kg/kg
b_d	Biomass deactivation rate constant	1.0 d^{-1}
f_{per}	Molar mass ratio of oxygen to hydrogen peroxide	0.94
ε	Hydrogen peroxide disproportionation efficiency	1.0
α	Dissolved oxygen exsolution rate constant	100 d^{-1}
C^{sat}_{Ox}	Dissolved oxygen saturation constant	0.042 kg/m^3

The conductivities and effective porosities used in the TCE model are the same as those developed from the tracer test model. Both TCE and toluene are stripped from the water by the vapor stripper, TCE by 97% and toluene at 93%. These levels are based on data observed at the upper and lower screens of the vapor stripping well for each constituent. Finally, a retardation factor, R, of 1.6 was used for TCE. No retardation is used for toluene.

The results of the full BEHIVS cometabolic bioremediation model are shown in Figures 27 and 28. The model includes TCE sources near wells N01, N04, D04, and N14. In the deep aquifer (Figure 28) there appears to be additional sources near wells N18 and around MW21/N07. Additionally, the behavior of the source at D04 is likely more complex than was included in this model. The deep aquifer model results show a reasonably good match to the TCE data. Especially upgradient of the vapor stripping well, at N01 and N04, the model replicates the 'sloshing' back and forth of clean water as the vapor stripping well is turned on and off. One location where the fit could be improved is at monitoring well N05. The difficulty at this location was the apparent need for a faster flow path for the low TCE concentrations (which must be coming from biotreatment well two) while maintaining the lower concentrations seen in the tracer test results.

In the shallow aquifer, the TCE concentrations show much greater variability than the model produces. Additionally, it appears possible that a source exists in the shallow aquifer near N18, potentially as TCE sorbed onto clay layers in the upper alluvium. The general fit of the model to the data is good.

5.8 Comparison of TCE Treatment Processes

Figures 29 and 30 present TCE transport results with no bioactivity, i.e., the biotreatment wells are pumping but no toluene is injected into the system. It is difficult to see much difference between these results and those from the previous two figures. However, the results of bioactivity are pronounced in at later times at N05, N07, MW21, and of course the biotreatment wells. When TCE concentrations are low, the biological activity eliminates the tailing seen in the concentrations of Figures 29 and 30. This is consistent with the notation that cometabolic bioremediation is limited to reductions of about 400 µg/L in at this site under these conditions.

5.9 Nature of TCE Sources

The BEHIVS rebound study (February through June 2002) helped to identify locations for TCE sources in the treatment area—almost all in the deep aquifer. It is likely that these sources are sorbed and slowly desorbing or there is residual TCE that is scattered throughout the site, perhaps in unconnected fractures in the bedrock. Prior to the rebound study, some locations (i.e., N01, N04, N18) on the edge of the treatment area show signs of a source. As the vapor stripping well was turned on and off and the flow direction changed, the TCE concentration in these locations rises and falls. This is especially well illustrated by monitoring well N04. When the vapor stripping well is on, TCE concentrations fall (with a time delay). When the well is off, TCE levels rise again. This behavior was replicated in the BEHIVS model by inserting a very simple TCE source just on the upgradient side of N04. The source was represented by a high concentration extremely low flow flux distributed over source nodes. After much exploration of the effects of varying source locations, it was determined that the "sources" of TCE had to be very small (<1 meter) to achieve the high response behavior seen in the data. If the source covered a larger area, the TCE concentrations are elevated and do not fluctuate with the frequency seen in the data.

From the rebound data alone, there appears to be some source of TCE near wells N01, N04, D04 (seen near day 50), N14, and N18. Additionally, there appears to be a lower concentration TCE source in the vicinity of biotreatment well one and monitoring well N07. This source only becomes apparent in the rebound period. The model was able to match some of these sources (N01, N04) quite well, some of them reasonably well D04, N07, N14) and some not well at all (N18). It is believed that with continued modeling, these sources could easily be located. Figure 31 shows the locations of suspected TCE sources used in the model. As an additional note, TCE data suggest the possible location of a source in the upper aquifer in the vicinity of N18 that would be the cause of the concentration increase from day 100 to day 150. Again, we were unable to pinpoint the location of this source in the given time but believe it could be represented with additional modeling effort.

It appears that highly localized hot-spot sources of TCE exist in the bedrock. These local sources are likely to be on the scale of decimeters to a few meters. The dissolved phase TCE in the aquifer is not in equilibrium with these sources that continuously emit solute. The TCE concentrations in the deep zone appear to be controlled by either dissolution of residual TCE, slow diffusion-controlled desorption, or diffusion of a dense highly concentrated dissolved phase that is trapped and immobile. Each of these sources would exhibit similar behavior and cannot be distinguished without further analyses and field investigation. Their locations can be targeted to some degree using the model.

The model shows great sensitivity to the location of small TCE sources. Using concentrations at monitoring well N04 deep, Figure 32 illustrates how the source location can be identified. The figure shows the location of the suspected TCE source that is approximately 1 m^2 in area. It is just upgradient of N04 deep (the dark blue circle). The correct location is likely the one that yields a simulated concentration history at N04 that reproduces the observed values. By moving this source less than 2 m to the north or south, the simulated values at N04 do not reproduce the data. When in the incorrect location, the TCE concentrations seen at the monitoring well do not show the variability seen in the original source. Because of this sensitivity, determination of the rebound sources required some ‘prospecting’, trying sources at different nearby locations. As part of this process, larger source areas were also used, however expanding the coverage of the source did not reproduce the variability in the concentration seen in the data.

The simplistic source representation used here was helpful for quickly determining source locations; the next step in this analysis would be representing these sources in a more complex/kinetic fashion. The representation would be as rate limited sorption or kinetic dissolution from a residual source. This would allow the source concentration to respond to flow and transport conditions surrounding it in a more realistic fashion.

5.10 Alternate Treatment Scenarios

The final model results explore ‘what if’ questions regarding operation of treatment systems at this site. The first scenario involves operating the **vapor stripping well only**, beginning on August 13, 2001 and running continuously for 250 days. These results are shown in Figures 33 and 34. The expected reduction in TCE concentration is seen throughout the treatment area in the lower aquifer. However, the TCE concentrations remain higher than those seen in the actual BEHIVS operation. This is likely due to the lack of recycling, since only one recirculating well is operating. Without the biotreatment wells pumping in the opposite direction, the contaminated water passes through the vapor stripper once and then leaves the system. Under these operating conditions the spatial area that is affected by the vapor stripping well is larger. So there would be less reduction in TCE concentration, but concentrations would be lowered to some degree over a larger volume.

Figures 35 and 36 show the TCE results if **all three treatment wells are pumping with vapor stripping** occurring at the two (current) biotreatment wells. All three wells are pumping water from the lower aquifer and injecting it into the upper aquifer. TCE levels in the lower aquifer are reduced even further than in the previous scenario due to some of the water undergoing a second pass of the vapor stripper. Again, TCE concentrations remain a little higher than those seen in the actual BEHIVS operation due to lack of recycling.

The same scenario as above, with **all three treatment wells are pumping with vapor stripping but with the biotreatment wells pumping in the opposite direction**, is shown in Figures 37 and 38. These results show the great benefits of the recycling system. TCE concentrations at a number of locations (e.g., N08, N07, MW21, N11, MW23, N12, N10, and the biotreatment wells) drop down to near zero. Other locations (N18, N19, N05) see significant reductions in TCE concentrations. Clearly the juxtaposition of recirculating wells pumping in opposite directions is critical to achieving low TCE concentrations.

6.0 CONCLUSIONS

1. Operation of the BEHIVS system resulted in reducing the lower aquifer zone TCE concentrations by 91 percent in the treatment area, with 10 of the 14 monitoring wells showing concentration reductions of between 94 and 97 percent. Average TCE concentrations in the upper aquifer zone within the treatment area were reduced by 56 percent. The total TCE mass removal was 8.1 kg, 7.1 kg of which resulted from in-well vapor stripping and 1.0 kg from biotreatment.

2. TCE concentrations within the BEHIVS study area at Site 19 before the start of the BEHIVS system averaged 4,600 µg/L in the lower portion of the aquifer and 1,240 µg/L in the upper portion of the aquifer. Concentrations in the lower aquifer varied from an average low of 2,480 µg/L at monitoring location N02-L to a high of 8,300 µg/L at monitoring location N04-L. The range in the upper aquifer was 450 µg/L at monitoring location N13-U and a high of 2,930 µg/L at monitoring location N08-U.

3. With an air to water ratio between 73 and 90, TCE removal by single-pass vapor stripping averaged 95.4 percent, and generally ranged between 94 and 97 percent.

4. With an injected toluene concentration of 12 mg/L, maximum percentage removal of TCE through biological treatment was about 70 percent, and the maximum µg/L removal at higher TCE concentrations was about 400 µg/L. Higher percentage removals were obtained with influent TCE concentrations of 400 µg/L or less. At high influent TCE concentrations, percentage removals were less. No more than 400 µg/L TCE could be removed by a single pass through the biotreatment wells.

5. Rebound studies conducted over a 4 1/2-month period after BEHIVS operation was discontinued indicated that sources of TCE exist in the lower aquifer along a northwest-southeast path from N04-L to N10-L. Here, rebound brought TCE concentrations up to near the pre-operational level within about 3 1-2 months after BEHIVS operation was stopped. Periodic operation of the BEHIVS system would likely be valuable in preventing high TCE concentrations from migrating down gradient at Site 19.

7.0 RECOMMENDATIONS

For treatment of the TCE hot-spot source area, this demonstration suggests that in-well vapor stripping is a viable option to greatly reduce TCE concentrations. The use of multiple vapor-stripping wells in the upflow and downflow mode should be explored. The approach can target local high concentration sources whose reduction or removal requires multiple pore volumes flowing over the source. Recirculating and sequentially treating contaminated groundwater using in-well vapor stripping is preferable to pump-and-treat in such circumstances. Single-pass stripping ratios of greater than 95% are clearly achievable.

The vapor stripping system operated very efficiently in removing TCE from the lower aquifer and functioned well throughout most of the demonstration. However, a design/construction flaw involving an inadequate connection between the well screen and the infiltration gallery resulted in clogging during the final two weeks of the demonstration. This was not a problem at other locations on Site 19 where infiltration galleries were used in conjunction with in-well vapor stripping. Prior to clogging the BEHIVS vapor-stripping well functioned properly. In future use of a vapor stripping system, it is recommended that a direct connection be made between the vapor stripping well casing and the groundwater delivery channels radiating out from the vapor stripping system to prevent such clogging. If this is not done, it defeats the purpose of the infiltration gallery.

The biotreatment wells operated most efficiently with TCE concentrations below about 400 µg/L. It is recommended that BEHIVS design (combination of vapor stripping and biotreatment) be such as to keep higher concentrations from reaching the biological treatment system. The biotreatment system is mainly for polishing after high concentration sites have been "knocked down."

The BEHIVS system suffered problems with both toluene and dissolved oxygen delivery. The difficulty with toluene delivery is the large delivery tube size needed to prevent clogging, which requires retention of too much toluene. A new design is needed to correct this problem. One possibility is the installation of an air flow line connected at the surface to the toluene feed line so that toluene delivered by a pump would be blown down to the static mixer, rather than flowing by gravity. For the oxygen regulation, larger tubing is needed for delivery, and a fail-safe device is needed that would stop toluene delivery if the oxygen flow were stopped for some reason.

The locations of localized concentrated sources of TCE to within a few meters can likely be targeted using modeling combined with limited field data. This was demonstrated on a pilot basis in this work. It appears that highly localized hot-spot sources (< 1 m^2) of TCE exist in the bedrock in this region of Site 19. The TCE concentrations in the bedrock appear to be controlled by either dissolution of residual TCE, slow diffusion-controlled desorption, or diffusion of a dense highly concentrated dissolved phase that is trapped and immobile. Each of these sources would exhibit similar behavior and cannot be distinguished without further analyses and field investigation.

8.0 REFERENCES

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Gandhi, R.K, G.D. Hopkins, M.N. Goltz, S.M. Gorelick, and P.L. McCarty, Full-Scale demonstration of *in situ* cometabolic biodegradation of trichloroethylene in groundwater, 2: Analysis of field data using numerical modeling**,** *Water Resources Research*, 38(4), 2002.

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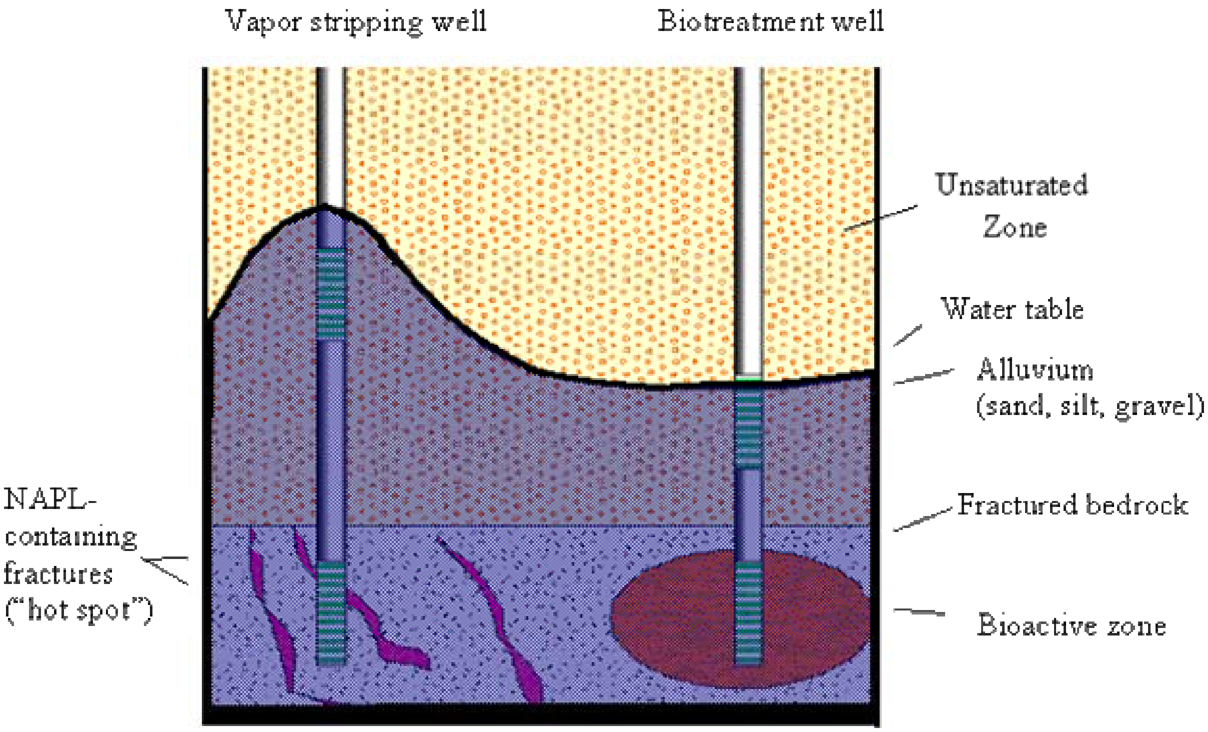


Figure 1. Schematic plan view of the BEHIVS treatment system.

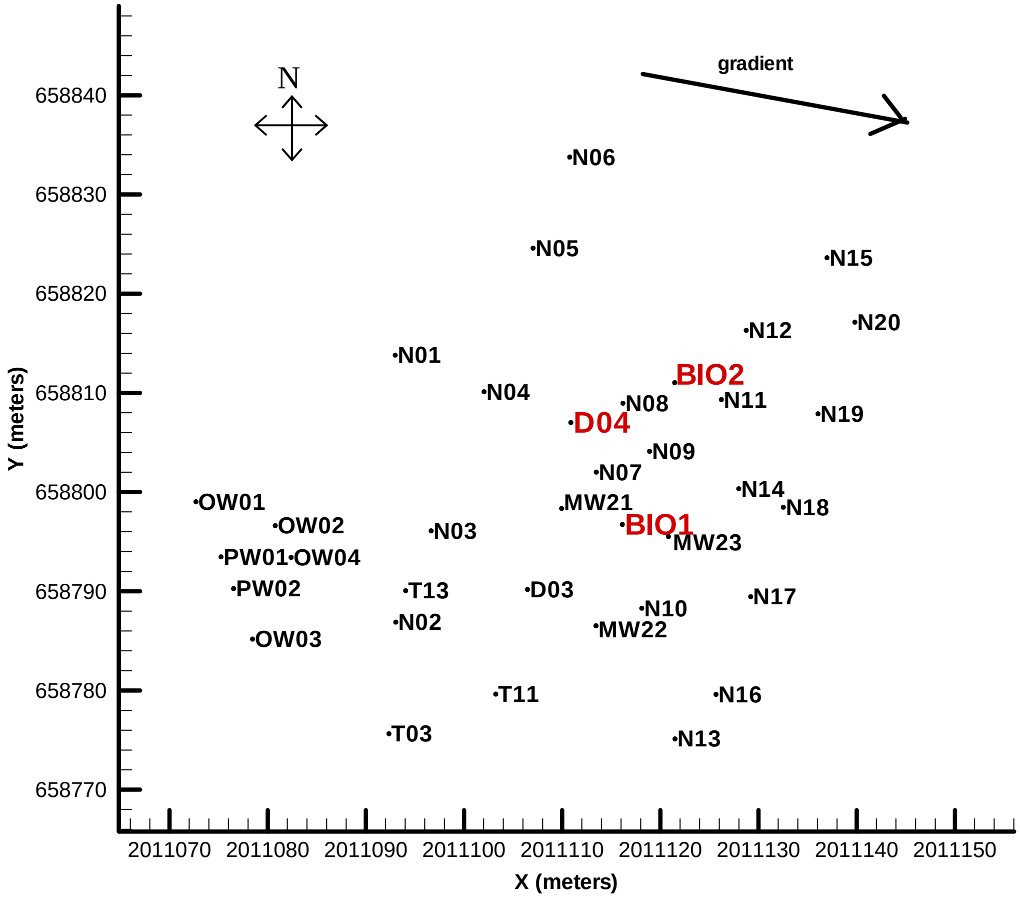
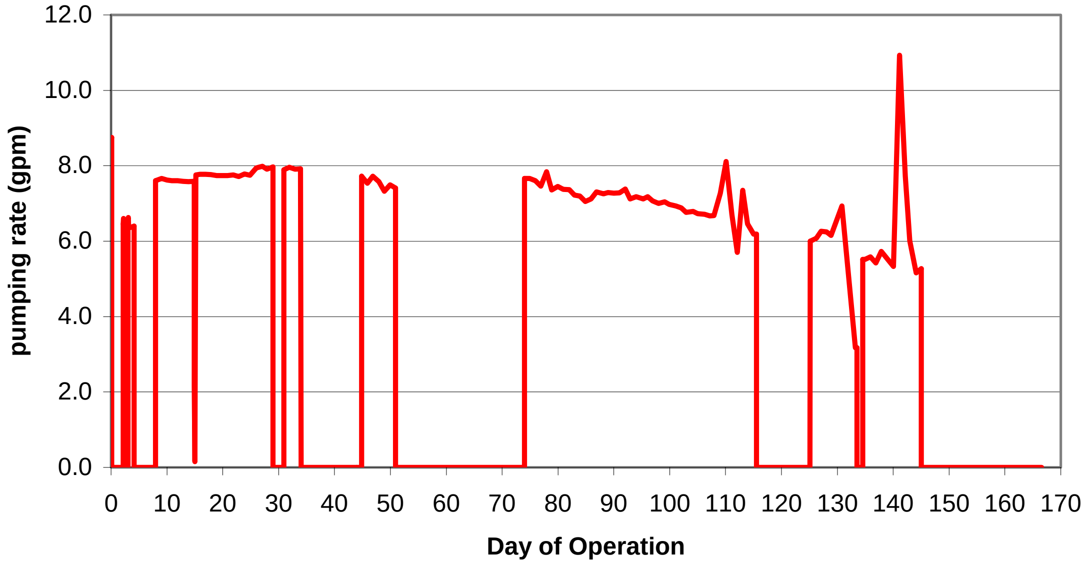


Figure 2. Plan view showing locations of the BEHIVS in-well vapor stripper (D04), the two biotreatment wells (BIO1 and BIO2), and monitoring wells.

a) water flowrates



b) air pumping rates

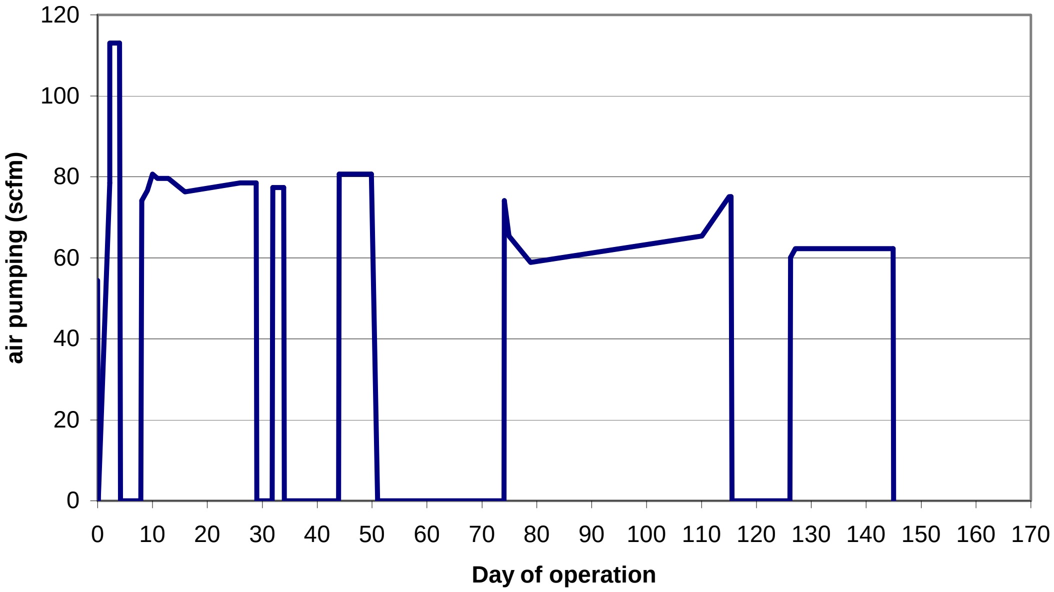


Figure 3. Operation of In-Well Vapor Stripper, water flowrates and air pumping rates.

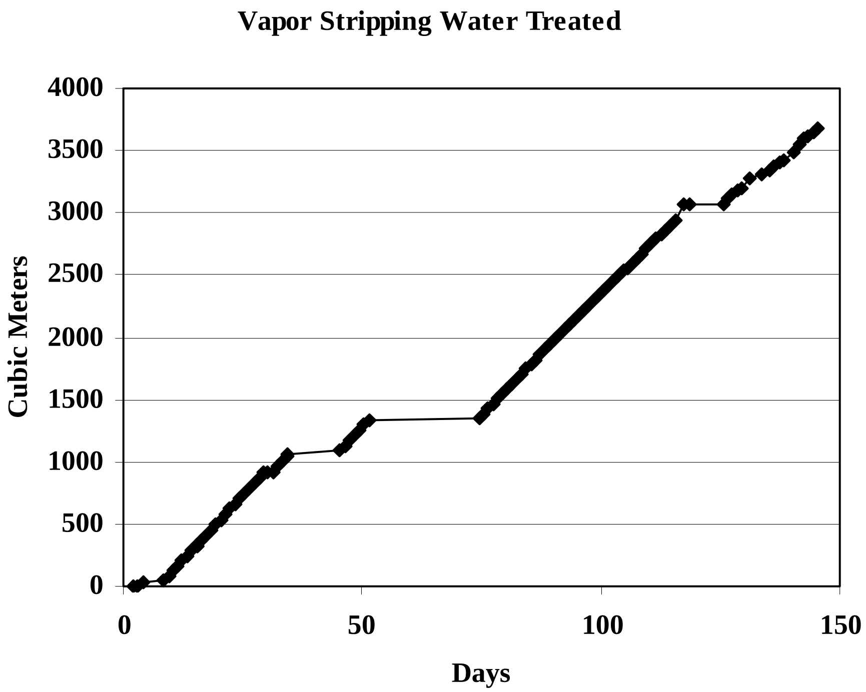


Figure 4. Total water treated by vapor stripping well.

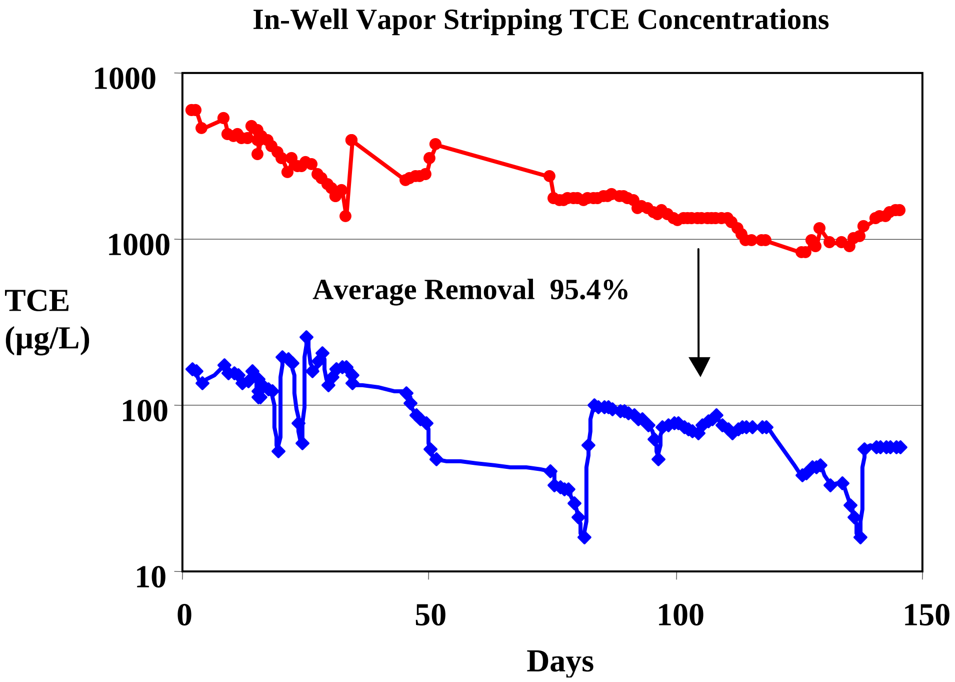


Figure 5. Measured TCE concentrations at vapor stripping well. Note: The difference in concentration between the upper (blue) screen and lower (red) screen is the reduction in TCE concentration which averaged 95.4%. Note: A logarithmic scale is used for concentrations which are in units of µg/L.

