MONITORING WELL COMPARISON STUDY:

AN EVALUATION OF DIRECT-PUSH

Versus

CONVENTIONAL MONITORING WELLS

May 1, 2002

A Study Conducted By

BP Corporation North America Inc.,

And

The Underground Storage Tank (UST) Programs of
U.S. Environmental Protection Agency
Regions 4, Atlanta GA
And
Region 5, Chicago, IL

EXECUTIVE SUMMARY

This project was undertaken to determine whether measurements of groundwater parameters obtained using direct-push wells are comparable to those obtained from conventional monitoring wells. Direct-push monitoring wells contained no filter pack and were pushed into the subsurface; conventional monitoring wells contained filter packs and were installed with typical drilling and completion methods. The measured parameters were groundwater levels, chemical concentrations (BTEX, MTBE, TSS, and naphthalene), hydraulic conductivity, and natural attenuation (geochemistry) parameters. The study was conducted at two sites in Ohio and two sites in Georgia and they were chosen so there was a wide-range of soils, conductivities, and concentrations.

The following conclusions can be drawn:

- Groundwater levels measured in conventional versus direct-push monitoring wells are nearly identical.
- For MTBE measurements, there is no difference between the concentrations measured in samples from direct-push and conventional monitoring wells.
- For BTEX measurements, there is no difference between the concentrations measured in samples from direct-push and conventional monitoring wells across three of the sites. For one site, the measurements were consistently and significantly higher in samples obtained from the direct-push wells, suggesting a systematic error. Subsequent analysis and sampling suggests that the screen or borehole may have become contaminated during installation of the direct-push well.
- The mean hydraulic conductivity from the conventional wells is 4.4 times greater than from the direct-push wells, also suggesting a systematic error or problem.
- The concentrations of Total Suspended Solids were significantly higher in samples from direct-push wells than those from conventional wells which likely results from the lack of a filter pack and possibly incomplete well development.
- The naphthalene concentrations exhibited slightly higher concentrations in samples from direct-push wells than those from conventional wells, but the result was not consistent across all sites, and there was considerable spatial variability.
- The consistently lower hydraulic conductivity and higher TSS concentrations in the direct-push wells, the variability in naphthalene concentrations, and possibly the difference in BTEX concentrations at the Granville site are believed to be due to poor well development of the direct-push wells.
- For geochemical parameters indicative of natural attenuation (dissolved oxygen, carbon dioxide, ferrous iron, nitrate, methane, alkalinity, and sulfate), the statistical analysis indicates that there is no difference in concentrations measured in samples obtained from direct-push and conventional monitoring wells. The caveat is that there is only a small amount of data and it exhibits some variability.

The analysis of the data suggests that, provided the wells are properly developed, there is good reason to believe that all measurements obtained from direct-push monitoring wells are equivalent to those obtained from conventional monitoring wells.

LESSONS LEARNED

The study was well planned and the procedures were well documented and carried out. Future studies would do well to adopt most of what was conducted in this study. There are five lessons learned:

- Direct-push wells need to be developed properly. The direct-push wells in this study were developed by simple purging of the well. Other methods such as using a surge block should be considered (Henebry & Robbins, 2000).
- The statistical analysis was more complex than that applied in many previous monitoring well studies which used non-parametric methods. The complex statistical analysis, making use of transformation, linear models, and normal statistics, not only enhanced the usefulness of the small data set, but it also highlighted questionable data. This demonstrated its usefulness and its application should be considered in future studies.
- Hydraulic conductivities often varied by more than a factor of two when comparing calculated results for the same well but on different dates. This was not noted at the time, and care should be taken to determine if well parameters may have changed and affected the results.
- The fraction of organic carbon in the soil should be measured in order to check whether some concentrations might correlate with TSS.
- The sampling and analytical methods used to determine the concentrations of the geochemistry parameters should be reviewed to determine the extent that they could contribute to the variability in the data. Perhaps new methods should be used in future studies.

INTRODUCTION

Monitoring well installation using direct-push technology is potentially useful and cost effective, and the use of direct-push technology is increasing. Many state regulatory agencies are hesitant to make decisions using data generated with direct push instruments. The authors expect that this report will help assuage some of these concerns and provide a sound basis for further work. The objective of the work reported here was to determine whether direct-push wells yield results that are comparable to conventional monitoring wells for water level measurements, ground-water chemical concentrations, hydraulic conductivity, and natural attenuation (geochemistry) parameters. The project was coordinated with the Underground Storage Tank (UST) Programs of the United States Environmental Protection Agency (US EPA) Region 4 and the US EPA Region 5, the Georgia Environmental Protection Division (GEPD) Underground Storage Tank Program, and the Ohio Department of Commerce, Bureau of UST Regulations (BUSTR).

Conventional wells versus direct-push wells were compared at four retail fuel stations with dissolved-phase hydrocarbon plumes. Sites were chosen using existing conventional wells to screen the geologies and to choose three wells at each site that exhibited a range of concentrations. The sites were located in Brunswick, Georgia; Marietta, Georgia; Granville, Ohio; and Toledo, Ohio,. Table 1 lists individual site characteristics. Concentration ranges were 10- to 100-µg/L, 100- to 1,000-µg/L, and 1,000- to 10,000-µg/L. From the results presented below, it will be evident that a wide range of conditions was studied. Each of the sites is described in more detail in Appendices A-D.