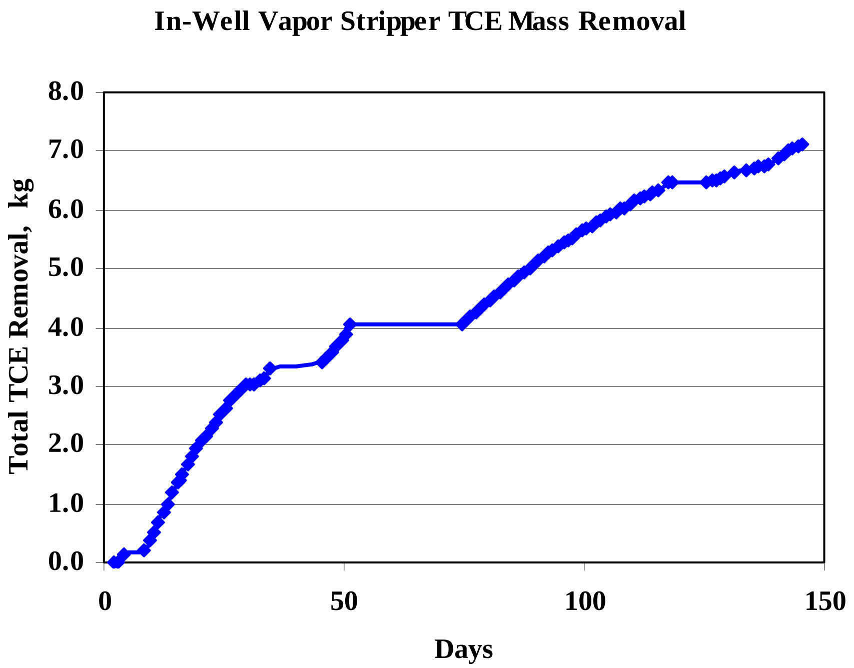


Figure 6. Mass of TCE removed by vapor stripping well, calculated as the difference between integrated masses through upper and lower wellscreens.

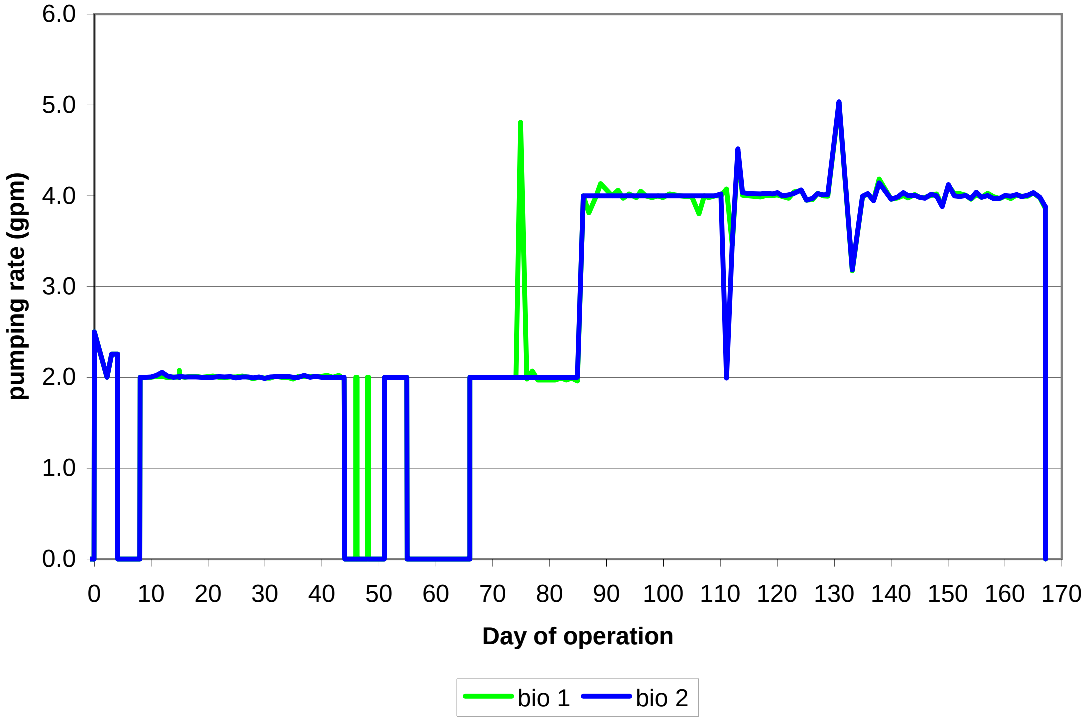


Figure 7. Measured pumping rates at biotreatment wells.

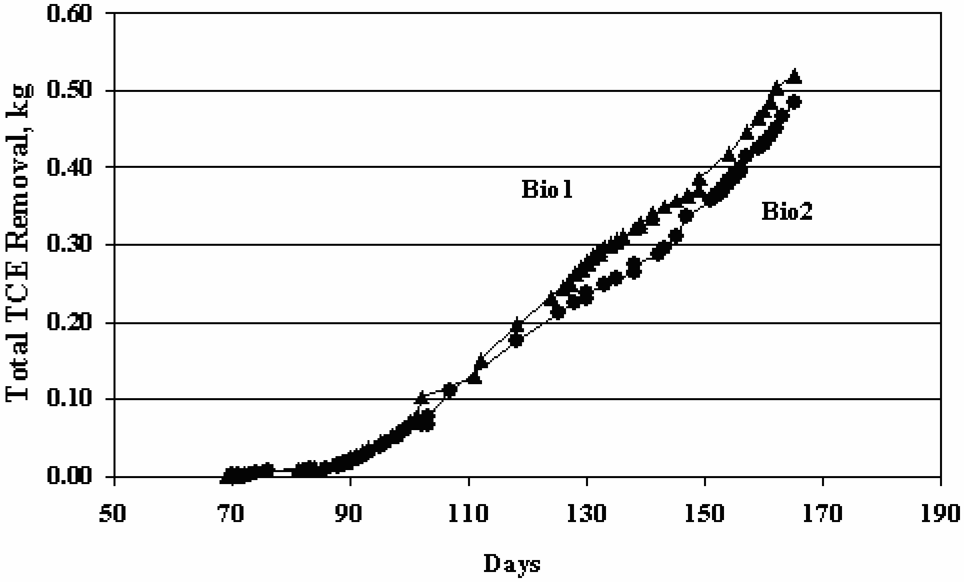


Figure 8. Mass TCE removed by biological treatment.

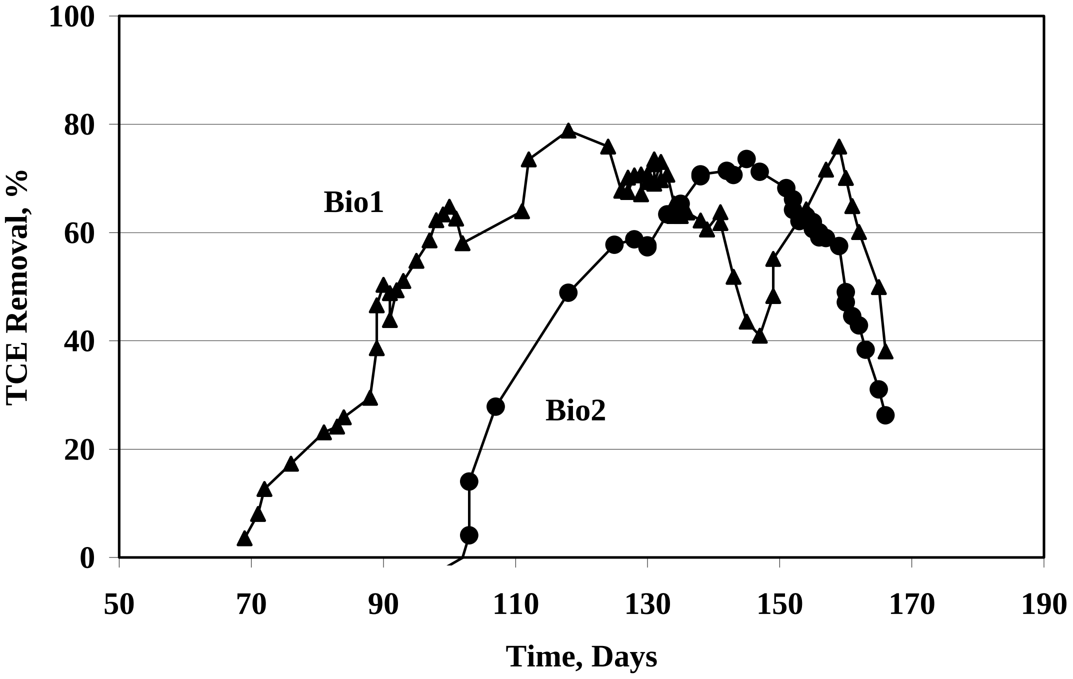


Figure 9. Percentage TCE removal by biological treatment.

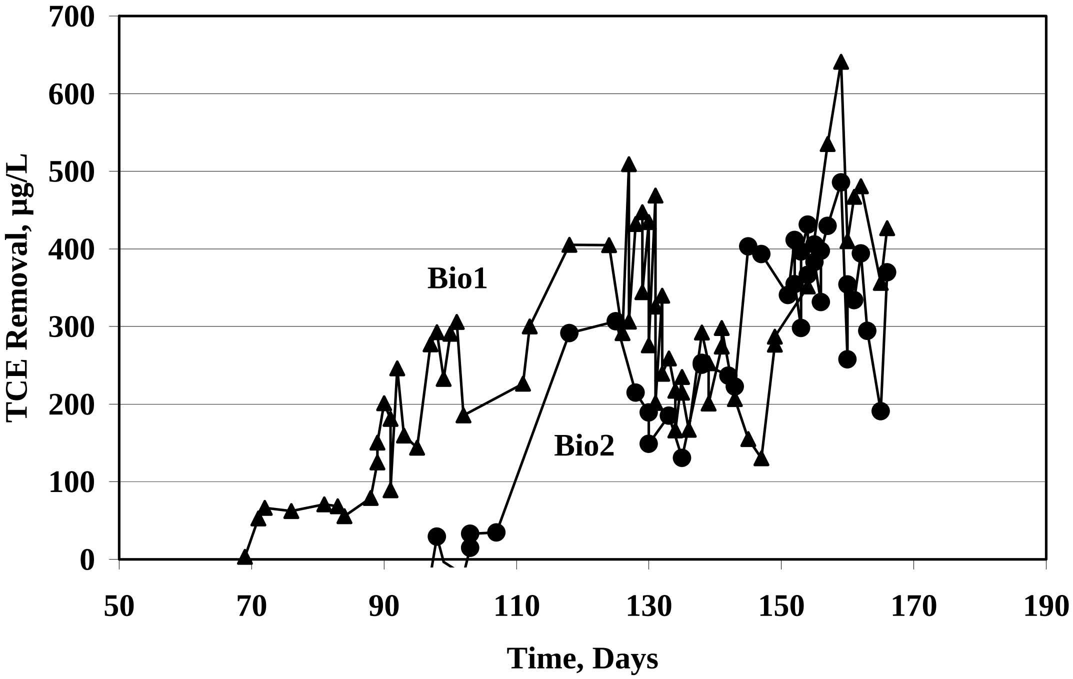


Figure 10. TCE concentration removal by biological treatment.

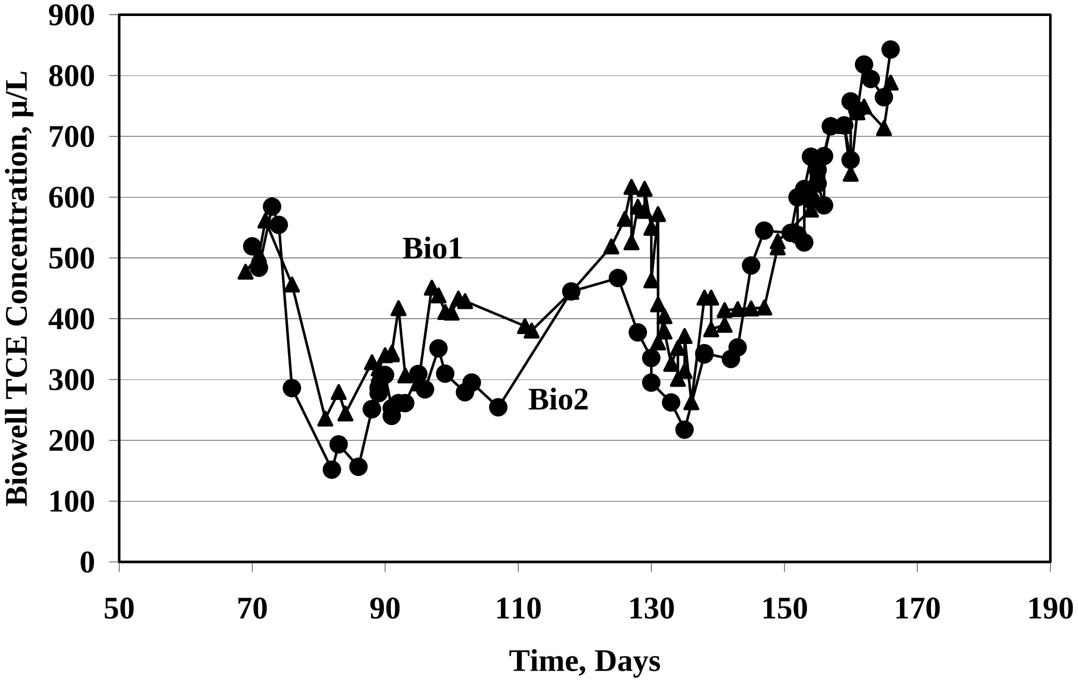


Figure 11. TCE influent concentration to biological treatment wells.

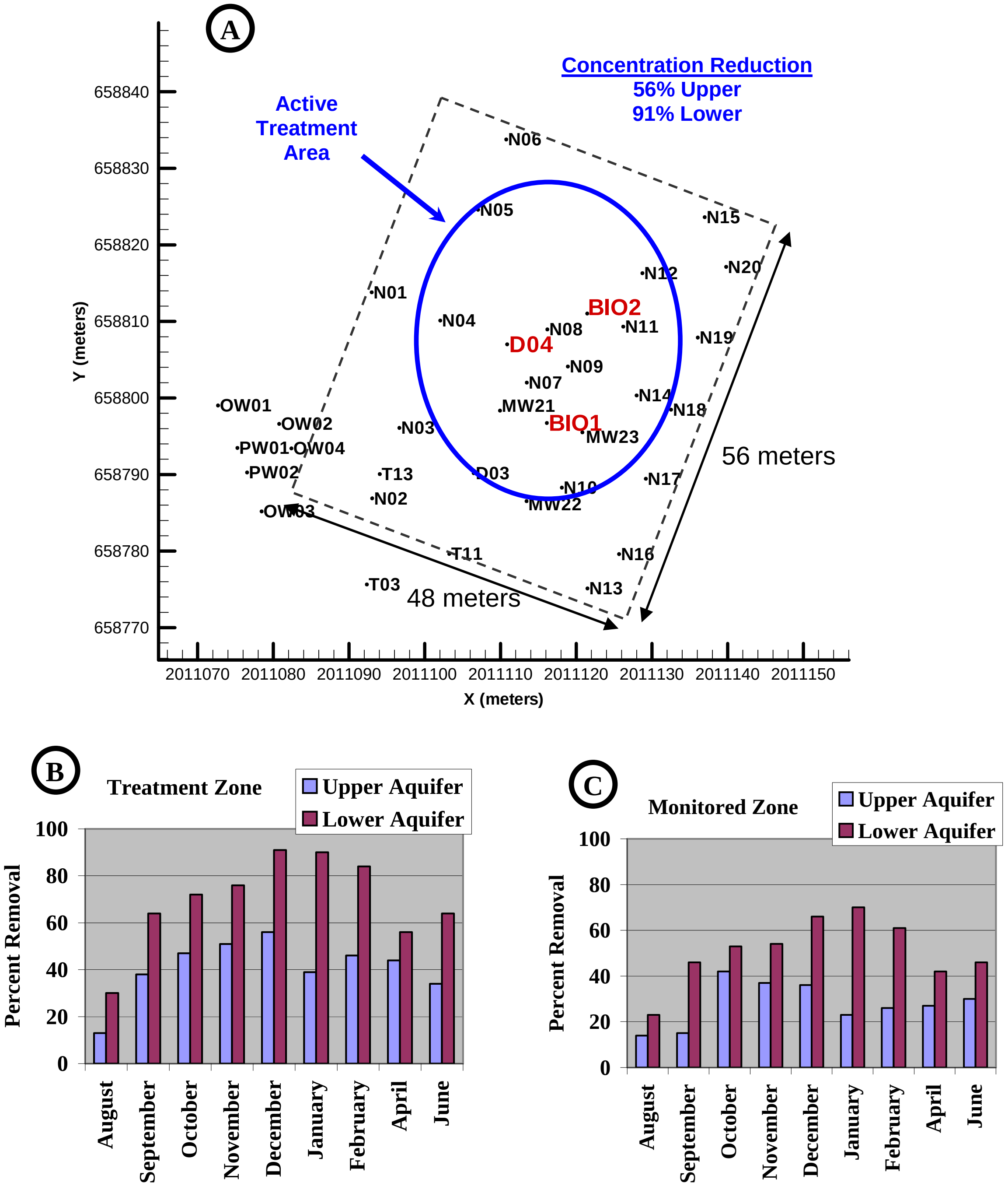
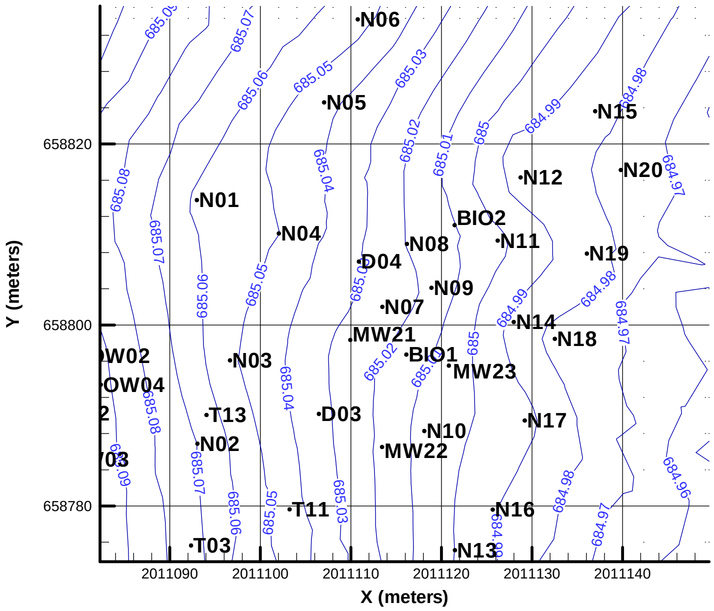


Figure 12. Percentage of TCE removal by BEHIVS treatment in the upper and lower portions of the aquifer at Edwards Air Force Base. Note: Figures showing (A) map of treatment zone, (B) monthly percent removal in the treatment zone, and (C) monthly percent removal in the monitored zone.

a) shallow aquifer



b) deep aquifer

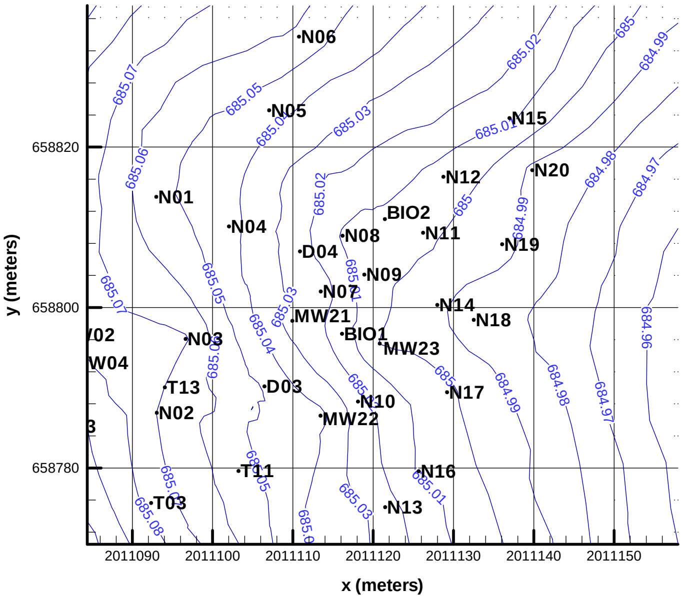


Figure 13. BEHIVS site heads measured on July 27, 2001 for shallow (684 meters—top map) and deep (677 meters—bottom map) wellscreens. Note: This map represents flow conditions prior to BEHIVS system startup; no wells are pumping.

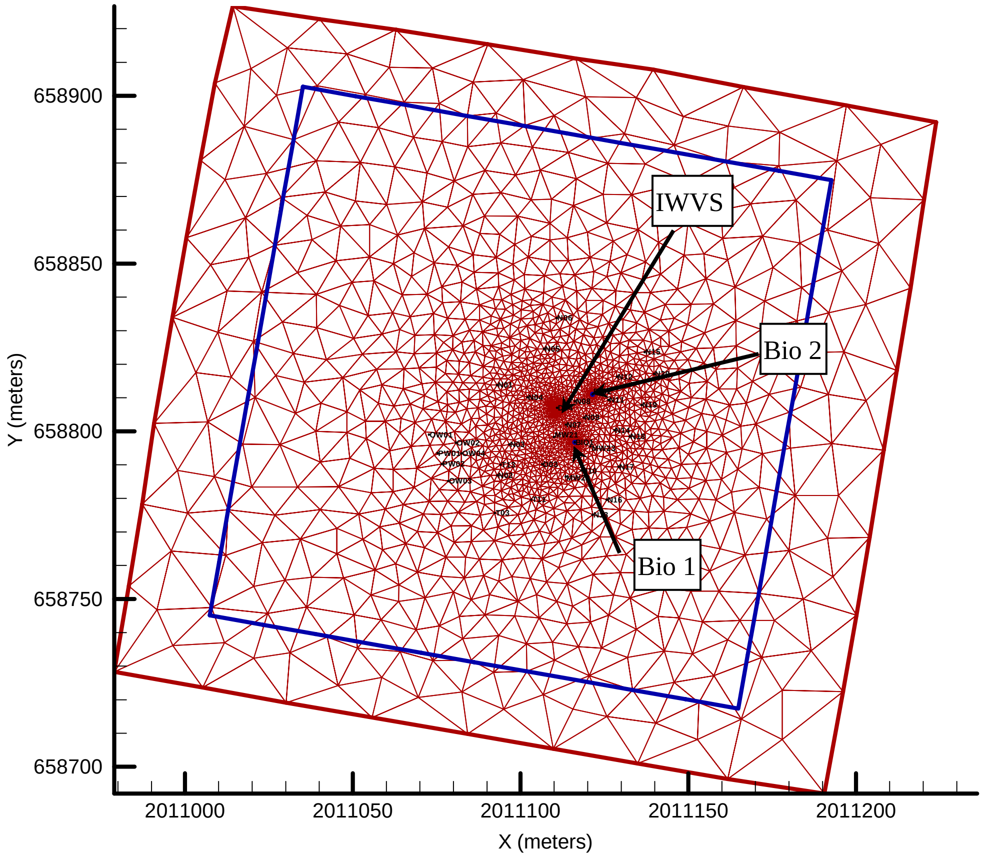


Figure 14. Plan view of the BEHIVS model grid with enlarged domain. Note: The blue inner boundary shows the old model domain. The grid consists of 26,726 nodes and 49,205 elements over 13 vertical layers.

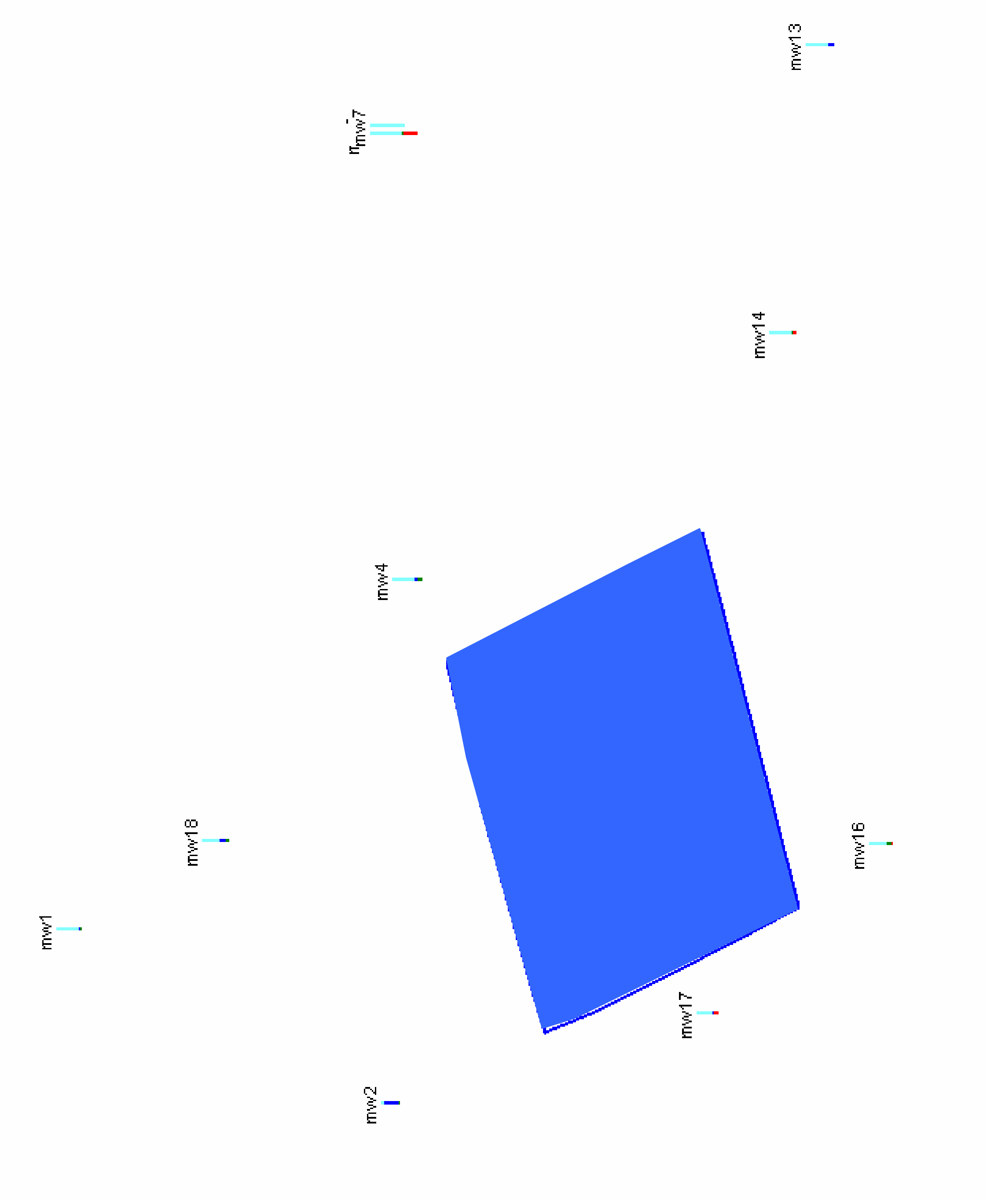


Figure 15. Location of boreholes used to characterize BEHIVS site. Note: The blue square is the boundary of the BEHIVS model domain; the BEHIVS monitoring and treatment wells are clustered in its center.

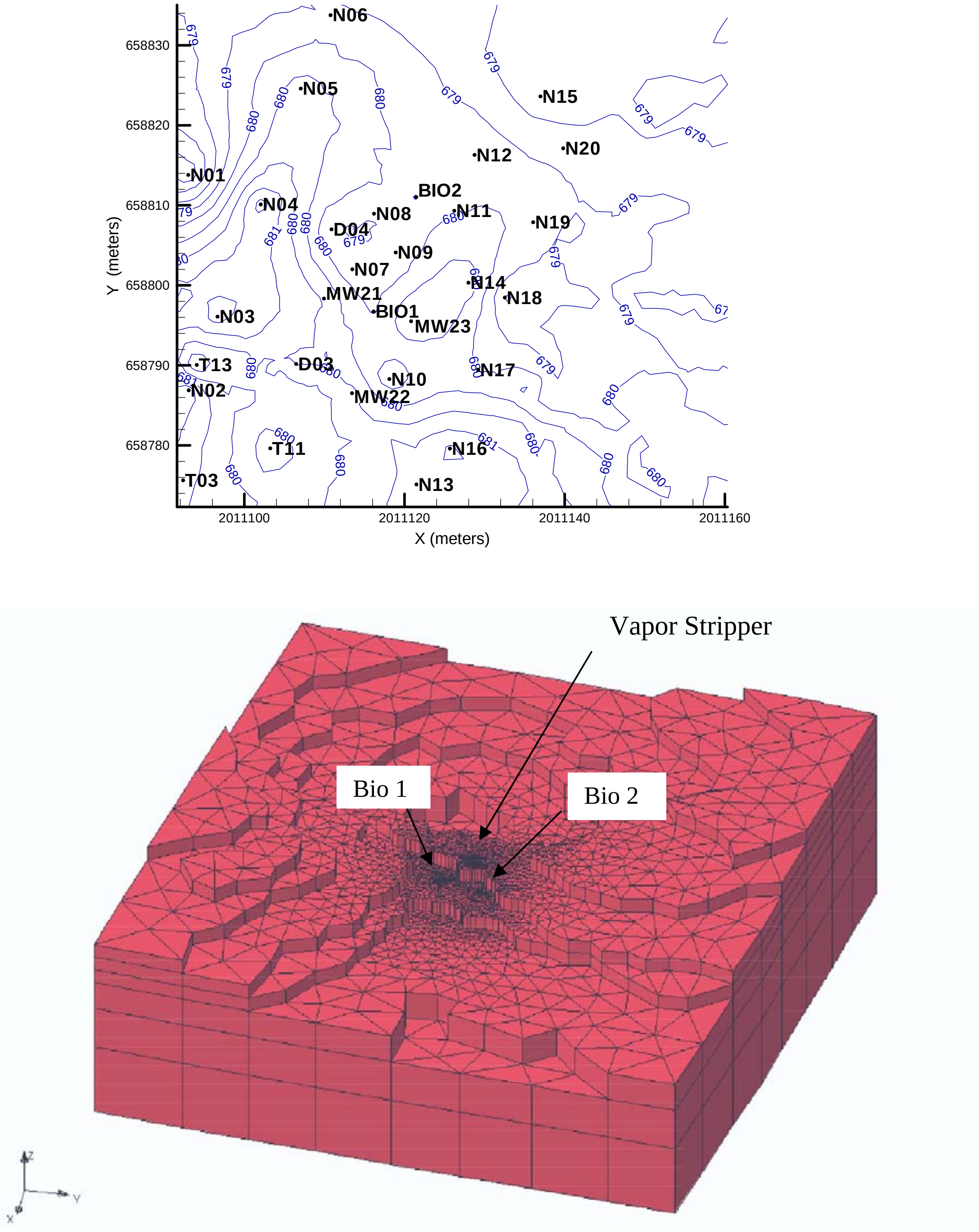


Figure 16. Aquifer bottom /competent bedrock elevation (in meters) in BEHIVS model.

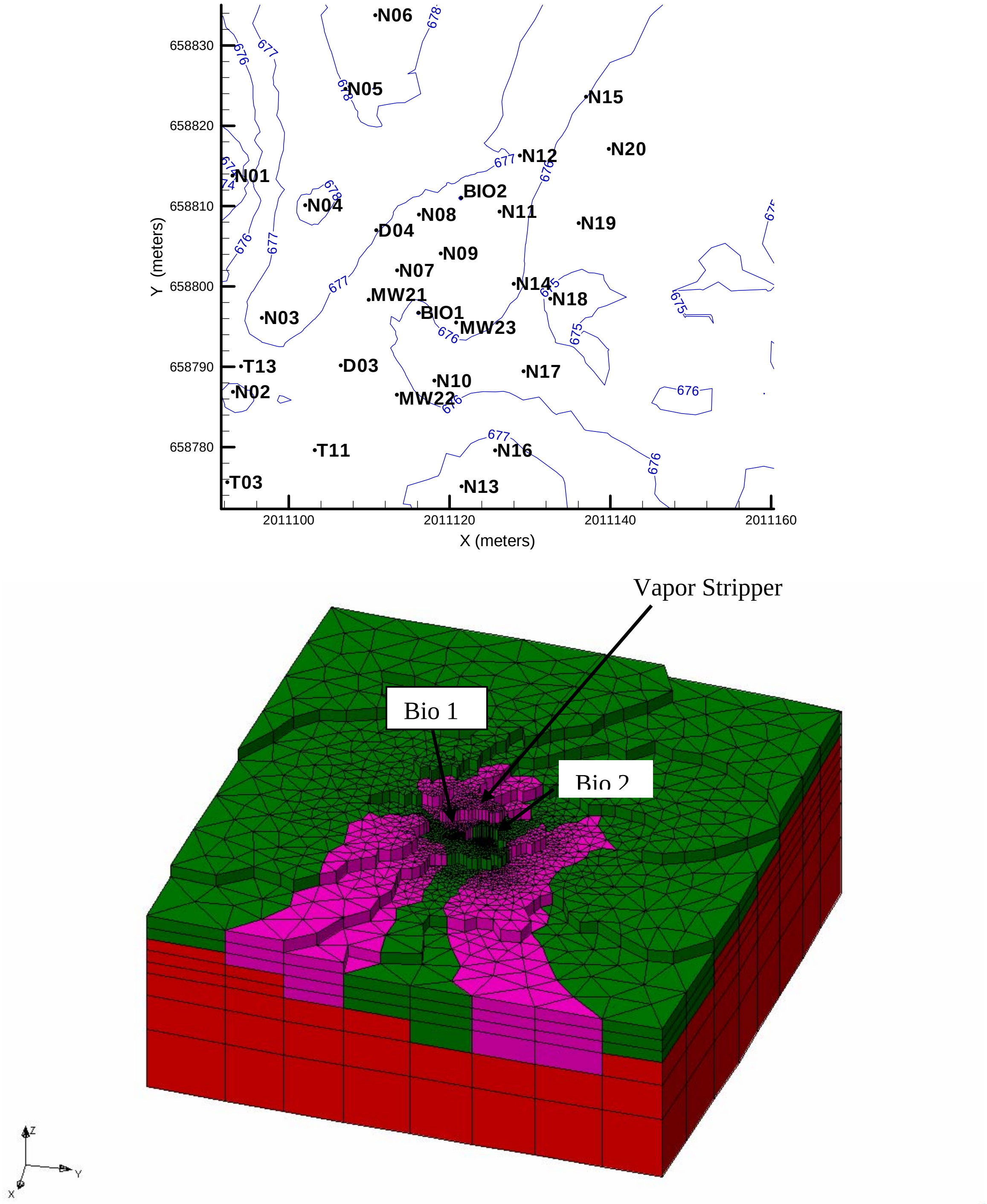


Figure 17. Weathered bedrock elevation (in meters) in BEHIVS model. Note: The green material is the weathered bedrock and red is the competent bedrock below. The pink material is the low conductivity zone within the lower aquifer.

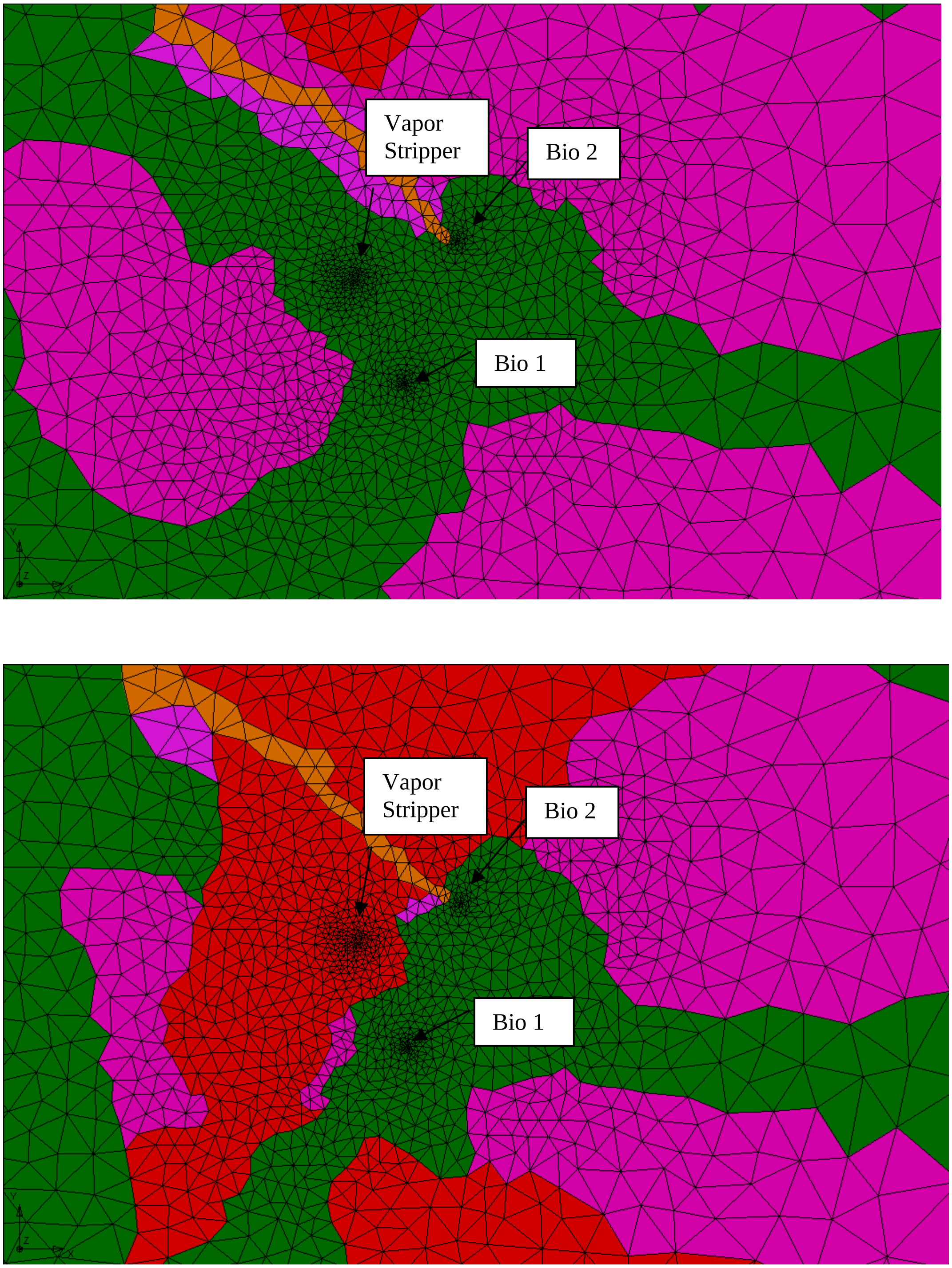
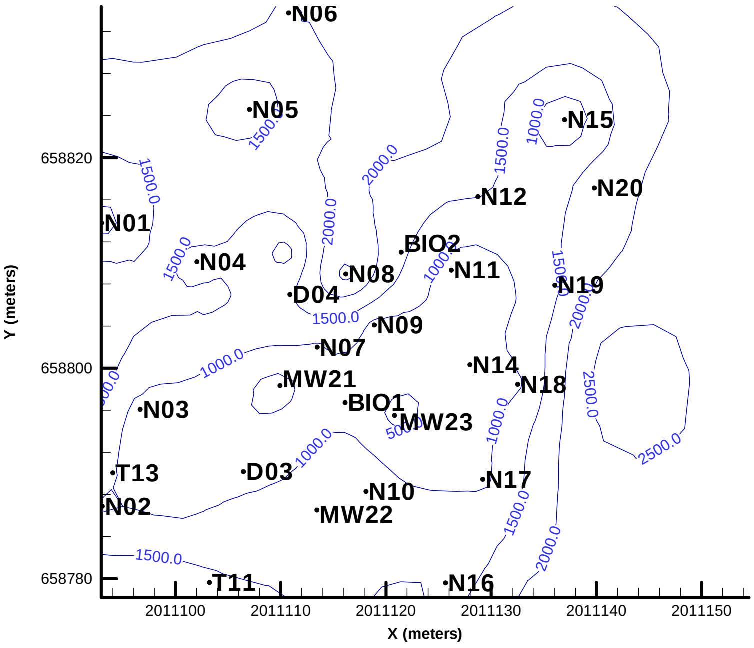


Figure 18. Model material types in lower aquifer. Note: The upper figure represents the upper portion of the lower aquifer, and the lower figure represents the lower portion of the lower aquifer. The green area is the weathered bedrock; red is competent bedrock. The pink areas are the low conductivity zone. The orange channel is the high conductivity channel leading to monitoring well N05.

a) shallow aquifer



b) deep aquifer

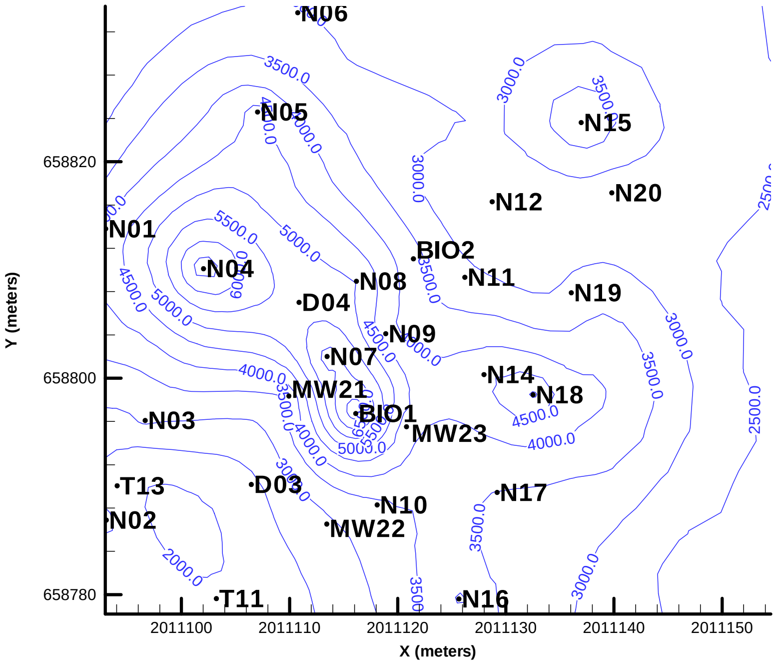
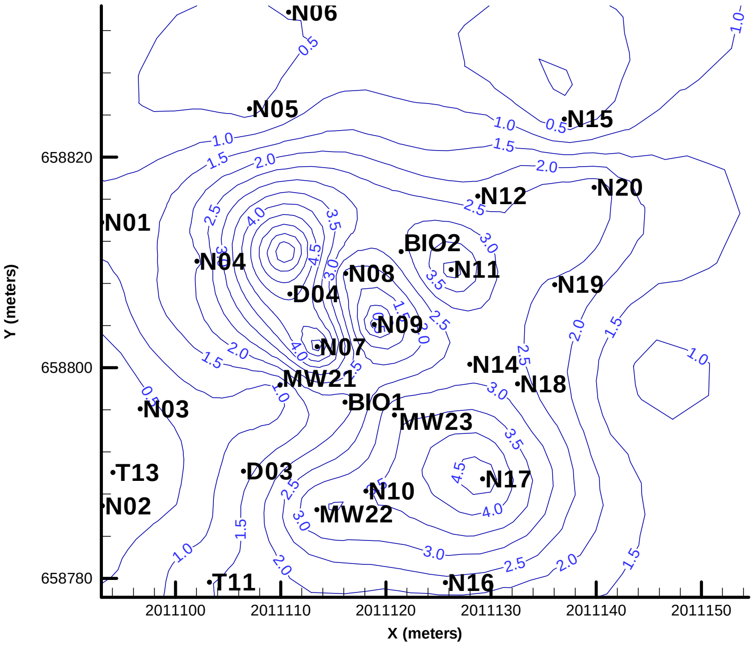


Figure 19. TCE initial conditions in BEHIVS model in a) shallow and b) deep aquifers.

a) shallow aquifer



b) deep aquifer

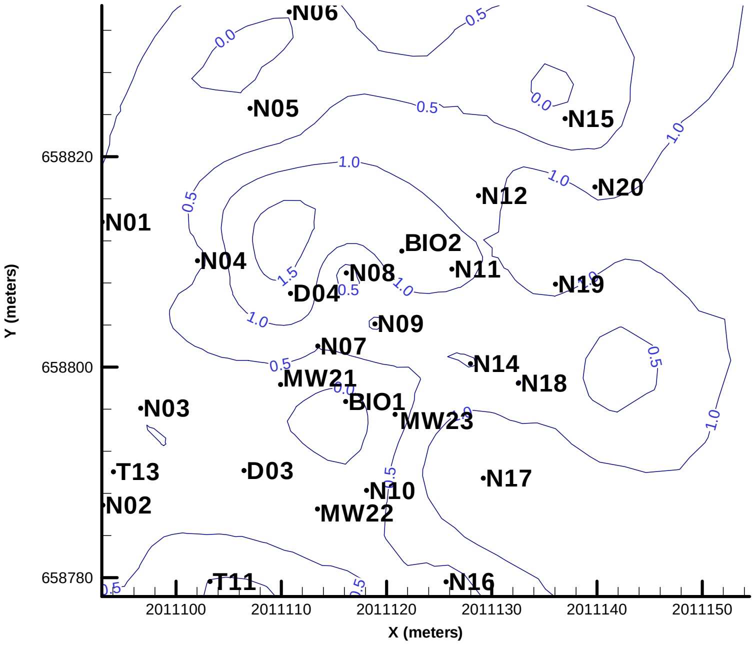


Figure 20. Dissolved oxygen initial conditions in BEHIVS model in a) shallow and b) deep aquifers.

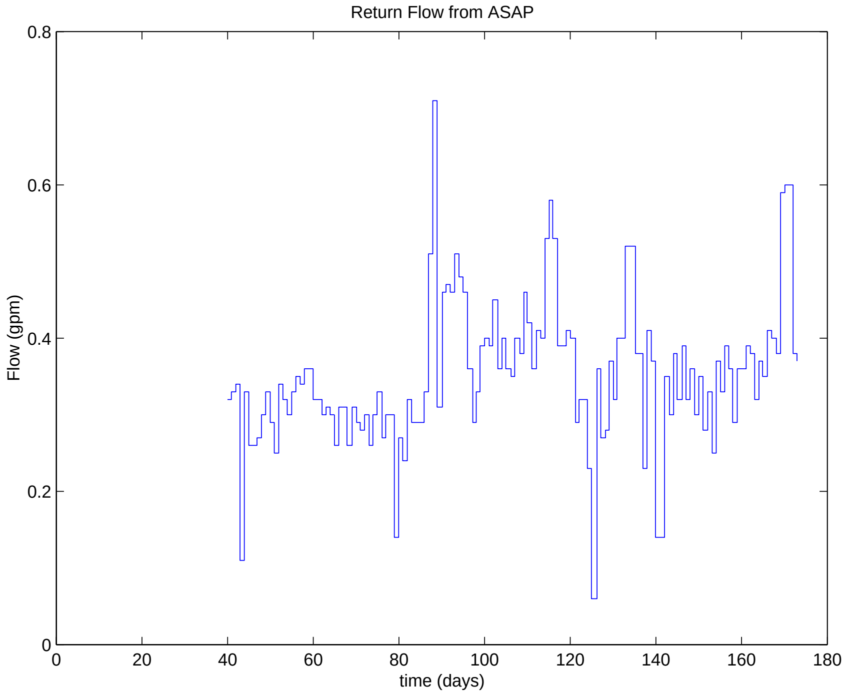


Figure 21. Sampling return water flow volume. Note: This water is injected into the biotreatment wells until January 9, 2002, at which point it is returned via the upper screen of the IWVS.

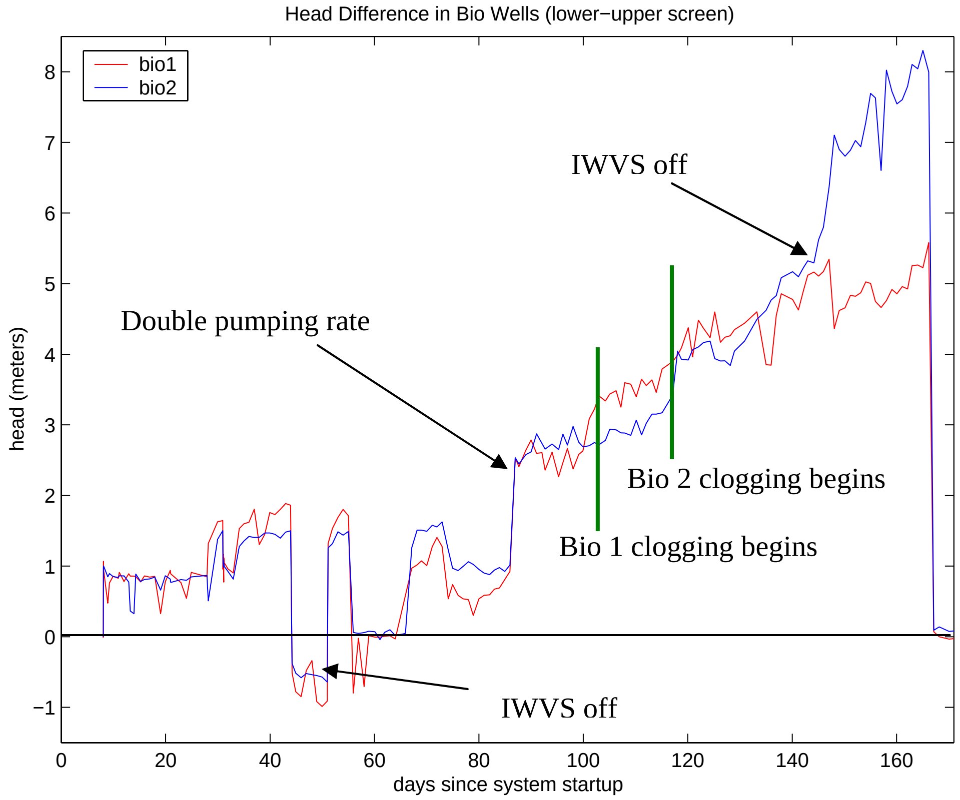


Figure 22. Pressure differential measured from lower to upper screens in biotreatment wells.

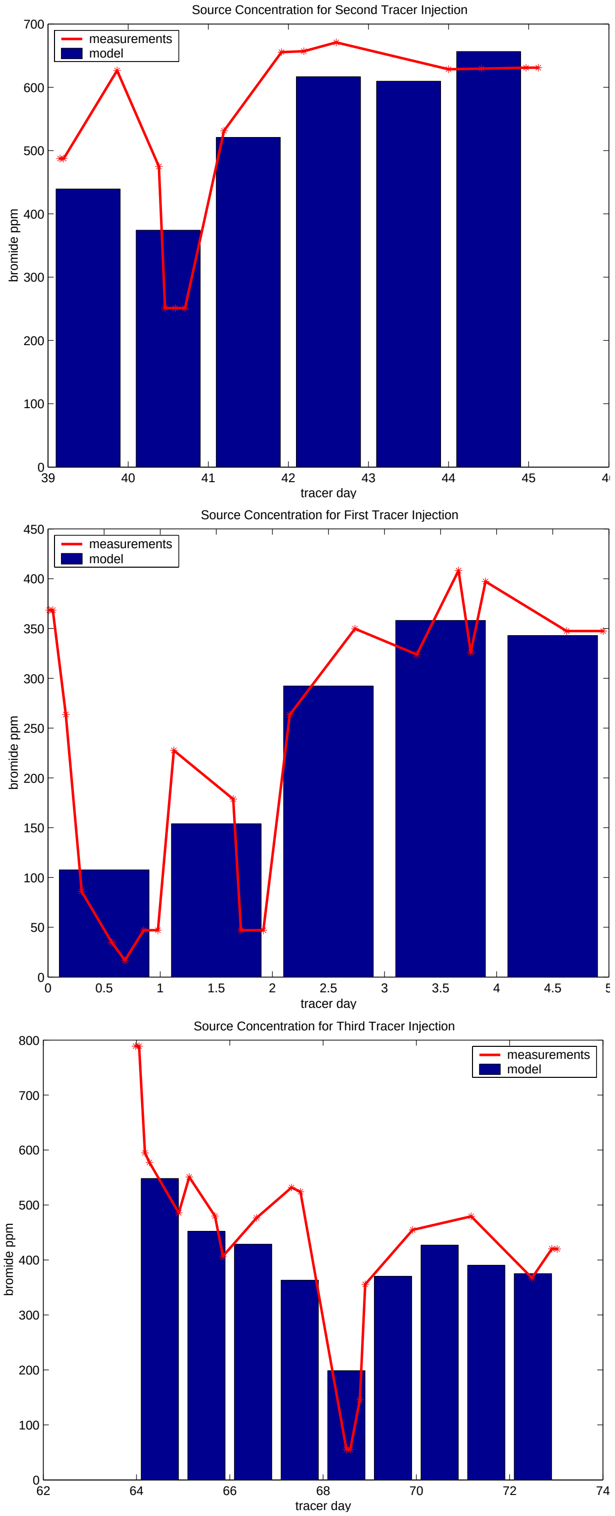
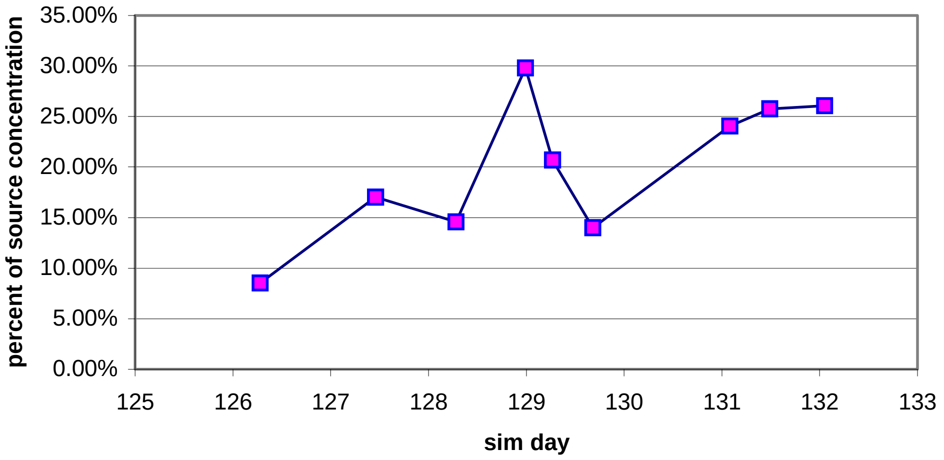


Figure 23. Modeled bromide injection for BEHIVS tracer test. Note: The blue bars are the mass averaged model concentrations (for a one-day time step) and the red stars are measurements.

a) biotreatment well one



b) biotreatment well two

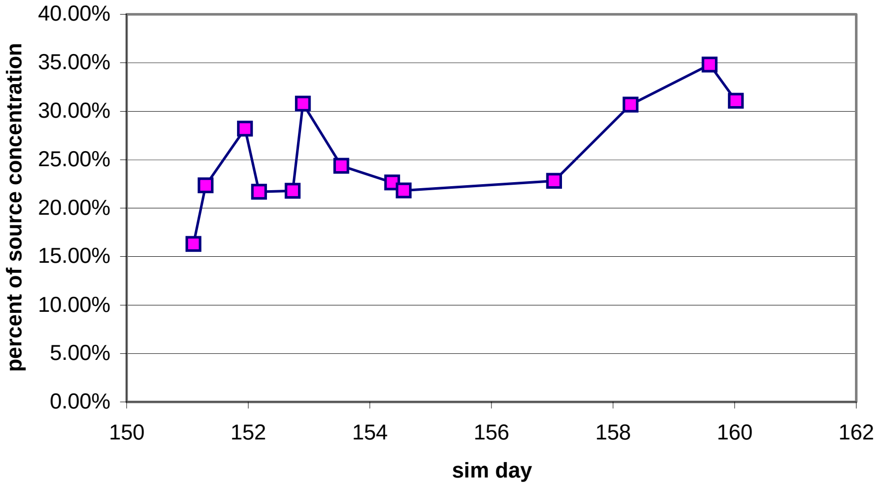


Figure 24. Bromide recycling at biotreatment wells during tracer test. Note: The figures show the percent of source concentration that instantaneously appears at the non-injection screen.

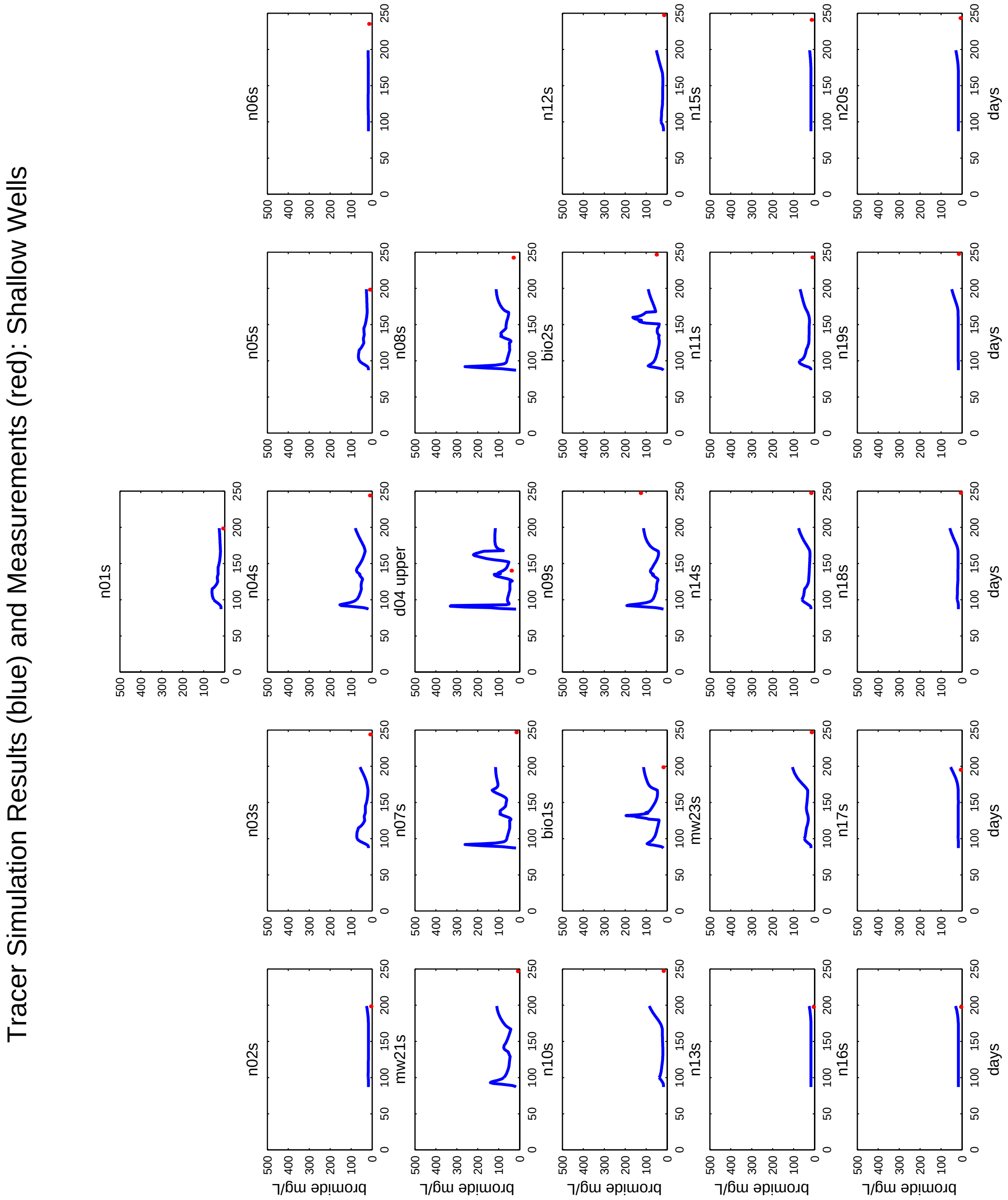


Figure 25. BEHIVS tracer model fit to measured bromide over time at shallow wellscreens. Note: The blue lines are model results for monitoring well locations and red dots are measurements.

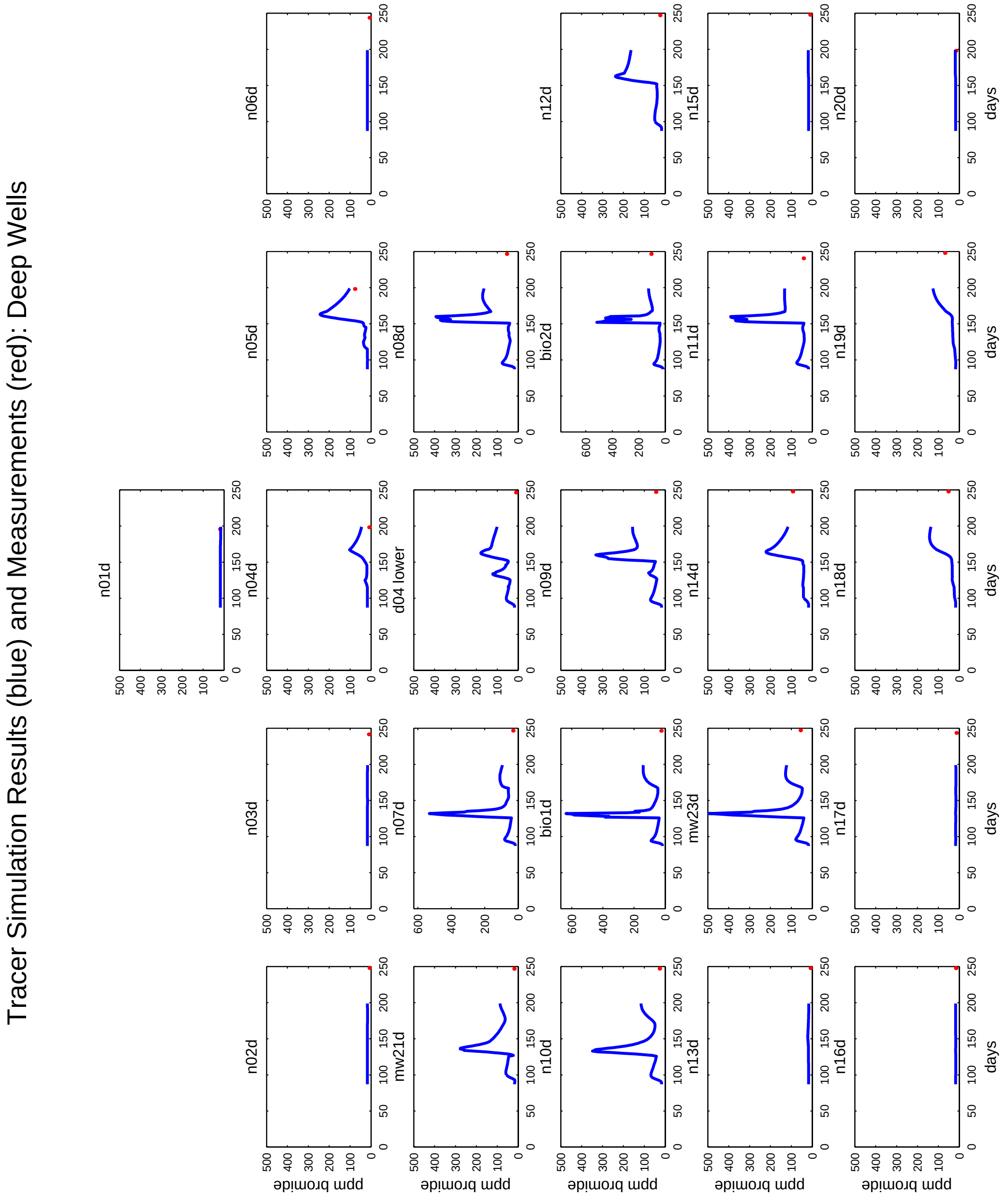


Figure 26. BEHIVS tracer model fit to measured bromide over time at deep wellscreens. Note: The blue lines are model results for monitoring well locations and red dots are measurements.

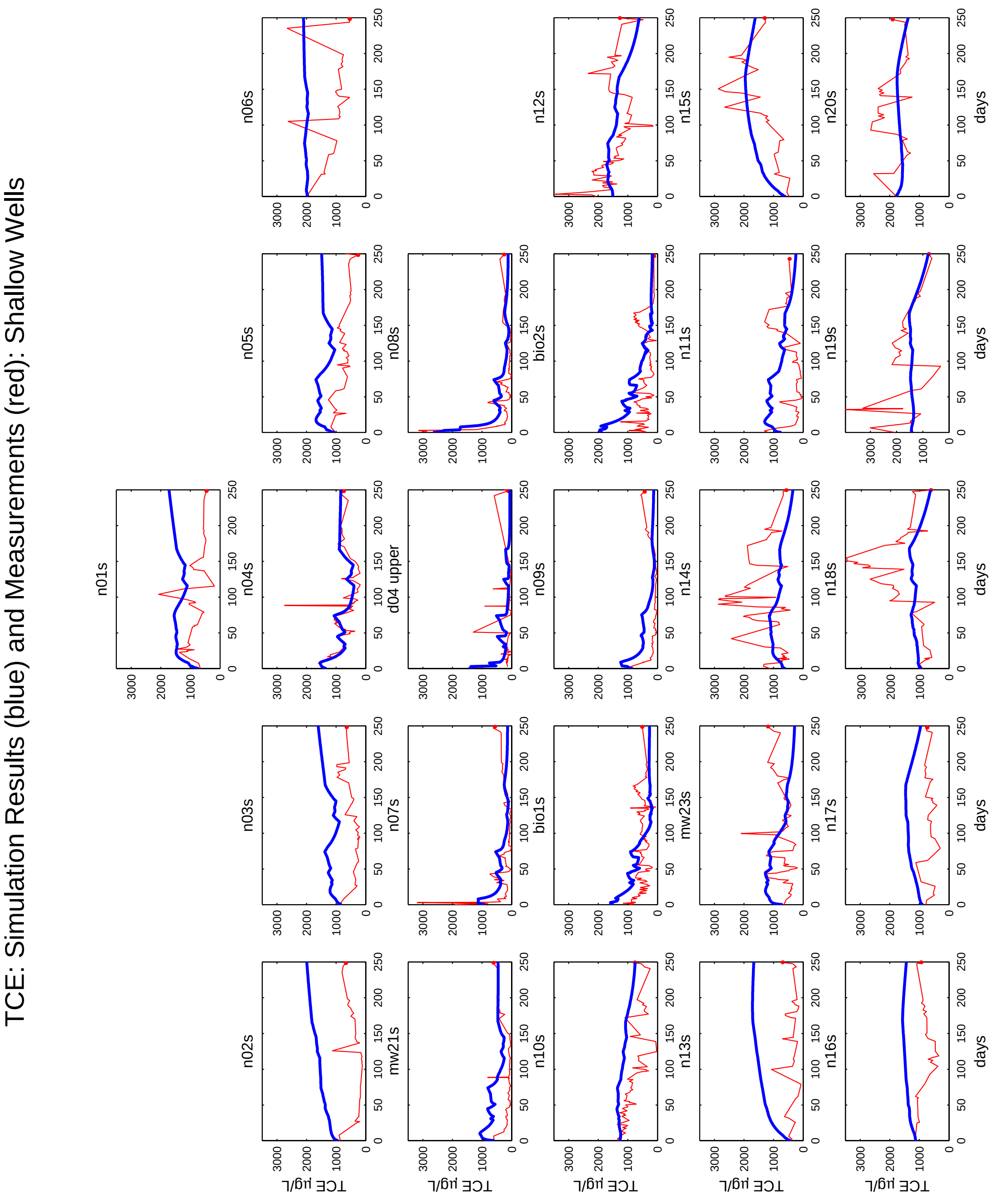


Figure 27. BEHIVS bioremediation model fit to measured TCE over time at shallow wellscreens. Note: The blue lines are model results for monitoring well locations and red dots are measurements.

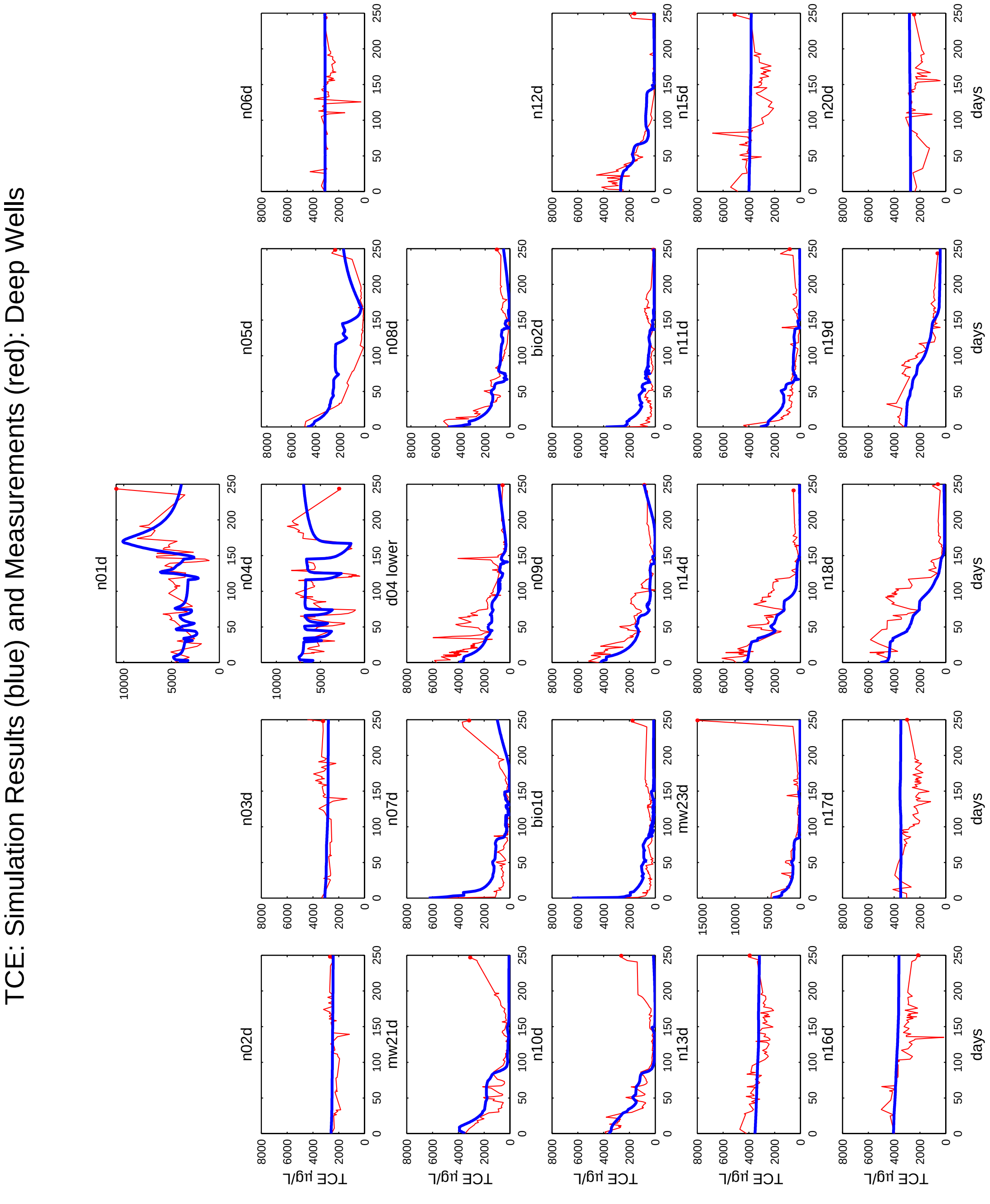


Figure 28. BEHIVS bioremediation model fit to measured TCE over time at deep wellscreens. Note: The blue lines are model results for monitoring well locations and red dots are measurements.

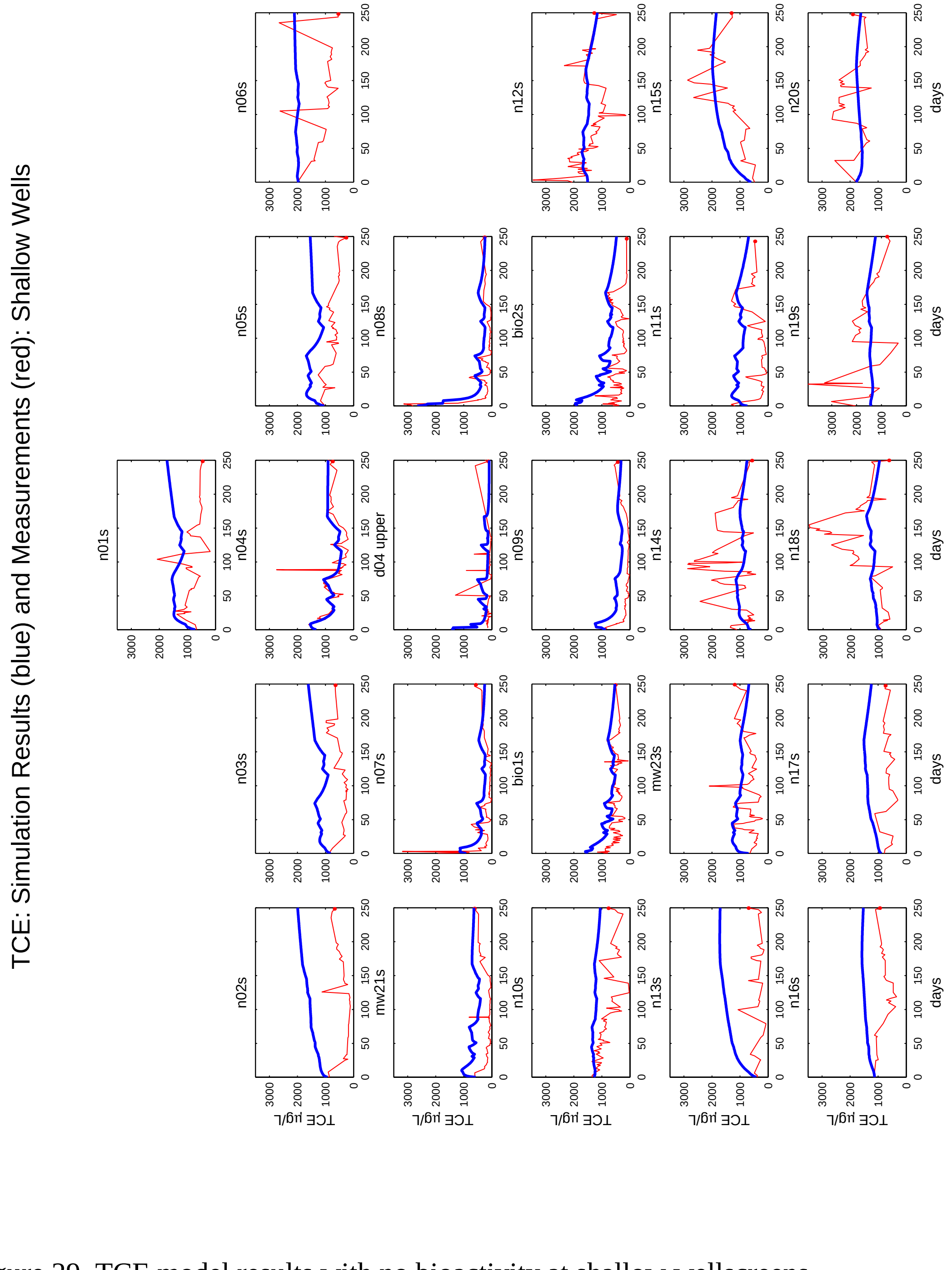

TCE: Simulation Results (blue) and Measurements (red): Shallow Wells

Figure 29. TCE model results with no bioactivity at shallow wellscreens.

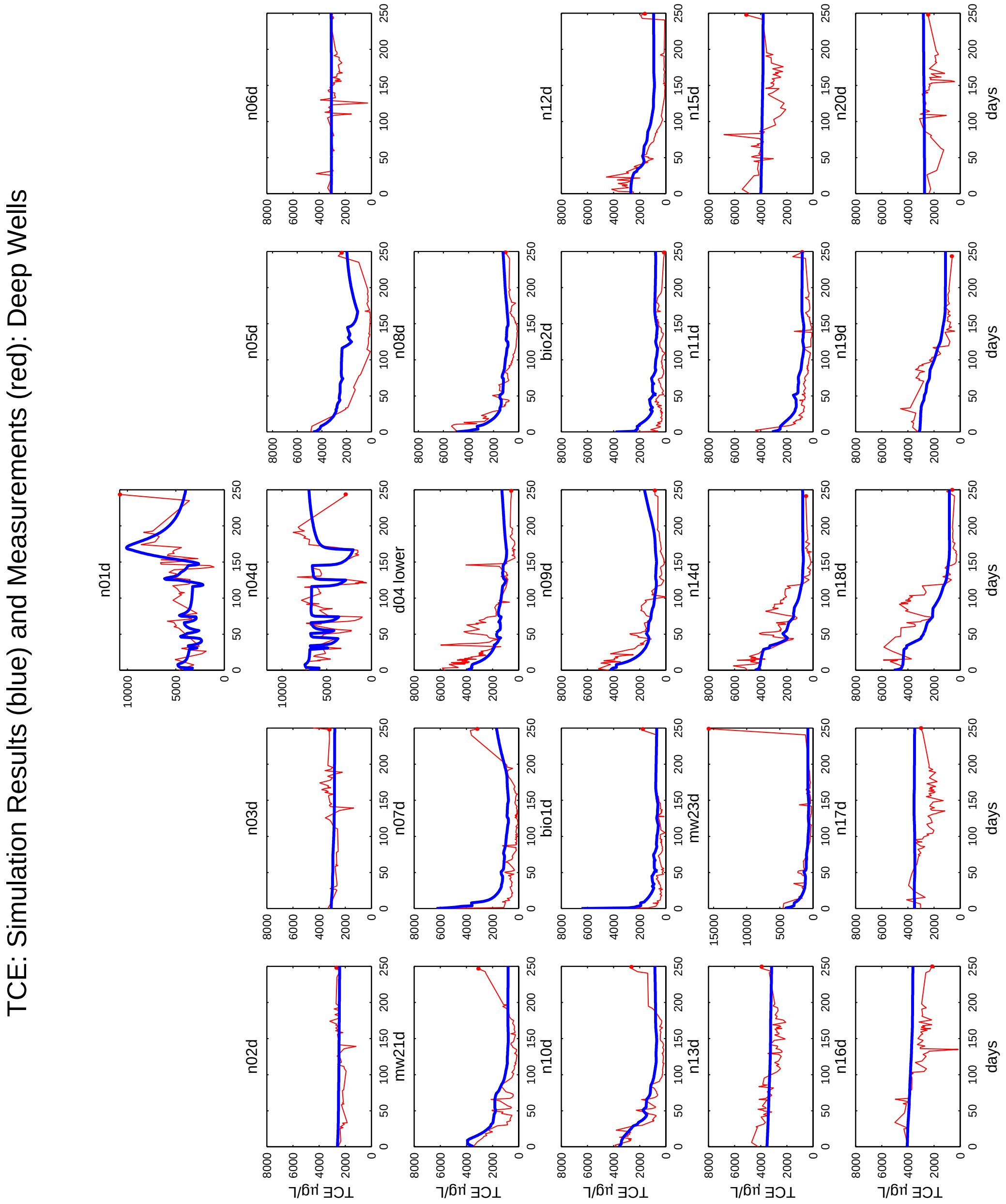


Figure 30. TCE model results with no bioactivity at deep wellscreens.

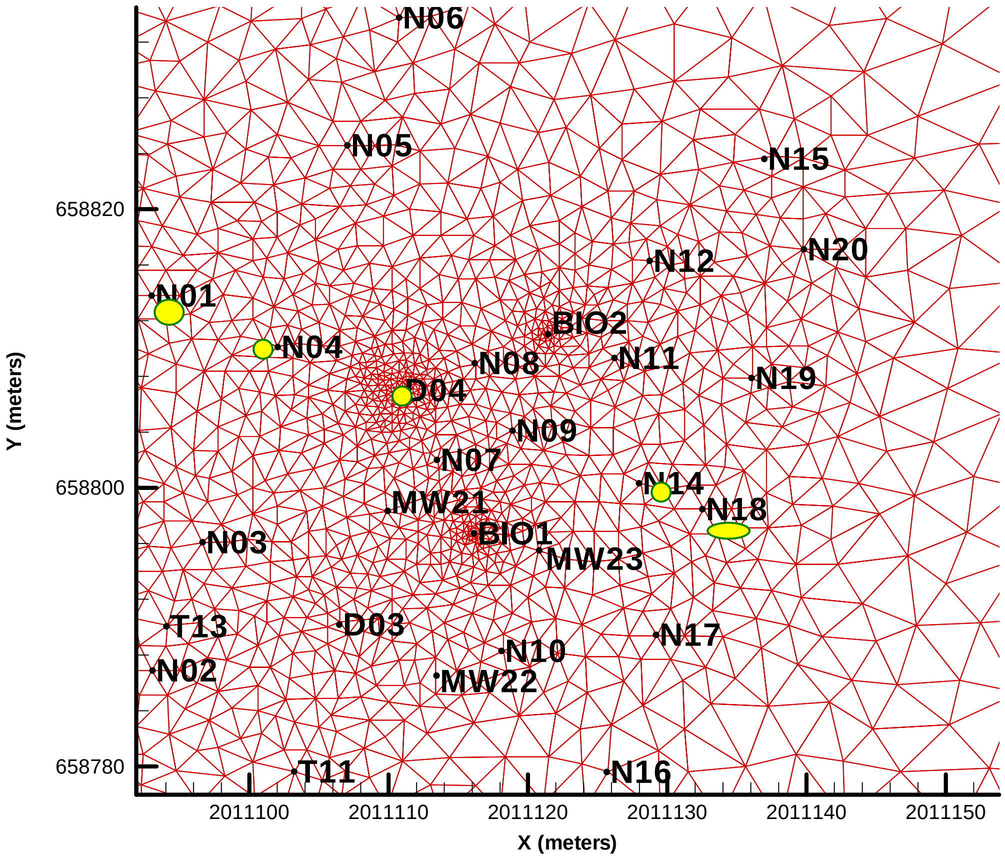


Figure 31. Location of TCE rebound sources (yellow circles). Note: These sources are very localized, in most cases consisting of two model nodes. The source locations near the upgradient wells (N01 and N04) are more certain than the other locations.

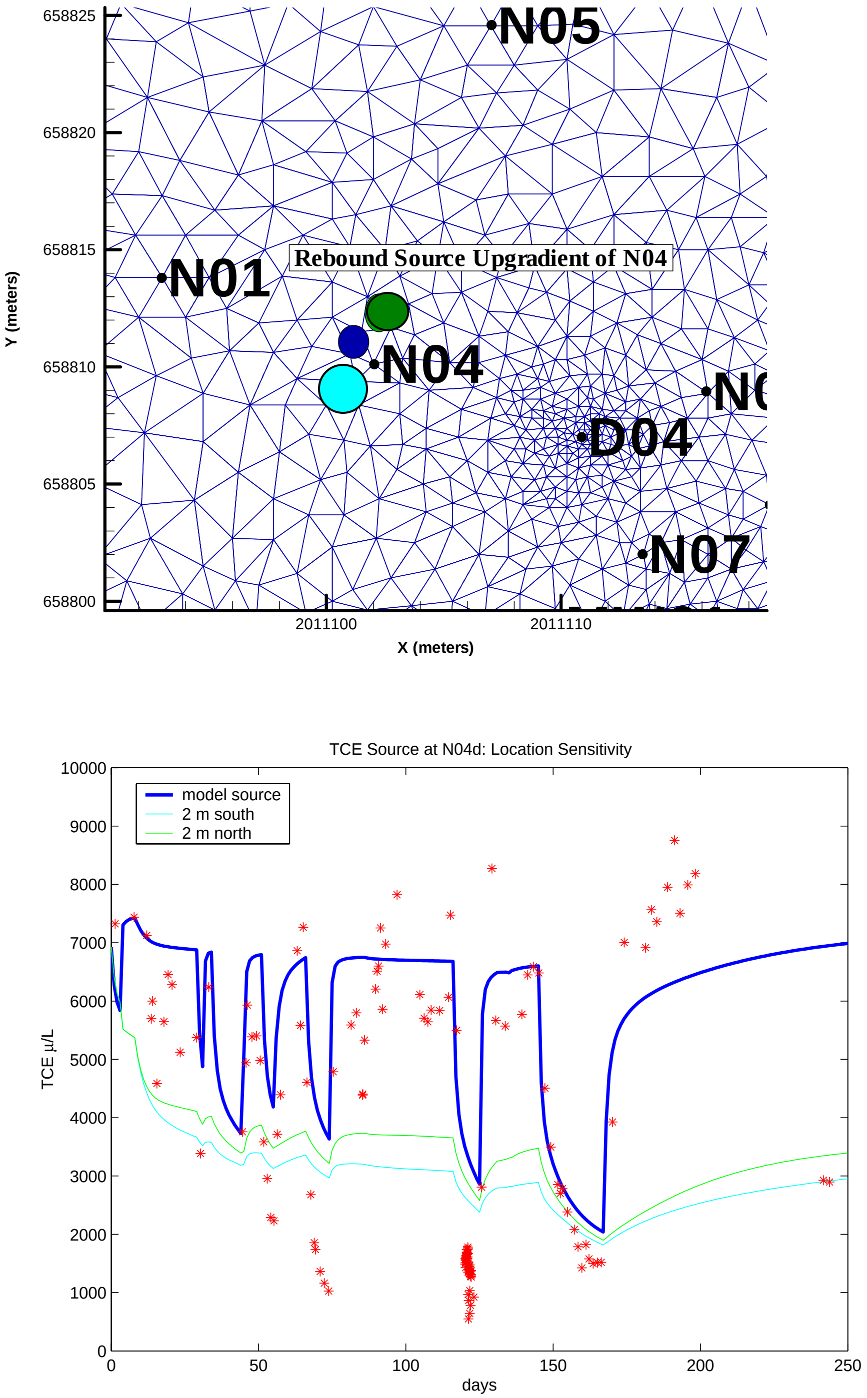


Figure 32. The effect of small differences (on the order of two meter) in TCE source locations. Note: Red dots are TCE measurements at well. The upper figure shows the likely source location as a dark blue dot. The dots to the north (green) and south (light blue) correspond to the green and light blue model results in the lower figure—less likely source locations.

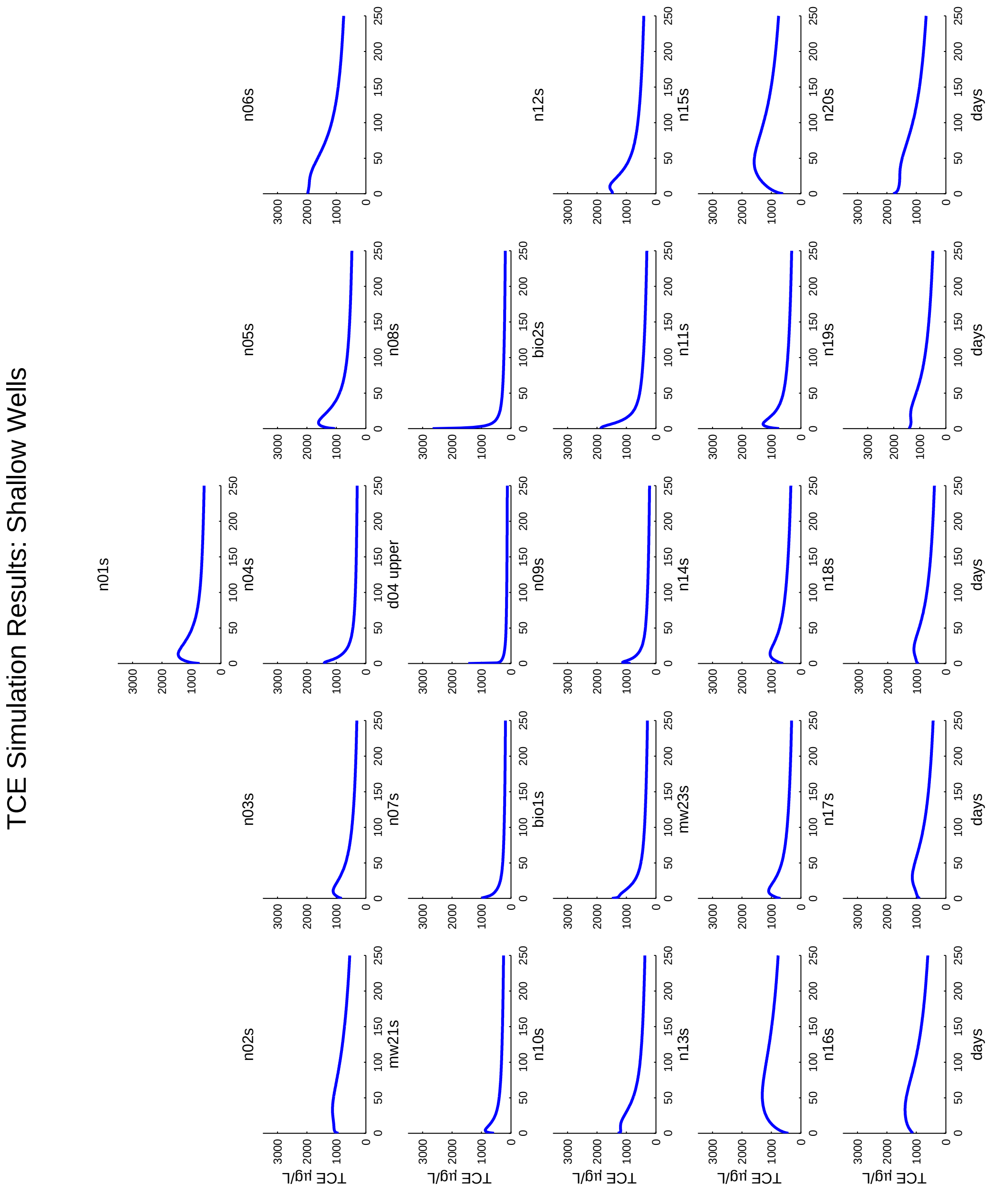


Figure 33. TCE model results at shallow wellscreens with biotreatment wells turned off. Note: Only the vapor stripper is operational.

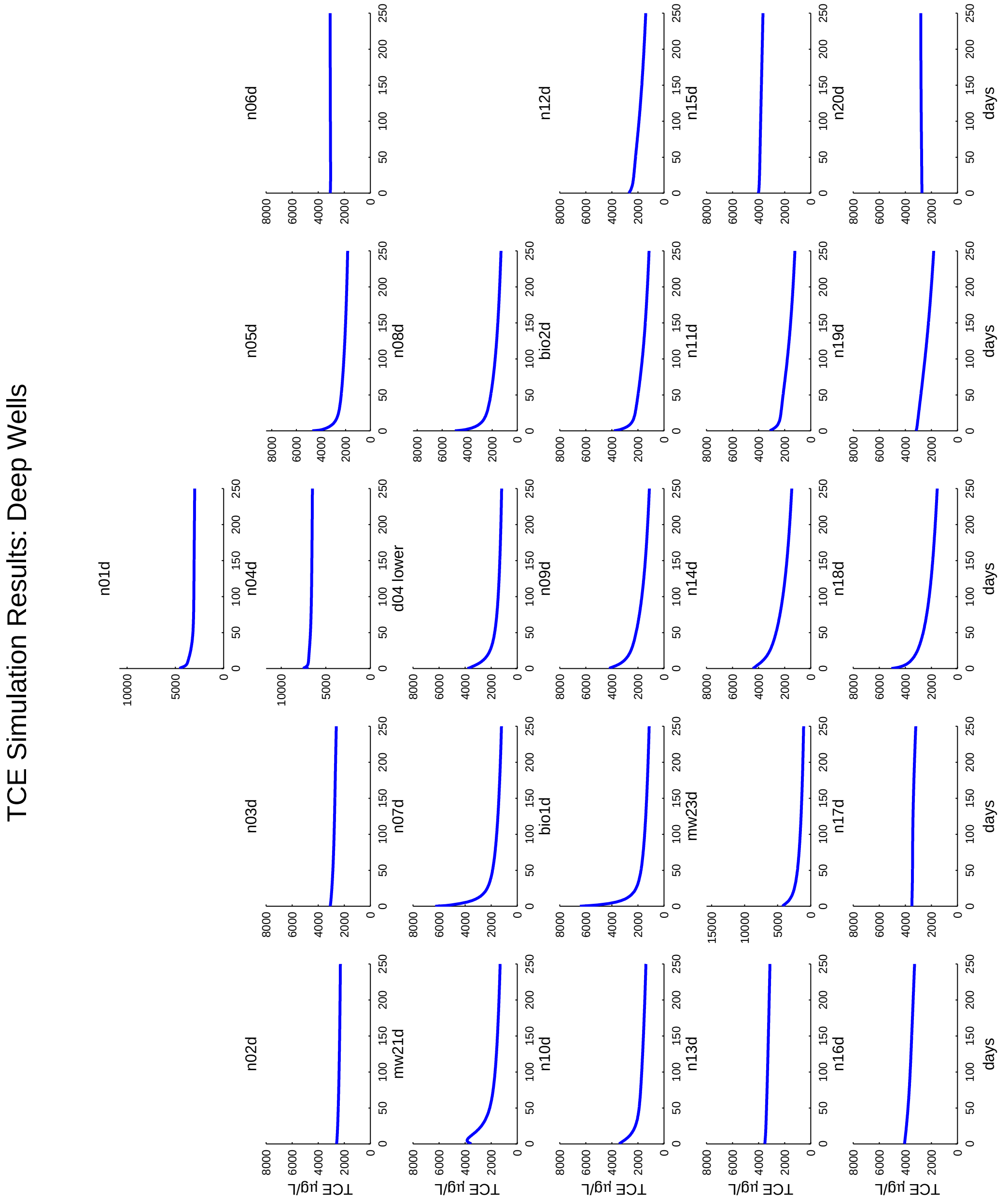


Figure 34. TCE model results at deep wellscreens with biotreatment wells turned off. Note: Only the vapor stripper is operational.

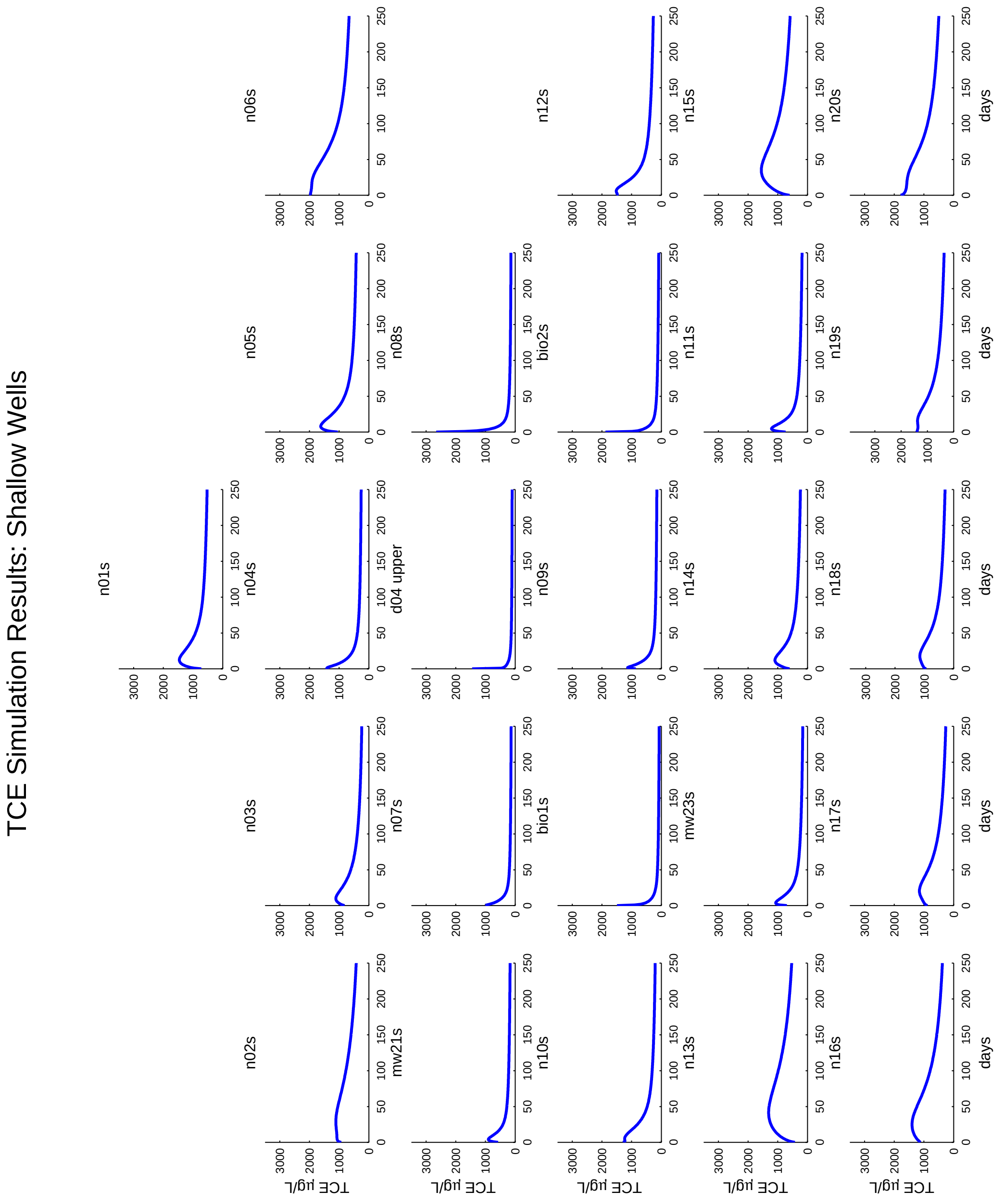


Figure 35. TCE model results at shallow wellscreens with all three treatment wells vapor stripping, pumping from lower aquifer and injecting in upper aquifer.

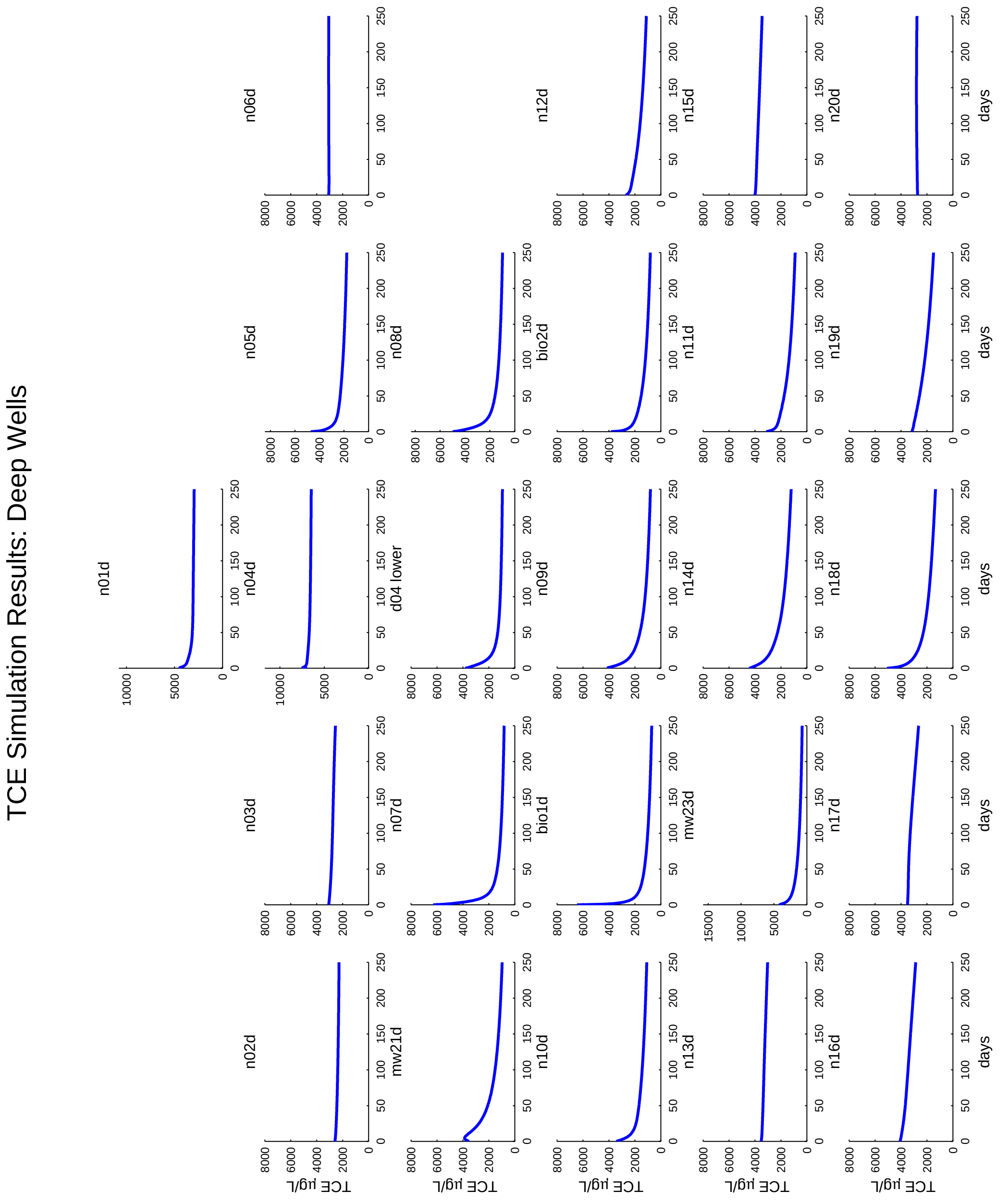


Figure 36. TCE model results at deep wellscreens with all three treatment wells vapor stripping, pumping from lower aquifer and injecting in upper aquifer.

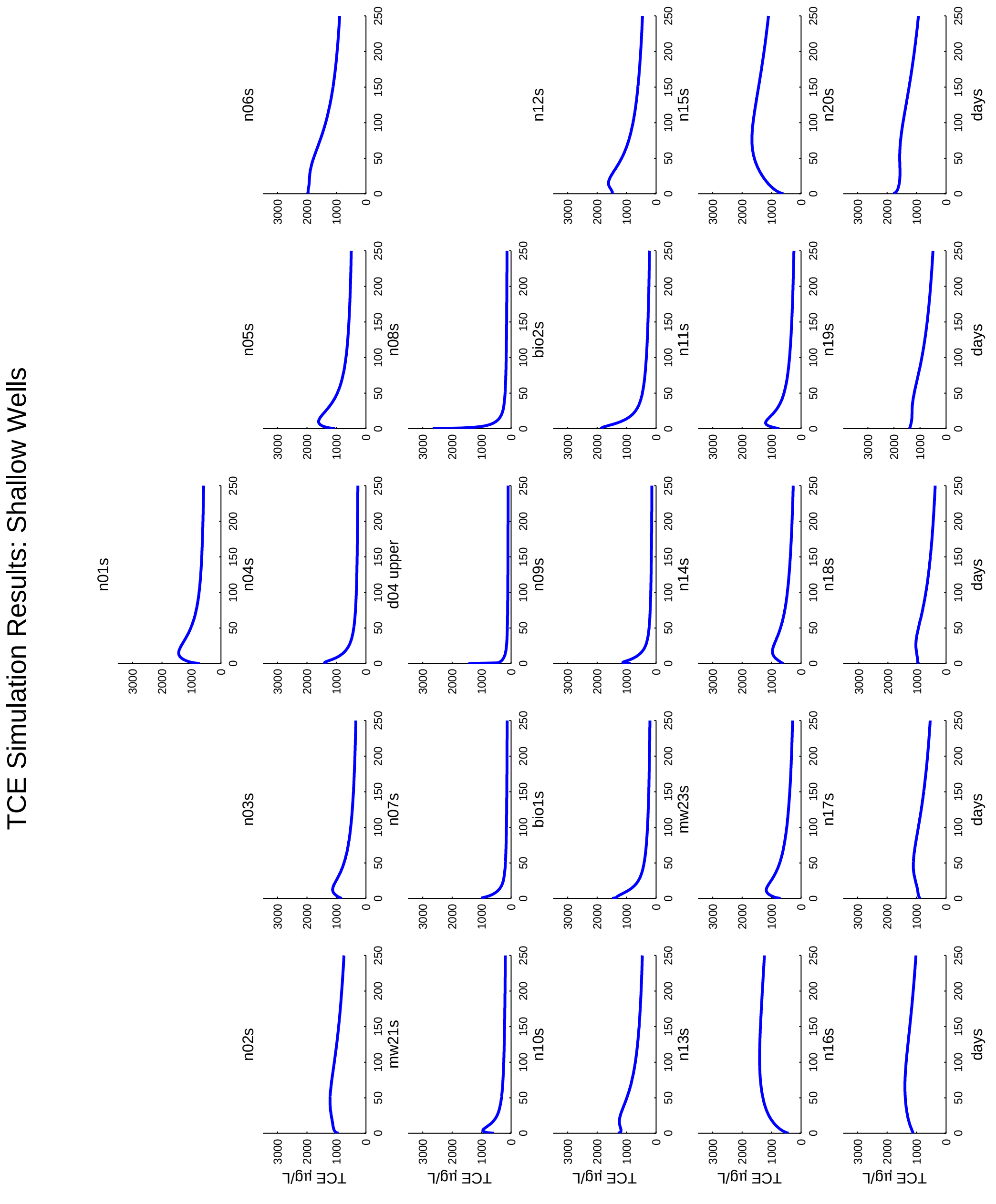


Figure 37. TCE model results at shallow wellscreens with all three treatment wells vapor stripping, biotreatment wells pumping upper to lower and vapor well pumping lower to upper.

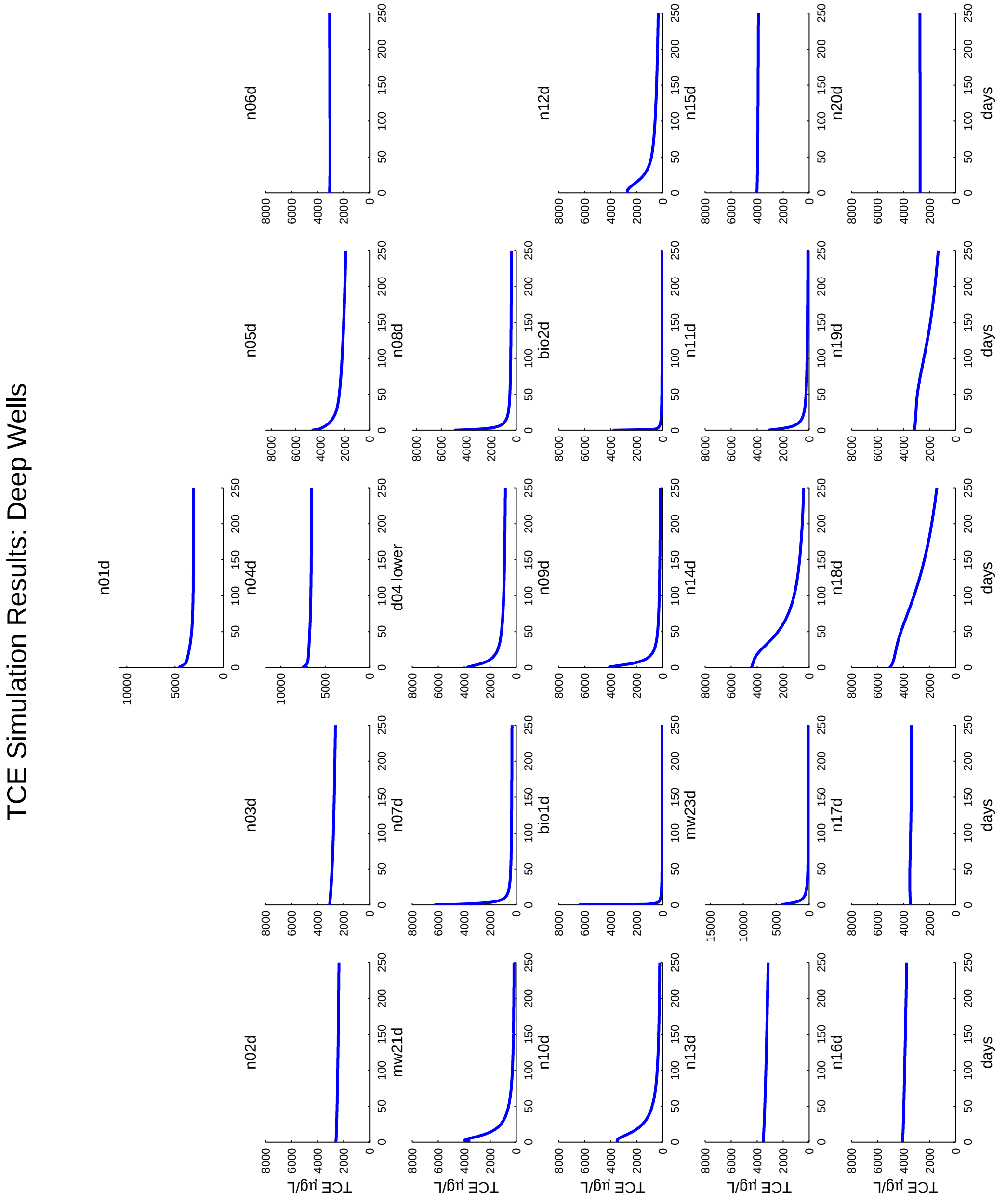


Figure 38. TCE model results at deep wellscreens with all three treatment wells vapor stripping, biotreatment wells pumping upper to lower and vapor well pumping lower to upper.

Appendix A: Details of BEHIVS System Design

A.1 In-Well Vapor Stripping Well Design

The in-well vapor stripping (IWVS) well was installed through a 16” borehole produced by air rotary casing hammer (ARCH) method. Casing refusal occurred at 66 ft (20.1 m) below ground level (BGL), indicating solid bedrock. Following this point, the drilling was open bore to a total depth of 93 feet (28.3 m) BGL.

The IWVS well is composed of a 10” stainless steel (SS) blank section extending 3 feet (1 m) above ground level to 11 feet (3.3 m) BGL, followed by 15 feet (4.6 m) of wire wound screened section. Thus the upper screen zone was 11 feet to 26 feet (3.3 - 7.9 m) BGL. A 2-foot section of 10” blank with a transition to 6” SS blank lies between the upper and lower screens. The lower 6” screened section is 42.5 to 92.5 feet (13 - 28.2 m) BGL. The lower sand pack, 41 to 93 feet (12.5 – 28.3 m) BGL provided connection to any bedrock fractures in the range of 66 to 93 feet (20.1 – 28.3 m) BGL.

A bentonite/concrete seal was placed between 30 and 39 feet (9.1 – 11.9 m) BGL as well as in the upper 9 feet (2.7 m) of borehole. Screened sections of the borehole were backfilled with #3 Lonestar sand. Transition sands (finer grades) were placed at the interface to the bentonite seals.

In addition to the IWVS well, three 2” monitoring wells were also installed within the 16” borehole. These monitoring wells were composed of 2” schedule 40 PVC blank pipe with 2 ft (0.6 m) of SS wire wound screens at the bottom. The screened sections were placed at 23.5 to 25.5 ft BGL (DO4-A), 42.5 to 44.5 ft BGL (DO4-B) and 90.5 to 92.5 ft BGL (DO4-C).

Three infiltration galleries were install prior to the IWVS well installation. The galleries were produced by trenching 1.5 X 14 X 15 foot deep trenches starting 2 feet from the center of the proposed IWVS well location at 120^{o} spacing. The lower foot was back-filled with #3 Lonestar sand and a 10 foot X 4”slotted PVC screen was installed with a 2” riser at the outer end of the screened section, used for measurement of water level in the infiltration gallery. Approximately

10 feet of #3 Lonestar sand was then backfilled over the infiltration screened pipe and a second 2” screened pipe was placed in the trench with a riser on the outer end to be used as part of a vodose zone extraction system. Another foot of #3 Lonestar sand was backfilled and the entire trench was covered with plastic sheeting. The remainder, approximately 2 feet, of trench was back filled with native material.

The primary eductor for the IWVS well was 3 inch SS well casing extending from approximately 2 feet BGL to 67 BGL. A welded 8 inch diameter flange was located 30 ft BGL and supported the eductor on the transition of 10” to 6” well casing. Neoprene rubber was used to form a seal below the flange thus isolating the upper and lower screened sections. At the bottom of the 3 inch casing used as the eductor, a transition to 3/4” SS pipe was made and 3/4” pipe extended the water inlet to 91 ft BGL. Installed 5 feet below this transition was a Signet paddle wheel flow sensor for measuring water flow through the IWVS well. At the upper end of the eductor, a 8 inch X 2 ft sump surrounded the eductor pipe. This sump had piece of 2 inch well casing attached with a 2 to ¾ reducer at the bottom. This sump functioned for the placement of a Grundfos Rediflo-2 sampling pump for collection of IWVS effluent (DO4-U). On the exterior of the eductor and approximately 10 feet below the supporting flange, a pressure transducer (In-Situ) was attached for monitoring the head in the lower screened section. Another pressure transducer was attached to the eductor above the supporting flange to monitor head within the upper screened section of the IWVS well.

Air was supplied through a 1 inch SS pipe extending down into the eductor and 28 feet below static water table. The lower one foot of the 1” pipe was slotted with about 40 slots ½ way through the pipe from various directions using a 4” hand grinder. The end of the pipe was capped. A Grundfos Rediflo-2 pump was placed about 2 feet below the slotted section of the air supply for ground water sampling of the influent to the IWVS well (DO4-L)

A 6 inch diameter deflector plate was installed on the 1” air supply pipe 1 inch below the top of the PVC sump of the eductor to prevent the air/water mixture from blowing out of the well into the air outlet and forcing much of the water to flow through the sump. Note, when operating a 100 cfm air flow, velocity within the eductor pipe is approximately 38 ft/sec.

The top of the well was sealed with a 10 inch SS blind flange. This flange produces the support for the 1 inch air supply line as well as sealing fittings for the two pressure transducers, two sampling pumps and the flow sensor. In addition, a two inch nipple was welded to the flange to provide for an air outlet. Three additional ports were available for chemical augmentation lines, of which, one was used to add bromide tracer.

Air was supplied to the IWVS well from a 10 HP (3 phase) blower, Koch. The blower speed was controlled via a variable frequency controller (ABB) thus allowing the direct control of air flow rates by controlling blower motor speed. In general, the blower was operated at about 40 hertz. IWVS well air effluent air was treated via two GAC tanks in series with the effluent recycled back to the IWVS well. A ¾ inch ball valve was connected to the blower inlet for the necessary makeup air to minimize the vacuum placed on the GAC effluent port and thus decrease blower heat. Note: blower air output was consistently above 80^o C, PVC pipe should not be used as an air supply to the IWVS well.

A.2 Biotreatment Well Design

The biotreatment wells were installed through a 14” borehole produced by ARCH rig. Total borehole depths were approximately 62 ft BGL with the bottom of the well casings placed at 60 ft BGL. The well casings are double screened (wire wound SS, 6 inch) with the lower screens at 50 to 60 ft BGL and the upper screens at 30 to 40 ft BGL. Backfill sand is #3 Lonestar with transition sand interfaced to the bentonite seals, upper seal at 25 ft BGL and the lower seal at 42 to 47 ft BGL. The upper section, the riser, 30 ft BGL to surface, is constructed of PVC. The 6 inch diameter is the minimum which can accommodate the down hole components.

Both biotreatment wells are operated in the “down flow” mode, pulling ground water in from the upper screen, augmenting the chemical composition with toluene, oxygen, hydrogen peroxide and bromide for tracer tests. To create the flow, a Grundfos environmental 4 inch pump with a ½ HP Franklin 3 phase motor is used. Attached to the outlet of the pump is a block for chemical augmentation, followed by a static mixer. All plumbing components are standard ¾" diameter SS pipes and fittings. Following the static mixer, a street elbow connected to a standard elbow reverses flow direction. A pipe then extends past the pump and a pair of 45^o elbows allows for alignment to the offset ¾" pipe passing through the custom made inflatable packer (Aardvark). Another pair of 45^o elbows allows for alignment to a 2 foot pipe connected to the Signet paddle wheel flow sensor and 2 foot pipe outlet. The inflatable packer also has through connection seals for 3/8" sample line connected to a Grundfos Rediflo-2 pump, the pump's motor leads, flow sensor electrical leads and a In-Situ pressure transducer. Since the biotreatment wells are operated in a downflow mode and pure oxygen gas is added, a gas vent is needed to prevent gas build up below the packer. This is a 3/8" line through the packer and extending well above the static water table.

After the downhole packer assembly was lowered into the well with a crane, a Grundfos RediFlo-2 pump for the upper section was added as well as another In-Situ pressure transducer. After completing all connections, the pump motor speed was controlled by a variable frequency drive (ABB) connected to a Signet flow controller. This allowed the measured ground water flow to directly control the pump motor speed.

Chemical feed lines were delivered to the well head via buried ¼" SS tubes then reduced to 1/8" Teflon tubes to carry chemicals to the block providing chemical augmentation of the packer assembly. The toluene supply line was common for both biotreatment wells with electrical solenoids at the well head to control the actual toluene pulse; timing for the toluene pump and pulse control was provided by a Chrontroller, McMaster-Carr. To restrict the flow rate of the toluene, it was necessary to insert a short piece of 1/16" OD, 0.010" ID SS tubing. Note: for this system, toluene flow rate was less than 4 ml/min. Hydrogen peroxide was pumped for a 100 gallon tank via a gear pump and rotometer for flow control and similarly needed a 1/16" OD, 0.020" ID SS tubing restriction. Oxygen gas flow was measure via a mass flow meter, controlled manually via a needle valve on a rotometer.

A.3 Monitoring Well Design

Twenty nested wells were installed to monitor the performance of the BEHIVS system. The nested wells were composed of two, 2 inch diameter wells in each 10 inch diameter borehole produced by ARCH rig. In each pair, one well was set monitor the upper zone and the other monitoring well was set to monitor the lower zone. Each lower zone monitoring well was composed of a 5 foot SS wire wound screen, 45 or 50 feet blank SS section and a 10 foot blank PVC riser. When placed, the exact screen interval was based upon final borehole depth, 50 to 60 feet. The final depth of each monitoring well was determined by drill resistance into the bedrock formation. The upper zone monitoring wells were composed of a 5 foot SS wire wound screen, 25 feet blank SS section and a 10 foot blank PVC riser. The upper monitoring wells were consistently placed with the screens covering 29 to 34 feet BGL. The boreholes were backfilled with #3 Lonestar sand around the screen sections, transition sands to interface with bentonite/concrete seals.

After extensive well development, each monitoring well was instrumented with a Grundfos RediFlo-2 pump set at 45 from top of the well casing for the lower zone well and approximately 32 feet from the top of the well casings for the upper zone wells. In addition, 3 existing dual nest wells and 9 older wells were also instrumented with Grundfos monitoring pumps, for a total of 55 samples locations. Including the 4 sample locations at the two biotreatment wells and the 5 sample locations at the IWVS well, a total of 64 sample locations were used to monitor this field site.

A.4 On-Line Analytical System

The BEHIVS performance was monitored using an automated system (Automated Sampling and Analysis Platform, ASAP) that collects and analyzes samples around the clock. The ASAP is composed of:

1) a sampling manifold to connect to each of the 64 locations via 3/8 inch SS tubing,
2) a Grundfos interface manifold which selects and control each of the Grundfos pumps,

3) a liquid interface manifold connected to a trapping manifold for the preparation of volatile compounds for GC analysis, and
4) a HPLC manifold for the preparation for direct reading anion chromatograph samples.

Additional components of the analytical system include a GC with tandum FID and PID detectors, HPLC pump and electoconductivity detector for anion IC, integrators for conversion of detector outputs to compound concentrations, dissolved oxygen and pH probes. A central PC completes the analytical system connecting to each of the other instruments providing results storage in a database, real time graphs and remote access for control and database transfer.

Appendix B: Pre-Operational Characteristics of Aquifer Chemical Constituents

Table B1. Trichloroethene concentrations during BEHIVS pre-startup period, September 30, 2000 through July 31, 2001, using FID detector. Concentrations in µg/L.

Table B2. Cis-1,2-Dichloroethene concentrations during BEHIVS pre-startup period, September 30, 2000, through July 31, 2001. Concentrations in µg/L.

Table B3. 1,1-Dichloroethene concentrations during BEHIVS pre-startup period, September 30, 2000, through July 31, 2001. Concentrations in µg/L.

Table B4. Ratio of cDCE to TCE concentrations during BEHIVS pre-startup- period, September 30, 2000, through July 31, 2001. Concentrations in µg/L.

Table B5. Trichloroethene concentrations during BEHIVS pre-startup period, September 30, 2000, through July 31, 2001, using PID detector. Concentrations in µg/L.

Table B6. Chloride concentrations during BEHIVS pre-startup period, September 30, 2000 through July 31, 2001. Concentrations in mg/L.

Table B7. Sulfate concentrations during BEHIVS pre-startup period, September 30, 2000, through July 31, 2001. Concentrations in mg/L.

Table B8. Ratio of sulfate to chloride concentrations during BEHIVS pre-startup period, September 30, 20002 through July 31, 2001. Concentrations in mg/L.

Table B9. Dissolved oxygen concentrations during BEHIVS pre-start-up period, September 30, 2000, through July 31, 2001. Concentrations in mg/L.

Table B10. Concentrations of constituents in samples from miscellaneous wells during BEHIVS pre-startup period, September 30, 2000, through July 31, 2001.

Table B1. Trichloroethene concentrations during BEHIVS pre-startup period, September 30, 2000 through July 31, 2001, using FID detector. Concentrations in µg/L.

Well Number	Upper Aquifer				Lower Aquifer			
	n	Average	Std Dev	Std Dev Average	n	Average	Std Dev	Std Dev Average
D04-C					44	4,960	1,277	0.26
DO4-B	37	2,193	505	0.23				
Bio1	4	659	52	0.08	4	6,862	563	0.08
Bio2	3	608	439	0.72	3	4,982	200	0.04
N-01	51	815	198	0.24	48	6,955	1,382	0.20
N-02	47	797	123	0.15	46	2,475	217	0.09
N-03	42	927	133	0.14	40	3,352	431	0.13
N-04	49	1,712	259	0.15	47	8,273	1,082	0.13
N-05	38	1,000	153	0.15	36	6,056	948	0.16
N-06	42	1,323	334	0.25	39	3,450	408	0.12
N-07	41	808	376	0.47	41	4,574	1,787	0.39
N-08	42	2,932	179	0.06	41	5,637	856	0.15
N-09	46	810	133	0.16	42	4,209	326	0.08
N-10	42	1,109	150	0.13	44	3,718	610	0.16
N-11	41	1,051	201	0.19	41	3,823	558	0.15
N-12	41	2,317	335	0.14	40	3,684	599	0.16
N-13	41	459	56	0.12	40	4,169	570	0.14
N-14	45	1,136	284	0.25	42	5,117	422	0.08
N-15	37	690	159	0.23	39	5,001	1,060	0.21
N-16	38	932	232	0.25	38	4,677	436	0.09
N-17	38	775	77	0.10	36	3,694	457	0.12
N-18	40	1,568	487	0.31	40	4,959	383	0.08
N-19	36	2,178	525	0.24	36	3,516	355	0.10
N-20	36	2,256	331	0.15	33	3,090	629	0.20
MW21	38	616	206	0.33	37	4,278	668	0.16
MW22	34	1,533	286	0.19	34	3,305	452	0.14
MW23	36	919	125	0.14	39	5,075	1,332	0.26
Overall	985	1,270	278	0.22	970	4,567	784	0.17

Table B2. Cis-1,2-Dichloroethene concentrations during BEHIVS pre-startup period, September 30, 2000, through July 31, 2001. Concentrations in µg/L.

Well Number	Upper Aquifer				Lower Aquifer			
	n	Average	Std Dev	$\frac{\text{Std Dev}}{\text{Average}}$	n	Average	Std Dev	$\frac{\text{Std Dev}}{\text{Average}}$
D04-C					43	40	9	0.23
DO4-B	37	22	5	0.23				
Bio1	4	7	1	0.11	4	51	5	0.09
Bio2	1	17			3	50	4	0.08
N-01	51	7	2	0.25	48	52	10	0.19
N-02	47	8	1	0.15	45	18	2	0.13
N-03	42	8	1	0.16	40	22	3	0.13
N-04	49	16	3	0.18	47	60	8	0.14
N-05	38	10	2	0.18	34	66	9	0.13
N-06	42	12	3	0.26	39	55	5	0.10
N-07	41	8	3	0.40	42	38	12	0.33
N-08	41	30	2	0.07	40	51	7	0.13
N-09	45	8	1	0.17	42	40	3	0.08
N-10	41	11	1	0.13	40	28	3	0.10
N-11	41	12	2	0.20	40	38	5	0.13
N-12	41	22	3	0.13	40	34	5	0.16
N-13	40	5	1	0.10	39	33	3	0.09
N-14	43	12	3	0.22	42	49	4	0.09
N-15	37	6	2	0.24	36	43	7	0.16
N-16	37	9	2	0.22	38	38	4	0.10
N-17	38	8	1	0.09	36	39	5	0.13
N-18	40	16	5	0.29	40	52	7	0.14
N-19	36	20	4	0.22	35	30	3	0.10
N-20	36	23	4	0.19	30	31	5	0.16
MW21	38	6	2	0.34	37	33	6	0.17
MW22	34	13	2	0.16	34	23	3	0.12
MW23	36	10	2	0.17	38	46	12	0.27
Overall	976	12	3	0.21	952	40	6	0.16

Table B3. 1,1-Dichloroethene concentrations during BEHIVS pre-startup period, September 30, 2000, through July 31, 2001. Concentrations in µg/L.

Well Number	Upper Aquifer				Lower Aquifer			
	n	Average	Std Dev	Std Dev/Average	n	Average	Std Dev	Std Dev/Average
D04-C					20	8	5	0.61
DO4-B	30	2	1	0.35				
Bio1	0				3	6	0	0.03
Bio2	0				3	7	1	0.08
N-01	23	1	1	1.10	38	8	5	0.57
N-02	19	2	5	2.39	4	14	6	0.48
N-03	9	2	1	0.62	4	13	8	0.62
N-04	29	1	1	0.50	42	8	4	0.46
N-05	32	2	6	2.65	33	10	5	0.50
N-06	17	2	1	0.54	3	15	2	0.14
N-07	7	3	2	0.77	29	6	4	0.66
N-08	28	3	1	0.41	34	8	4	0.47
N-09	15	1	2	1.10	38	5	3	0.63
N-10	26	1	1	1.06	8	5	4	0.80
N-11	25	1	1	1.04	36	5	4	0.74
N-12	6	6	3	0.52	4	17	3	0.17
N-13	26	1	1	1.86	14	4	3	0.90
N-14	27	1	1	0.74	42	6	3	0.43
N-15	13	1	1	0.88	1	15		
N-16	4	3	2	0.69	25	4	3	0.69
N-17	4	2	1	0.63	2	10	5	0.44
N-18	18	2	2	0.92	38	6	2	0.34
N-19	26	2	1	0.38	22	4	5	1.03
N-20	7	3	1	0.52	1	35		
MW21	5	2	1	0.61	3	10	7	0.71
MW22	26	1	1	0.59	2	18	1	0.08
MW23	14	1	1	0.80	3	14	10	0.72
Overall	436	2	2	1.19	452	7	4	0.60

Table B4. Ratio of cDCE to TCE concentrations during BEHIVS pre-startup- period, September 30, 2000, through July 31, 2001. Concentrations in µg/L.

Well Number	Upper Aquifer			Lower Aquifer		
	cDCE	TCE	cDCE/TCE	cDCE	TCE	cDCE/TCE
D04-C				40	4,960	0.008
DO4-B	22	2,193	0.010			
Bio1	7	659	0.011	51	6,862	0.007
Bio2	17	608	0.028	50	4,982	0.010
N-01	7	815	0.009	52	6,955	0.007
N-02	8	797	0.010	18	2,475	0.007
N-03	8	927	0.009	22	3,352	0.007
N-04	16	1,712	0.009	60	8,273	0.007
N-05	10	1,000	0.010	66	6,056	0.011
N-06	12	1,323	0.009	55	3,450	0.016
N-07	8	808	0.010	38	4,574	0.008
N-08	30	2,932	0.010	51	5,637	0.009
N-09	8	810	0.010	40	4,209	0.010
N-10	11	1,109	0.010	28	3,718	0.008
N-11	12	1,051	0.011	38	3,823	0.010
N-12	22	2,317	0.009	34	3,684	0.009
N-13	5	459	0.011	33	4,169	0.008
N-14	12	1,136	0.011	49	5,117	0.010
N-15	6	690	0.009	43	5,001	0.009
N-16	9	932	0.010	38	4,677	0.008
N-17	8	775	0.010	39	3,694	0.011
N-18	16	1,568	0.010	52	4,959	0.010
N-19	20	2,178	0.009	30	3,516	0.009
N-20	23	2,256	0.010	31	3,090	0.010
MW21	6	616	0.010	33	4,278	0.008
MW22	13	1,533	0.008	23	3,305	0.007
MW23	10	919	0.011	46	5,075	0.009
Overall	12	1,270	0.009	40	4,567	0.009

Table B5. Trichloroethene concentrations during BEHIVS pre-startup period, September 30, 2000, through July 31, 2001, using PID detector. Concentrations in µg/L.

Well Number	Upper Aquifer				Lower Aquifer			
	n	Average	Std Dev	Std Dev / Average	n	Average	Std Dev	Std Dev / Average
D04-C					46	4,802	1135	0.24
DO4-B	38	1,938	384	0.20				
Bio1	4	663	42	0.06	4	6,352	397	0.06
Bio2	3	626	464	0.74	3	4,814	119	0.02
N-01	52	769	199	0.26	48	6,569	1360	0.21
N-02	47	749	132	0.18	46	2,424	265	0.11
N-03	42	941	136	0.14	40	3,179	509	0.16
N-04	49	1,565	258	0.16	48	7,548	1130	0.15
N-05	39	907	152	0.17	37	5,740	973	0.17
N-06	42	1,262	265	0.21	39	3,492	394	0.11
N-07	41	797	348	0.44	42	4,221	1532	0.36
N-08	41	2,814	159	0.06	41	5,400	728	0.13
N-09	46	755	119	0.16	43	3,804	286	0.08
N-10	42	989	115	0.12	44	3,489	588	0.17
N-11	41	957	178	0.19	41	3,597	474	0.13
N-12	41	2,266	305	0.13	40	3,711	539	0.15
N-13	41	421	43	0.10	40	3,869	544	0.14
N-14	45	1,000	248	0.25	42	4,563	361	0.08
N-15	37	660	158	0.24	39	4,835	993	0.21
N-16	39	926	231	0.25	38	4,282	479	0.11
N-17	38	725	60	0.08	36	3,721	425	0.11
N-18	40	1,477	443	0.30	40	4,470	360	0.08
N-19	36	1,918	347	0.18	36	3,328	291	0.09
N-20	36	2,201	222	0.10	33	3,196	541	0.17
MW21	38	601	201	0.33	37	4,249	668	0.16
MW22	34	1,286	168	0.13	35	3,350	451	0.13
MW23	37	847	127	0.15	40	5,130	1244	0.24
Overall	989	1,183	248	0.21	978	4,348	726	0.17

Table B6. Chloride concentrations during BEHIVS pre-startup period, September 30, 2000 through July 31, 2001. Concentrations in mg/L.

Well Number	Upper Aquifer				Lower Aquifer			
	n	Average	Std Dev	Std Dev / Average	n	Average	Std Dev	Std Dev / Average
D04-C					13	2,483	470	0.19
DO4-B	11	1,882	270	0.14				
Bio1	4	1,835	223	0.12	4	3,112	131	0.04
Bio2	3	2,193	448	0.20	3	2,633	331	0.13
N-01	18	1,853	95	0.05	17	3,063	281	0.09
N-02	19	1,983	172	0.09	20	2,533	427	0.17
N-03	17	2,086	180	0.09	17	2,818	231	0.08
N-04	17	1,976	180	0.09	17	3,470	301	0.09
N-05	16	1,979	169	0.09	10	2,285	107	0.05
N-06	18	2,049	101	0.05	14	1,487	889	0.60
N-07	19	1,932	102	0.05	15	2,569	193	0.08
N-08	18	1,764	87	0.05	18	2,266	80	0.04
N-09	21	1,950	67	0.03	20	2,048	91	0.04
N-10	20	2,165	90	0.04	18	2,715	105	0.04
N-11	20	1,984	130	0.07	19	2,678	212	0.08
N-12	19	1,966	96	0.05	17	2,440	227	0.09
N-13	18	1,837	86	0.05	18	2,561	253	0.10
N-14	19	1,898	478	0.25	17	2,103	182	0.09
N-15	12	1,836	124	0.07	13	1,497	167	0.11
N-16	13	1,996	253	0.13	10	2,494	127	0.05
N-17	12	2,078	279	0.13	10	2,035	169	0.08
N-18	11	2,044	255	0.12	10	2,161	75	0.03
N-19	10	2,305	247	0.11	11	2,590	375	0.14
N-20	10	1,969	149	0.08	8	2,318	363	0.16
MW21	13	1,875	125	0.07	13	2,581	103	0.04
MW22	13	2,335	270	0.12	11	2,828	390	0.14
MW23	13	2,180	272	0.12	13	2,667	347	0.13
Overall	384	1,988	197	0.10	356	2,478	380	0.15

Table B7. Sulfate concentrations during BEHIVS pre-startup period, September 30, 2000, through July 31, 2001. Concentrations in mg/L.

Well Number	Upper Aquifer n	Upper Aquifer Average	Upper Aquifer Std Dev	Upper Aquifer Std Dev / Average	Lower Aquifer n	Lower Aquifer Average	Lower Aquifer Std Dev	Lower Aquifer Std Dev / Average
D04-C					12	1,411	472	0.33
DO4-B	9	1,284	201	0.16				
Bio1	4	1,229	213	0.17	4	1,702	241	0.14
Bio2	3	1,729	656	0.38	3	1,481	309	0.21
N-01	22	1,265	306	0.24	19	1,540	230	0.15
N-02	20	1,207	172	0.14	20	1,560	405	0.26
N-03	19	1,217	306	0.25	19	1,599	385	0.24
N-04	18	1,241	127	0.10	20	1,550	259	0.17
N-05	17	1,252	163	0.13	10	1,180	143	0.12
N-06	18	1,286	335	0.26	17	894	112	0.13
N-07	19	1,329	286	0.22	20	1,399	189	0.13
N-08	20	1,252	213	0.17	18	1,374	228	0.17
N-09	21	1,215	321	0.26	20	1,313	225	0.17
N-10	20	1,365	157	0.11	19	1,548	270	0.17
N-11	20	1,267	222	0.18	20	1,275	224	0.18
N-12	18	1,214	174	0.14	17	1,124	176	0.16
N-13	19	1,228	173	0.14	18	1,475	279	0.19
N-14	18	1,233	216	0.18	17	1,259	263	0.21
N-15	15	1,163	178	0.15	17	933	609	0.65
N-16	15	1,295	231	0.18	12	1,460	357	0.24
N-17	14	1,582	775	0.49	11	1,210	227	0.19
N-18	13	1,264	345	0.27	11	1,244	177	0.14
N-19	13	1,199	427	0.36	12	1,255	273	0.22
N-20	12	1,223	348	0.28	10	1,371	838	0.61
MW21	14	1,661	1122	0.68	14	1,878	733	0.39
MW22	14	1,801	546	0.30	14	1,995	599	0.30
MW23	14	1,547	318	0.21	14	1,718	524	0.30
Overall	409	1,309	332	0.25	388	1,406	373	0.27

Table B8. Ratio of sulfate to chloride concentrations during BEHIVS pre-startup period, September 30, 20002 through July 31, 2001. Concentrations in mg/L.

Well	Upper Aquifer			Lower Aquifer		
Number	Chloride	Sulfate	Sulfate/Chloride	Chloride	Sulfate	Sulfate/Chloride
D04-C				2,483	1,411	0.57
DO4-B	1,882	1,284	0.68			
Bio1	1,835	1,229	0.67	3,112	1,702	0.55
Bio2	2,193	1,729	0.79	2,633	1,481	0.56
N-01	1,853	1,265	0.68	3,063	1,540	0.50
N-02	1,983	1,207	0.61	2,533	1,560	0.62
N-03	2,086	1,217	0.58	2,818	1,599	0.57
N-04	1,976	1,241	0.63	3,470	1,550	0.45
N-05	1,979	1,252	0.63	2,285	1,180	0.52
N-06	2,049	1,286	0.63	1,487	894	0.60
N-07	1,932	1,329	0.69	2,569	1,399	0.54
N-08	1,764	1,252	0.71	2,266	1,374	0.61
N-09	1,950	1,215	0.62	2,048	1,313	0.64
N-10	2,165	1,365	0.63	2,715	1,548	0.57
N-11	1,984	1,267	0.64	2,678	1,275	0.48
N-12	1,966	1,214	0.62	2,440	1,124	0.46
N-13	1,837	1,228	0.67	2,561	1,475	0.58
N-14	1,898	1,233	0.65	2,103	1,259	0.60
N-15	1,836	1,163	0.63	1,497	933	0.62
N-16	1,996	1,295	0.65	2,494	1,460	0.59
N-17	2,078	1,582	0.76	2,035	1,210	0.59
N-18	2,044	1,264	0.62	2,161	1,244	0.58
N-19	2,305	1,199	0.52	2,590	1,255	0.48
N-20	1,969	1,223	0.62	2,318	1,371	0.59
MW21	1,875	1,661	0.89	2,581	1,878	0.73
MW22	2,335	1,801	0.77	2,828	1,995	0.71
MW23	2,180	1,547	0.71	2,667	1,718	0.64
Overall	1,988	1,309	0.66	2,478	1,406	0.57

Table B9. Dissolved oxygen concentrations during BEHIVS pre-start-up period, September 30, 2000, through July 31, 2001. Concentrations in mg/L.

Well Number	Upper Aquifer n	Upper Aquifer Average	Upper Aquifer Std Dev	Upper Aquifer Std Dev / Average	Lower Aquifer n	Lower Aquifer Average	Lower Aquifer Std Dev	Lower Aquifer Std Dev / Average
D04-C					11	0.30	0.31	1.04
DO4-B	11	2.09	1.24	0.59				
Bio1	4	1.02	0.07	0.07	4	0.13	0.11	0.82
Bio2	3	7.31	0.08	0.01	3	0.06	0.06	1.01
N-01	16	1.33	0.36	0.27	15	0.85	1.65	1.94
N-02	16	0.26	0.19	0.72	16	0.21	0.15	0.73
N-03	14	0.42	0.18	0.43	13	0.17	0.16	0.92
N-04	17	1.79	0.51	0.28	17	0.43	0.19	0.43
N-05	13	0.41	0.15	0.36	5	1.17	1.90	1.63
N-06	12	0.60	0.23	0.38	13	0.17	0.18	1.08
N-07	13	4.75	2.75	0.58	13	2.48	2.40	0.97
N-08	12	1.98	0.41	0.21	12	0.46	0.25	0.53
N-09	14	1.03	2.13	2.07	15	1.25	0.24	0.19
N-10	13	4.34	0.79	0.18	13	0.50	0.37	0.74
N-11	13	3.24	1.25	0.39	13	0.94	0.60	0.64
N-12	13	1.71	0.65	0.38	13	1.06	0.53	0.50
N-13	13	1.46	0.44	0.30	13	0.31	0.19	0.62
N-14	16	3.56	1.44	0.40	14	0.73	0.21	0.29
N-15	13	0.29	0.21	0.71	12	0.33	0.27	0.81
N-16	11	3.23	1.03	0.32	12	0.50	0.35	0.69
N-17	12	5.62	0.37	0.06	11	1.44	0.43	0.30
N-18	13	2.95	0.40	0.14	13	0.73	0.20	0.28
N-19	11	2.10	0.21	0.10	11	0.95	0.19	0.20
N-20	11	2.94	0.11	0.04	11	1.01	0.16	0.16
MW21	11	0.56	0.19	0.35	10	0.45	0.20	0.45
MW22	10	3.54	0.33	0.09	11	0.21	0.20	0.95
MW23	11	3.86	0.34	0.09	11	1.01	0.75	0.74
Overall	316	2.23	1.28	0.57	305	0.71	0.57	0.80

Table B10. Concentrations of constituents in samples from miscellaneous wells during BEHIVS pre-startup period, September 30, 2000, through July 31, 2001.

	Well Number								
Constituent	OW-01	OW-02	OW-03	OW-04	PW-01	PW-02	T03	T11	T13
TCE, µg/L									
n	35	44	33	36	34	36	36	34	32
Average	1,204	1,412	2,064	2,877	1,196	2,021	371	2,431	2,815
Std Dev	167	167	247	455	130	289	39	300	297
Coef Var	0.14	0.12	0.12	0.16	0.11	0.14	0.11	0.12	0.11
cDCE, µg/L									
n	33	33	32	35	29	29	34	32	31
Average	11.3	11.2	14.8	19.9	9.6	13.5	4.3	17.7	24.3
Std Dev	1.5	1.1	2.0	2.5	0.9	1.6	0.5	2.0	2.2
Coef Var	0.13	0.10	0.14	0.13	0.09	0.12	0.11	0.11	0.09
1,1-DCE, µg/L									
n	3	3	3	4	2	4	8	2	2
Average	1.60	8	10	12	150	115	1.93	12	61
Std Dev	0.84	109	68	6	20	5	4.20	10	59
Coef Var	0.52	1.27	0.61	0.50	0.13	0.47	2.17	0.88	0.97
Chloride, mg/L									
n	12	13	17	12	11	14	10	12	13
Average	1,996	1,948	2,587	2,693	2,112	2,537	1,791	2,506	2,364
Std Dev	72	68	211	79	79	94	49	52	92
Coef Var	0.04	0.04	0.08	0.03	0.04	0.04	0.03	0.02	0.04
Sulfate, mg/L									
n	12	13	16	13	11	14	12	13	13
Average	1,335	1,285	1,488	1,581	1,378	1,486	1,313	1,489	1,571
Std Dev	158	168	141	181	133	164	120	168	257
Coef Var	0.12	0.13	0.09	0.11	0.10	0.11	0.09	0.11	0.16
DO, mg/L									
n	11	11	16	10	11	11	10	10	11
Average	0.90	0.91	0.23	0.18	1.06	0.91	1.83	1.40	2.18
Std Dev	2.20	0.28	0.15	0.15	0.30	2.21	0.61	2.15	2.15
Coef Var	2.45	0.30	0.65	0.82	0.29	2.43	0.33	1.53	0.99

Appendix C: Monthly TCE Concentration Changes During BEHIVS Operation

Table C1. Average TCE concentrations measured at various sampling locations during August 2001 period, and comparisons with pre-operational TCE concentrations. **Bold values** are monitoring locations within the treatment zone.

	Upper Aquifer				Lower Aquifer			
	August		Initial		August		Initial	
Well	n	Average (µg/L)	Average (µg/L)	Change (Percent)	n	Average (µg/L)	Average (µg/L)	Change (Percent)
D04-C					**7**	**4,971**	**4,960**	**0%**
DO4-B	**6**	**3,673**	**2,193**	**68%**				
Bio1	**22**	**722**	**659**	**10%**	**18**	**1,955**	**6,862**	**-72%**
Bio2	**20**	**584**	**608**	**-4%**	**16**	**1,332**	**4,982**	**-73%**
N-01	7	751	815	-8%	7	4,160	6,955	-40%
N-02	6	910	797	14%	6	2,521	2,475	2%
N-03	5	833	927	-10%	5	3,180	3,352	-5%
N-04	**210**	**1,962**	**1,712**	**15%**	**11**	**6,312**	**8,273**	**-24%**
N-05	**5**	**1,124**	**1,000**	**12%**	**5**	**5,105**	**6,056**	**-16%**
N-06	3	1,935	1,323	46%	5	3,150	3,450	-9%
N-07	**22**	**619**	**808**	**-23%**	**13**	**2,057**	**4,574**	**-55%**
N-08	**19**	**1,248**	**2,932**	**-57%**	**13**	**4,282**	**5,637**	**-24%**
N-09	**20**	**509**	**810**	**-37%**	**14**	**4,248**	**4,209**	**1%**
N-10	**13**	**1,179**	**1,109**	**6%**	**12**	**3,019**	**3,718**	**-19%**
N-11	**13**	**492**	**1,051**	**-53%**	**14**	**2,059**	**3,823**	**-46%**
N-12	**14**	**1,859**	**2,317**	**-20%**	**15**	**2,928**	**3,684**	**-21%**
N-13	4	442	459	-4%	3	4,130	4,169	-1%
N-14	**14**	**774**	**1,136**	**-32%**	**14**	**4,714**	**5,117**	**-8%**
N-15	3	454	690	-34%	3	4,841	5,001	-3%
N-16	3	1,113	932	19%	3	4,079	4,677	-13%
N-17	6	676	775	-13%	6	3,373	3,694	-9%
N-18	8	823	1,568	-48%	8	4,912	4,959	-1%
N-19	7	1,697	2,178	-22%	7	3,419	3,516	-3%
N-20	4	1,316	2,256	-42%	3	2,567	3,090	-17%
MW21	**8**	**415**	**616**	**-33%**	**8**	**2,989**	**4,278**	**-30%**
MW22	8	905	1,533	-41%	8	2,846	3,305	-14%
MW23	**8**	**559**	**919**	**-39%**	**8**	**3,152**	**5,075**	**-38%**
Average for Treatment Zone		**1,123**	**1,276**	**-13%**		**3,509**	**5,089**	**-30%**
Average for Monitored Area		1,061	1,236	-14%		3,550	4,611	-23%

Table C2. Average TCE concentrations measured at various sampling locations during September 2001 period, and comparisons with pre-operational TCE concentrations. **Bold values** are monitoring locations within the treatment zone.

	Upper Aquifer				Lower Aquifer			
	September		Initial		September		Initial	
Well	n	Average (µg/L)	Average (µg/L)	Change	n	Average (µg/L)	Average (µg/L)	Change
D04-C					**17**	**2,520**	**4,960**	**-49%**
D04-B	**12**	**1,853**	**2,193**	**-16%**				
Bio1	**20**	**510**	**659**	**-23%**	**22**	**478**	**6,862**	**-93%**
Bio2	**20**	**486**	**608**	**-20%**	**25**	**537**	**4,982**	**-89%**
N-01	11	1,029	815	26%	7	2,564	6,955	-63%
N-02	7	661	797	-17%	6	2,174	2,475	-12%
N-03	8	394	927	-58%	6	2,744	3,352	-18%
N-04	**7**	**902**	**1,712**	**-47%**	**9**	**5,325**	**8,273**	**-36%**
N-05	**6**	**1,009**	**1,000**	**1%**	**4**	**2,132**	**6,056**	**-65%**
N-06	3	1,430	1,323	8%	5	3,216	3,450	-7%
N-07	**14**	**337**	**808**	**-58%**	**18**	**498**	**4,574**	**-89%**
N-08	**15**	**277**	**2,932**	**-91%**	**19**	**1,631**	**5,637**	**-71%**
N-09	**15**	**159**	**810**	**-80%**	**17**	**2,253**	**4,209**	**-46%**
N-10	**16**	**1,062**	**1,109**	**-4%**	**19**	**1,592**	**3,718**	**-57%**
N-11	**15**	**301**	**1,051**	**-71%**	**19**	**835**	**3,823**	**-78%**
N-12	**15**	**1,884**	**2,317**	**-19%**	**18**	**2,260**	**3,684**	**-39%**
N-13	10	3,753	459	718%	10	3,753	4,169	-10%
N-14	**7**	**994**	**1,136**	**-12%**	**10**	**2,951**	**5,117**	**-42%**
N-15	3	744	690	8%	10	4,086	5,001	-18%
N-16	4	1,353	932	45%	6	3,632	4,677	-22%
N-17	2	704	775	-9%	4	3,715	3,694	1%
N-18	2	757	1,568	-52%	4	5,128	4,959	3%
N-19	4	2,521	2,178	16%	3	3,922	3,516	12%
N-20	2	2,160	2,256	-4%	2	2,160	3,090	-30%
MW21	**16**	**162**	**616**	**-74%**	**18**	**1,135**	**4,278**	**-73%**
MW22	16	1,002	1,533	-35%	18	2,447	3,305	-26%
MW23	**16**	**750**	**919**	**-18%**	**18**	**1,251**	**5,075**	**-75%**
Average for Treatment Zone		**763**	**1,276**	**-38%**		**1,814**	**5,089**	**-64%**
Average for Monitored Area		1,046	1,236	-15%		2,498	4,611	-46%

Table C3. Average TCE concentrations measured at various sampling locations during October 2001 period, and comparisons with pre-operational TCE concentrations. **Bold values** are monitoring locations within the treatment zone.

	Upper Aquifer				Lower Aquifer			
	October		Initial		October		Initial	
Well	n	Average (µg/L)	Average (µg/L)	Change (Percent)	n	Average (µg/L)	Average (µg/L)	Change (Percent)
D04-C					**16**	**2796**	**4960**	**-44**
D04-B	**7**	**1,925**	**2,193**	**-12**				
Bio1	**15**	**441**	**659**	**-33**	**15**	**354**	**6,862**	**-95**
Bio2	**16**	**396**	**608**	**-35**	**13**	**388**	**4,982**	**-92**
N-01	6	759	815	-7	8	4,247	6,955	-39
N-02	5	183	797	-77	6	2,177	2,475	-12
N-03	6	276	927	-70	6	2,650	3,352	-21
N-04	**16**	**798**	**1,712**	**-53**	**16**	**3,888**	**8,273**	**-53**
N-05	**6**	**739**	**1,000**	**-26**	**4**	**1,157**	**6,056**	**-81**
N-06	5	1,048	1,323	-21	3	2,954	3,450	-14
N-07	**15**	**139**	**808**	**-83**	**12**	**628**	**4,574**	**-86**
N-08	**18**	**156**	**2,932**	**-95**	**9**	**1,198**	**5,637**	**-79**
N-09	**15**	**78**	**810**	**-90**	**15**	**1,654**	**4,209**	**-61**
N-10	**17**	**958**	**1,109**	**-14**	**15**	**1,217**	**3,718**	**-67**
N-11	**12**	**139**	**1,051**	**-87**	**14**	**653**	**3,823**	**-83**
N-12	**14**	**1,328**	**2,317**	**-43**	**13**	**1,282**	**3,684**	**-65**
N-13	5	167	459	-64	9	3,466	4,169	-17
N-14	**10**	**1,400**	**1,136**	**23**	**17**	**2,429**	**5,117**	**-53**
N-15	5	846	690	23	15	4,147	5,001	-17
N-16	5	895	932	-4	9	4,083	4,677	-13
N-17	5	687	775	-11	7	3,202	3,694	-13
N-18	5	963	1,568	-39	11	3,159	4,959	-36
N-19	4	1,039	2,178	-52	8	2,741	3,516	-22
N-20	4	1,423	2,256	-37	4	1,460	3,090	-53
MW21	**16**	**72**	**616**	**-88**	**15**	**992**	**4,278**	**-77**
MW22	17	984	1,533	-36	15	2,401	3,305	-27
MW23	**17**	**666**	**919**	**-28**	**16**	**1,428**	**5,075**	**-72**
Average for Treatment Zone		**660**	**1,276**	**-47%**		**1,433**	**5,089**	**-72%**
Average for Monitored Area		712	1,236	-42		2,183	4,611	-53

Table C4. Average TCE concentrations measured at various sampling locations during November 2001 period, and comparisons with pre-operational TCE concentrations. **Bold values** are monitoring locations within the treatment zone.

	Upper Aquifer				Lower Aquifer			
	November		Initial		November		Initial	
Well	n	Average (µg/L)	Average (µg/L)	Change (Percent)	n	Average (µg/L)	Average (µg/L)	Change (Percent)
D04-C					**9**	**4,144**	**4,960**	**-16%**
DO4-B	**8**	**1,450**	**2,193**	**-34%**				
Bio1	**19**	**426**	**659**	**-35%**	**21**	**341**	**6,862**	**-95%**
Bio2	**19**	**217**	**608**	**-64%**	**19**	**250**	**4,982**	**-95%**
N-01	8	1,112	815	36%	5	4,621	6,955	-34%
N-02	2	124	797	-84%	2	1,998	2,475	-19%
N-03	24	130	927	-86%	1	2,589	3,352	-23%
N-04	**13**	**595**	**1,322**	**-65%**	**16**	**6,002**	**8,273**	**-27%**
N-05	**13**	**648**	**1,000**	**-35%**	**3**	**440**	**6,056**	**-93%**
N-06	2	1,771	1,323	34%	4	3,034	3,450	-12%
N-07	**35**	**81**	**808**	**-90%**	**28**	**220**	**4,574**	**-95%**
N-08	**30**	**78**	**2,932**	**-97%**	**22**	**608**	**5,637**	**-89%**
N-09	**21**	**77**	**810**	**-91%**	**12**	**1,284**	**4,209**	**-69%**
N-10	**11**	**644**	**1,109**	**-42%**	**16**	**506**	**3,718**	**-86%**
N-11	**13**	**198**	**1,051**	**-81%**	**23**	**375**	**3,823**	**-90%**
N-12	**11**	**955**	**2,317**	**-59%**	**8**	**553**	**3,684**	**-85%**
N-13	2	714	459	55%	7	3,354	4,169	-20%
N-14	**15**	**1,960**	**1,136**	**73%**	**20**	**2,559**	**5,117**	**-50%**
N-15	3	1,202	690	74%	7	3,820	5,001	-24%
N-16	2	511	932	-45%	7	3,431	4,677	-27%
N-17	3	568	775	-27%	15	2,824	3,694	-24%
N-18	6	1,496	1,568	-5%	15	3,867	4,959	-22%
N-19	4	1,597	2,178	-27%	15	2,599	3,516	-26%
N-20	6	2,025	2,256	-10%	5	2,264	3,090	-27%
MW21	**26**	**140**	**616**	**-77%**	**10**	**709**	**4,278**	**-83%**
MW22	9	846	1,533	-45%	4	2,148	3,305	-35%
MW23	**12**	**794**	**919**	**-14%**	**20**	**494**	**5,075**	**-90%**
Average for Treatment Zone		**590**	**1,276**	**-51%**		**1,320**	**5,089**	**-76%**
Average for Monitored Area		783	1,236	-37%		2,117	4,611	-54%

Table C5. Average TCE concentrations measured at various sampling locations during December 2001 period, and comparisons with pre-operational TCE concentrations. **Bold values** are monitoring locations within the treatment zone.

	Upper Aquifer				Lower Aquifer			
	December		Initial		December		Initial	
Well	n	Average (µg/L)	Average (µg/L)	Change (Percent)	n	Average (µg/L)	Average (µg/L)	Change (Percent)
D04-C					**7**	**1,479**	**4,960**	**-70%**
DO4-B	**5**	**933**	**2,193**	**-57%**				
Bio1	**22**	**495**	**659**	**-25%**	**28**	**432**	**6,862**	**-94%**
Bio2	**11**	**311**	**608**	**-49%**	**13**	**320**	**4,982**	**-94%**
N-01	6	658	815	-19%	9	4,613	6,955	-34%
N-02	8	193	797	-76%	9	2,217	2,475	-10%
N-03	6	450	927	-51%	8	2,756	3,352	-18%
N-04	**11**	**347**	**1,712**	**-80%**	**57**	**2,125**	**8,273**	**-74%**
N-05	**8**	**742**	**1,000**	**-26%**	**7**	**191**	**6,056**	**-97%**
N-06	9	859	1,323	-35%	14	2,768	3,450	-20%
N-07	**11**	**66**	**808**	**-92%**	**27**	**142**	**4,574**	**-97%**
N-08	**12**	**60**	**2,932**	**-98%**	**9**	**184**	**5,637**	**-97%**
N-09	**12**	**56**	**810**	**-93%**	**14**	**488**	**4,209**	**-88%**
N-10	**6**	**442**	**1,109**	**-60%**	**25**	**208**	**3,718**	**-94%**
N-11	**5**	**443**	**1,051**	**-58%**	**10**	**192**	**3,823**	**-95%**
N-12	**5**	**927**	**2,317**	**-60%**	**7**	**203**	**3,684**	**-94%**
N-13	5	287	459	-37%	15	2,669	4,169	-36%
N-14	**5**	**1,658**	**1,136**	**46%**	**13**	**751**	**5,117**	**-85%**
N-15	6	1,556	690	126%	5	2,911	5,001	-42%
N-16	7	528	932	-43%	10	2,552	4,677	-45%
N-17	6	610	775	-21%	12	2,083	3,694	-44%
N-18	6	2,048	1,568	31%	11	1,141	4,959	-77%
N-19	7	1,900	2,178	-13%	7	1,244	3,516	-65%
N-20	6	2,134	2,256	-5%	8	2,689	3,090	-13%
MW21	**10**	**67**	**616**	**-89%**	**23**	**241**	**4,278**	**-94%**
MW22	5	1,460	1,533	-5%	7	1,460	3,305	-56%
MW23	**6**	**532**	**919**	**-42%**	**25**	**297**	**5,075**	**-94%**
Average for Treatment Zone		**506**	**1,276**	**-56%**		**518**	**5,089**	**-91%**
Average for Monitored Area		760	1,236	-36%		1,398	4,611	-66%

Table C6. Average TCE concentrations measured at various sampling locations during January 2002 period, and comparisons with pre-operational TCE concentrations. **Bold values** are monitoring locations within the treatment zone.

	Upper Aquifer				Lower Aquifer			
	January		Initial		January		Initial	
Well	n	Average (μg/L)	Average (μg/L)	Change (Percent)	n	Average (μg/L)	Average (μg/L)	Change (Percent)
D04-C					**16**	**951**	**4,960**	**-81%**
DO4-B	**16**	**745**	**2,193**	**-66%**				
Bio1	**16**	**633**	**659**	**-4%**	**12**	**627**	**6,862**	**-91%**
Bio2	**26**	**665**	**608**	**9%**	**26**	**623**	**4,982**	**-88%**
N-01	5	740	815	-9%	16	4,543	6,955	-35%
N-02	6	350	797	-56%	16	2,539	2,475	3%
N-03	6	460	927	-50%	17	3,276	3,352	-2%
N-04	**6**	**398**	**1,712**	**-77%**	**18**	**3,076**	**8,273**	**-63%**
N-05	**5**	**891**	**1,000**	**-11%**	**20**	**134**	**6,056**	**-98%**
N-06	5	953	1,323	-28%	20	2,747	3,450	-20%
N-07	**5**	**177**	**808**	**-78%**	**14**	**241**	**4,574**	**-95%**
N-08	**7**	**157**	**2,932**	**-95%**	**22**	**354**	**5,637**	**-94%**
N-09	**9**	**78**	**810**	**-90%**	**19**	**230**	**4,209**	**-95%**
N-10	**2**	**750**	**1,109**	**-32%**	**14**	**353**	**3,718**	**-91%**
N-11	**6**	**1,104**	**1,051**	**5%**	**21**	**254**	**3,823**	**-93%**
N-12	**5**	**1,497**	**2,317**	**-35%**	**22**	**108**	**3,684**	**-97%**
N-13	4	423	459	-8%	16	2,780	4,169	-33%
N-14	**5**	**1,518**	**1,136**	**34%**	**19**	**297**	**5,117**	**-94%**
N-15	4	2,366	690	243%	16	2,911	5,001	-42%
N-16	5	748	932	-20%	15	2,817	4,677	-40%
N-17	5	606	775	-22%	16	2,142	3,694	-42%
N-18	8	2,992	1,568	91%	18	449	4,959	-91%
N-19	6	1,740	2,178	-20%	17	882	3,516	-75%
N-20	6	2,311	2,256	2%	17	1,975	3,090	-36%
MW21	**8**	**163**	**616**	**-74%**	**16**	**367**	**4,278**	**-91%**
MW22	5	1,660	1,533	8%	14	1,204	3,305	-64%
MW23	**9**	**614**	**919**	**-33%**	**15**	**638**	**5,075**	**-87%**
Average for Treatment Zone		**671**	**1,276**	**-39%**		**590**	**5,089**	**-90%**
Average for Monitored Area		951	1,236	-23%		1,405	4,611	-70%

Table C7. Average TCE concentrations measured at various sampling locations during February 2002 period, and comparisons with pre-operational TCE concentrations. **Bold values** are monitoring locations within the treatment zone.

	Upper Aquifer				Lower Aquifer			
	February		Initial		February		Initial	
Well	n	Average (µg/L)	Average (µg/L)	Change (Percent)	n	Average (µg/L)	Average (µg/L)	Change (Percent)
D04-C					**9**	**465**	**4,960**	**-91%**
DO4-B	**5**	**1,263**	**2,193**	**-42%**				
Bio1	**9**	**374**	**659**		**0**		**6,862**	**-100%**
Bio2	**8**	**154**	**608**	**-75%**	**10**	**502**	**4,982**	**-90%**
N-01	7	529	815	-35%	6	7,570	6,955	9%
N-02	9	537	797	-33%	10	2,645	2,475	7%
N-03	8	834	927	-10%	10	3,159	3,352	-6%
N-04	**8**	**811**	**1,712**	**-53%**	**9**	**7,693**	**8,273**	**-7%**
N-05	8	527	1,000	-47%	10	291	6,056	-95%
N-06	7	806	1,323	-39%	8	2,568	3,450	-26%
N-07	**7**	**305**	**808**	**-62%**	**9**	**752**	**4,574**	**-84%**
N-08	**6**	**228**	**2,932**	**-92%**	**9**	**623**	**5,637**	**-89%**
N-09	**9**	**302**	**810**	**-63%**	**8**	**519**	**4,209**	**-88%**
N-10	**8**	**539**	**1,109**	**-51%**	**9**	**815**	**3,718**	**-78%**
N-11	**9**	**589**	**1,051**	**-44%**	**9**	**348**	**3,823**	**-91%**
N-12	**9**	**1,552**	**2,317**	**-33%**	**10**	**157**	**3,684**	**-96%**
N-13	7	378	459	-18%	9	2,685	4,169	-36%
N-14	**9**	**1,069**	**1,136**	**-6%**	**9**	**424**	**5,117**	**-92%**
N-15	9	1,945	690	182%	8	3,188	5,001	-36%
N-16	9	844	932	-9%	8	2,796	4,677	-40%
N-17	8	742	775	-4%	9	2,223	3,694	-40%
N-18	10	1,516	1,568	-3%	8	538	4,959	-89%
N-19	7	1,213	2,178	-44%	8	912	3,516	-74%
N-20	8	1,492	2,256	-34%	8	1,883	3,090	-39%
MW21	**10**	**412**	**616**	**-33%**	**10**	**820**	**4,278**	**-81%**
MW22	8	1,428	1,533	-7%	9	1,979	3,305	-40%
MW23	**9**	**915**	**919**	**0%**	**9**	**515**	**5,075**	**-90%**
Average for Treatment Zone		**646**	**1,276**	**-46%**		**1,071**	**5,089**	**-84%**
Average for Monitored Area		819	1,236	-26%		1,843	4,611	-61%

Table C8. Average TCE concentrations measured at various sampling locations during April 2002 period, and comparisons with pre-operational TCE concentrations. **Bold values** are monitoring locations within the treatment zone.

	Upper Aquifer				Lower Aquifer			
	April		Initial		April		Initial	
Well	n	Average (μg/L)	Average (μg/L)	Change (Percent)	n	Average (μg/L)	Average (μg/L)	Change (Percent)
D04-C					**3**	**614**	**1,277**	**-52%**
D04-B	**4**	**1,366**	**2,193**	**-38%**				
Bio1	**3**	**521**	**659**	**-21%**	**5**	**1,383**	**6,862**	**-80%**
Bio2	**2**	**124**	**608**	**-80%**	**4**	**126**	**4,982**	**-97%**
N-01	4	502	815	-38%	2	7,204	6,955	4%
N-02	3	749	797	-6%	4	2,557	2,475	3%
N-03	4	647	927	-30%	3	3,644	3,352	9%
N-04	**4**	**779**	**1,322**	**-54%**	**2**	**2,911**	**8,273**	**-65%**
N-05	5	524	1,000	-48%	4	2,097	6,056	-65%
N-06	3	1,249	1,323	-6%	3	3,029	3,450	-12%
N-07	**5**	**502**	**808**	**-38%**	**4**	**3,392**	**4,574**	**-26%**
N-08	**3**	**314**	**2,932**	**-89%**	**4**	**743**	**5,637**	**-87%**
N-09	**3**	**513**	**810**	**-37%**	**3**	**757**	**4,209**	**-82%**
N-10	**4**	**495**	**1,109**	**-55%**	**4**	**2,203**	**3,718**	**-41%**
N-11	**2**	**473**	**1,051**	**-55%**	**4**	**1,004**	**3,823**	**-74%**
N-12	**3**	**990**	**2,317**	**-57%**	**4**	**1,359**	**3,684**	**-63%**
N-13	4	405	459	-12%	4	3,632	4,169	-13%
N-14	**3**	**643**	**1,136**	**-43%**	**1**	**547**	**5,117**	**-89%**
N-15	4	1,299	690	88%	2	4,470	5,001	-11%
N-16	2	1,017	932	9%	3	2,370	4,677	-49%
N-17	3	687	775	-11%	2	2,931	3,694	-21%
N-18	3	1,003	1,568	-36%	3	692	4,959	-86%
N-19	3	701	2,178	-68%	2	632	3,516	-82%
N-20	3	1,614	2,256	-28%	1	2,458	3,090	-20%
MW21	**4**	**547**	**616**	**-11%**	**3**	**2,720**	**4,278**	**-36%**
MW22	2	2,144	1,533	40%	4	2,852	3,305	-14%
MW23	**5**	**1,049**	**919**	**14%**	**2**	**8,456**	**5,075**	**67%**
Average for Treatment Zone		**631**	**1,276**	**-44%**		**2,022**	**5,089**	**-56%**
Average for Monitored Area		802	1,236	-27%		2,492	4,611	-42%

Table C9. Average TCE concentrations measured at various sampling locations during June 2002 period, and comparisons with pre-operational TCE concentrations. **Bold values** are monitoring locations within the treatment zone.. **Bold values** are monitoring locations within the treatment zone.

	Upper Aquifer				Lower Aquifer			
	June		Initial		June		Initial	
Well	n	Average (µg/L)	Average (µg/L)	Change (Percent)	n	Average (µg/L)	Average (µg/L)	Change (Percent)
D04-C					**4**	**1,013**	**4,960**	**-80%**
D04-B	**4**	**1,467**	**2,193**	**-33%**				
Bio1	**0**		**659**		**7**	**1,635**	**6,862**	**-76%**
Bio2	**4**	**178**	**608**	**-71%**	**4**	**164**	**4,982**	**-97%**
N-01	4	564	815	-31%	6	6,499	6,955	-7%
N-02	4	672	797	-16%	5	2,397	2,475	-3%
N-03	3	679	927	-27%	5	2,995	3,352	-11%
N-04	**6**	**1,284**	**1,712**	**-25%**	**6**	**8,796**	**8,273**	**6%**
N-05	5	518	1,000	-48%	6	782	6,056	-87%
N-06	6	571	1,323	-57%	3	2,827	3,450	-18%
N-07	**4**	**566**	**808**	**-30%**	**3**	**3,357**	**4,574**	**-27%**
N-08	**7**	**353**	**2,932**	**-88%**	**4**	**1,123**	**5,637**	**-80%**
N-09	**4**	**630**	**810**	**-22%**	**3**	**1,006**	**4,209**	**-76%**
N-10	**2**	**1,401**	**1,109**	**26%**	**5**	**2,056**	**3,718**	**-45%**
N-11	**4**	**516**	**1,051**	**-51%**	**3**	**372**	**3,823**	**-90%**
N-12	**3**	**916**	**2,317**	**-60%**	**4**	**68**	**3,684**	**-98%**
N-13	5	423	459	-8%	3	2,961	4,169	-29%
N-14	**3**	**487**	**1,136**	**-57%**	**3**	**772**	**5,117**	**-85%**
N-15	3	662	690	-4%	3	3,810	5,001	-24%
N-16	2	727	932	-22%	4	2,972	4,677	-36%
N-17	4	1,097	775	42%	3	2,786	3,694	-25%
N-18	3	693	1,568	-56%	3	529	4,959	-89%
N-19	3	524	2,178	-76%	2	628	3,516	-82%
N-20	3	975	2,256	-57%	3	3,762	3,090	22%
MW21	**4**	**503**	**616**	**-18%**	**4**	**3,766**	**4,278**	**-12%**
MW22	4	1,776	1,533	16%	3	2,990	3,305	-10%
MW23	**5**	**1,206**	**919**	**31%**	**3**	**2,588**	**5,075**	**-49%**
Average for Treatment Zone		**771**	**1,276**	**-34%**		**1,964**	**5,089**	**-64%**
Average for Monitored Area		776	1,236	-30%		2,410	4,611	-46%

Table C10. Average cDCE concentrations measured at various sampling locations during December 2001 period, and comparisons with pre-operational cDCE concentrations. **Bold values** are monitoring locations within the treatment zone.

	Upper Aquifer				Lower Aquifer			
	December		Initial		December		Initial	
Well	n	Average (µg/L)	Average (µg/L)	Change (Percent)	n	Average (µg/L)	Average (µg/L)	Change (Percent)
D04-C					**3**	**13**	**40**	**-67%**
DO4-B	**1**	**6**	**22**	**-74%**				
Bio1	**20**	**5**	**7**	**-25%**	**27**	**4**	**51**	**-91%**
Bio2	**10**	**4**	**17**	**-75%**	**13**	**4**	**50**	**-92%**
N-01	6	6	7	-8%	10	36	52	-31%
N-02	9	4	8	-54%	7	17	18	-5%
N-03	6	5	8	-34%	7	20	22	-7%
N-04	**11**	**4**	**16**	**-75%**	**51**	**16**	**60**	**-74%**
N-05	**8**	**7**	**10**	**-27%**	**4**	**1**	**66**	**-98%**
N-06	3	8	12	-37%	13	42	55	-24%
N-07	**6**	**1**	**8**	**-88%**	**2**	**1**	**38**	**-97%**
N-08	**5**	**1**	**30**	**-96%**	**2**	**2**	**51**	**-95%**
N-09	**7**	**1**	**8**	**-81%**	**4**	**9**	**40**	**-77%**
N-10	**4**	**6**	**11**	**-45%**	**6**	**1**	**28**	**-97%**
N-11	**5**	**5**	**12**	**-58%**	**5**	**3**	**38**	**-91%**
N-12	**5**	**10**	**22**	**-55%**	**4**	**2**	**34**	**-94%**
N-13	4	3	5	-39%	8	21	33	-36%
N-14	**5**	**19**	**12**	**61%**	**4**	**16**	**49**	**-67%**
N-15	6	18	6	196%	5	30	43	-30%
N-16	6	7	9	-28%	8	24	38	-36%
N-17	5	7	8	-13%	6	22	39	-42%
N-18	6	23	16	46%	2	21	52	-59%
N-19	7	20	20	1%	3	15	30	-48%
N-20	6	22	23	-3%	7	28	31	-10%
MW21	**6**	**1**	**6**	**-79%**	**8**	**1**	**33**	**-97%**
MW22	5	13	13	-1%	4	10	23	-55%
MW23	**6**	**6**	**10**	**-40%**	**5**	**3**	**46**	**-94%**
Average for Treatment Zone		**6**	**14**	**-54%**		**6**	**45**	**-88%**
Average for Monitored Area		8	13	-28%		14	41	-62%

Table C11. Average cDCE concentrations measured at various sampling locations during June 2002 period, and comparisons with pre-operational cDCE concentrations. **Bold values** are monitoring locations within the treatment zone.

	Upper Aquifer				Lower Aquifer			
	June		Initial		December		June	
Well	n	Average (µg/L)	Average (µg/L)	Change (Percent)	n	Average (µg/L)	Average (µg/L)	Change (Percent)
D04-C					**4**	**11**	**40**	**-71%**
DO4-B	**3**	**18**	**22**	**-18%**				
Bio1			**7**		**1**	**43**	**51**	**-16%**
Bio2	**3**	**4**	**17**	**-78%**	**2**	**2**	**50**	**-96%**
N-01	4	6	7	-20%	1	52	52	0%
N-02	2	7	8	-10%	2	21	18	19%
N-03	1	8	8	5%	4	21	22	-4%
N-04	**6**	**13**	**16**	**-19%**			**60**	
N-05	**5**	**5**	**10**	**-47%**	**5**	**10**	**66**	**-85%**
N-06	5	6	12	-54%	3	47	55	-14%
N-07	**3**	**7**	**8**	**-14%**			**38**	
N-08	**4**	**5**	**30**	**-83%**	**4**	**11**	**51**	**-78%**
N-09	**2**	**7**	**8**	**-15%**	**2**	**8**	**40**	**-79%**
N-10	**1**	**13**	**11**	**18%**	**1**	**19**	**28**	**-31%**
N-11	**3**	**6**	**12**	**-49%**			**38**	
N-12	**3**	**11**	**22**	**-52%**			**34**	
N-13	5	5	5	-6%			33	
N-14	**2**	**6**	**12**	**-50%**	**3**	**7**	**49**	**-86%**
N-15	2	8	6	35%	1	39	43	-9%
N-16	2	8	9	-6%	4	26	38	-33%
N-17	3	10	8	25%			39	
N-18	1	8	16	-48%	2	5	52	-90%
N-19	1	7	20	-66%	2	6	30	-80%
N-20	1	12	23	-48%	3	42	31	35%
MW21	**4**	**5**	**6**	**-13%**	**2**	**33**	**33**	**-1%**
MW22	1	19	13	44%			23	
MW23	**4**	**12**	**10**	**22%**	**2**	**20**	**46**	**-56%**
Average for Treatment Zone		**9**	**14**	**-31%**		**17**	**45**	**-60%**
Average for Monitored Area		9	13	-22%		22	41	-41%

Table C12. Average 1,1-DCE concentrations measured at various sampling locations during December 2001 period, and comparisons with pre-operational 1,1-DCE concentrations. **Bold values** are monitoring locations within the treatment zone.

	Upper Aquifer				Lower Aquifer			
	June		Initial		December		June	
Well	n	Average (µg/L)	Average (µg/L)	Change (Percent)	n	Average (µg/L)	Average (µg/L)	Change (Percent)
D04-C							**8**	
DO4-B			**2**					
Bio1	**1**	**1**			**1**	**1**	**6**	**-89%**
Bio2	**1**	**1**			**2**	**1**	**7**	**-90%**
N-01			1		5	6	8	**-24%**
N-02			2		2	3	14	**-81%**
N-03			2		2	2	13	**-84%**
N-04			**1**		**5**	**5**	**8**	**-33%**
N-05	**5**	**1**	**2**	**-59%**			**10**	
N-06	1	1	2	-49%	3	4	15	-75%
N-07			**3**		**1**	**0**	**6**	**-96%**
N-08			**3**				**8**	
N-09			**1**				**5**	
N-10			**1**				**5**	
N-11			**1**		**1**	**3**	**5**	**-38%**
N-12			**6**				**17**	
N-13			1				4	
N-14			**1**				**6**	
N-15	3	3	1	192%			15	
N-16			3				4	
N-17			2		1	5	10	-47%
N-18	1	0	2	-78%	1	3	6	-47%
N-19			2		1	4	4	9%
N-20			3				35	
MW21			**2**				**10**	
MW22	1	1	1	-25%			18	
MW23	**1**	**1**	**1**	**-46%**			**14**	
Average for Treatment Zone		**1**	**2**	**-52%**		**2**	**8**	**-69%**
Average for Monitored Area		1	2	-11%		3	10	-58%

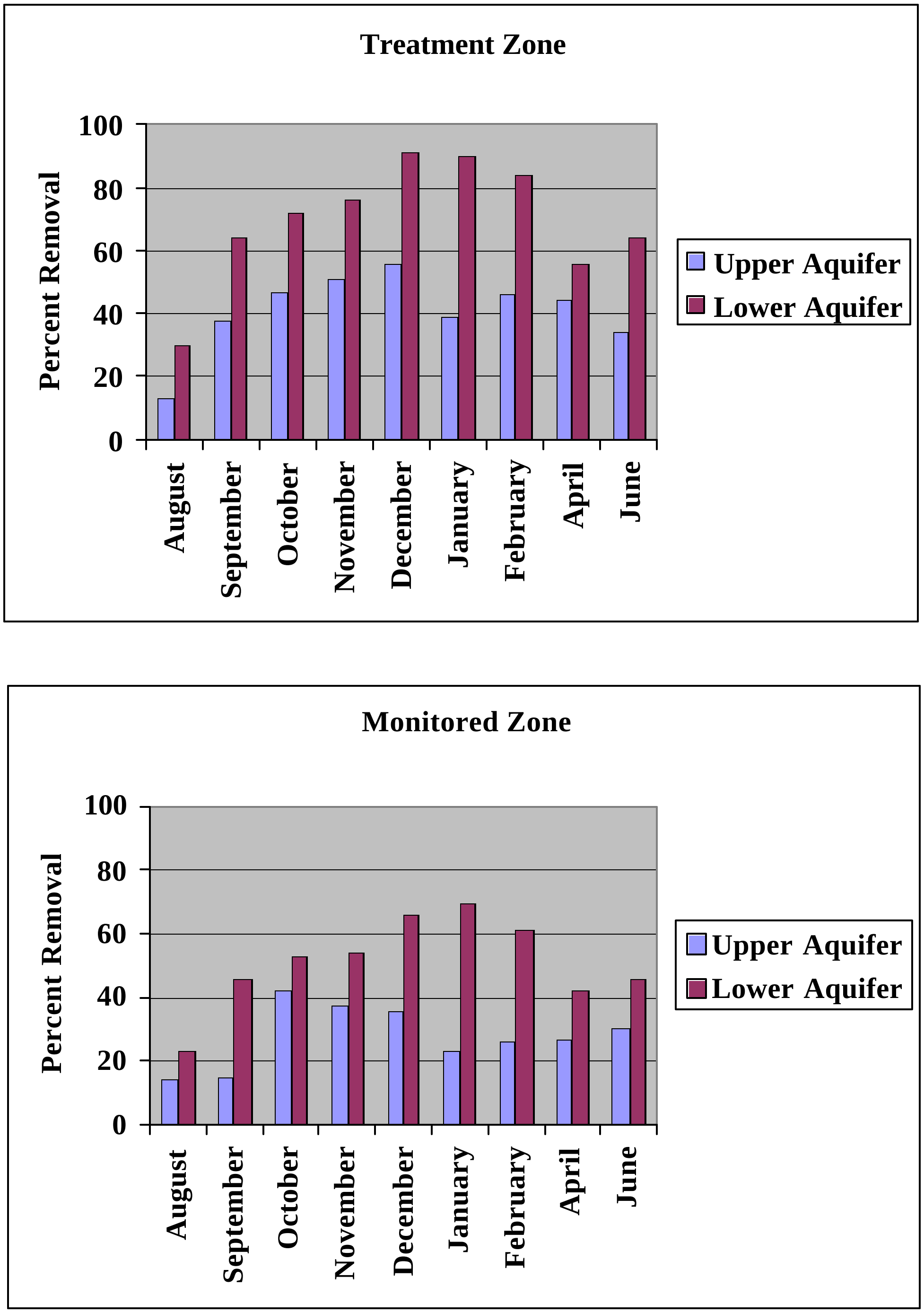


Figure C1. TCE percentage removals compared with initial values at start of in upper and lower aquifers with time for treatment zone and monitored zone.

Appendix D: Head Maps for BEHIVS System, July 2001 through January 2002

Throughout BEHIVS system operation, soundings (measured depth to groundwater) were taken at monitoring locations in the deep and shallow aquifer. Of the 21 head 'snapshots' taken, 15 represent steady-state flow conditions. Table D.1 indicates the dates and pumping conditions for each of these sets of data. Spatial maps of the flow system were created by kriging these data. The pre-operational head conditions (July 2001) are shown in Figure D-1. The remaining twelve maps (Figures D-2 through D-13) represent the flow system when all treatment wells are pumping (August 24, September 2, September 7, November 14, December 5, and January 5), when only the biotreatment wells are pumping (September 19, September 26, October 7, October 25, and January 16), and when only the IWVS is pumping (September 29.)

Table D.1: Steady state pumping conditions for BEHIVS head datasets.

Date	**IWVS pumping (gpm)**	**Bio1pumping (gpm)**	**Bio2 pumping (gpm)**
July 27, 2001	0	0	0
August 24, 2001	7.6	2	2
September 2, 2001	7.7	2	2
September 7, 2001	7.7	2	2
September 19, 2001	0	2	2
September 26, 2001	0	2	2
September 29, 2001	7.7	0	0
October 7, 2001	0	2	2
October 16, 2001	0	0	0
October 25, 2001	0	2	2
November 14, 2001	7.1	4	4
December 5, 2001	6.8	4	4
January 5, 2002	5.2	4	4
January 16, 2002	0	4	4
February 14, 2002	0	0	0