TABLE 1--Site Characteristics				
Site	Physiographic Province	Sediment Type	Mean Depth to Water	Maximum Benzene Conc.
Brunswick, Georgia	Barrier Island Sequence Coastal Plain	Permeable silty and clayey, fine to medium sands	5.11-ft	8,100-ug/L
Marietta, Georgia	Piedmont Central Uplands	Fine-grained soils and saprolite that mantle bedrock	13.05-ft	3,500-ug/L
Toledo, Ohio	Interior Plains Central Lowlands	Clayey silt with very thin, discontinuous laminae of clay	8.78-ft	1,300-ug/L
Granville, Ohio	Till Plain	Sandy silt over sand and gravel outwash	17.94-ft	8,500-ug/L

Conventional monitoring wells were either 2-inch or 4-inch diameter wells installed in accordance with state-approved methods prior to the study. Construction consisted of PVC casing connected to 10- or 15-foot long PVC screen intersecting the water table. They were installed with 4- or 8-inch diameter boreholes and the annular space was filled with a filter pack, a bentonite seal, and grout.

For each of three conventional wells at a site, a direct-push well, screened over basically the same interval, was installed 2.5 feet to the west. The screen of the direct-push well was set over basically the same interval as the conventional well to ensure that the sample will be obtained from similar geologic and hydraulic conditions as the conventional well provided the wells are properly developed and the screens are not clogged. Overall, there are 12 clusters and 24 wells (12 conventional wells and 12 direct-push wells).

The direct-push wells were installed with a Geoprobe[R] direct-push apparatus (Appendix E provides more details). During drilling, soil samples were taken for grain size analysis (Appendix F). Continuous soil samples were collected from the saturated zone that corresponded to the screened interval of the conventional well. These boring logs are available in the compendium of data available from EPA Region 5.

After soil sampling was completed and the boring reached the proper depth, the Geoprobe[R] rods were extracted from the bore. The direct-push well, which consisted of a 1-inch diameter, schedule 80 PVC screen and riser pipe, was properly assembled and inserted into the bore. The diameter of the bore was approximately 0.2-inches larger than the outer diameter of the well screen and riser, and no filter pack, bentonite, or grout was used in the annulus. The upper 2 feet of all direct-push wells was sealed at the surface with bentonite and neat cement grout. The surface finish of each of the direct-push wells consisted of a flush-mounted, 5-inch diameter, traffic-rated vault set in a 1 foot square concrete pad. Well construction diagrams were prepared for each direct-push well and are available in the data compendium retained by EPA. After they were installed, measuring points on the direct-push wells and all existing monitoring wells at the site were surveyed to a common datum. Each direct-push well was developed by purging.

There was no filter pack with the direct-push wells because this type of apparatus was not available at the time of installation. However, this may be an advantage because filter packs may not be needed. A filter pack in wells is designed to do two things: it increases the effective hydraulic diameter of a well and it retains most of the formation material thereby filtering fines from the well (Driscoll, 1986). Specifically for environmental monitoring wells, the filter pack is designed to exclude the entrance of fine silts, sands, and clays into a monitoring well. Therefore, the only effect the filter pack should have on analytical analyses from environmental monitoring wells is that sediment and formation fines are minimized. If a filter pack is used in the construction of an environmental monitoring well, it will affect the hydraulic diameter of the well, and it may influence the results of hydraulic conductivity tests such as slug tests if the filter pack is not properly accounted for in the calculations. There should be no real difference in the analytical results for dissolved phase constituents.

During the study, the wells were sampled four times, resulting in 768 analytical data values for MTBE, BTEX constituents, total BTEX, naphthalene, and total suspended solids. Water levels were measured on each of the wells prior to sampling. Additional data included duplicate samples. The data was collected between 16 September 1997 and 18 September 1998. Hydraulic conductivities were measured twice using rising head tests. The Brunswick, GA and Marietta, GA sites were also sampled for the geochemistry parameters: dissolved oxygen, pH, carbon dioxide, alkalinity, ferrous iron, total iron, nitrate, sulfate, and methane. Table 2 shows the sampling dates for each site.

An additional well redevelopment prior to sampling of direct-push well 18 at Granville, OH was performed in September 2001. This was done to test assertions regarding the possibility of skin effects (compaction of soil during soil sampling, smearing contaminated soil in the well bore during installation, or clogging screens during installation) and redevelopment.

TABLE 2--Sampling Dates			
Toledo, Ohio	**Marietta, Georgia**	**Granville, Ohio**	**Brunswick, Georgia**
MTBE, BTEX Constituents, Total BTEX, Naphthalene, And Total Suspended Solids			
16-18 September '98	29-31 December 1998	14-15 September 98	17-18 June 1998
17-19 June 1998	21-23 June 1998	15-16 June 1998	30-31 March 1998
23-25 March 1998	23-25 March 1998	26-28 March 1998	17-19 March 1998
15-16 December 1997	16-Sep-97	18-Dec-97	16-18 December 1997
			23-24 September '97
Geochemistry Parameters			
None Taken	25-26 June 1998	None Taken	22-23 June 1998
	25-27 March 1998		31 March - 2 April 1998
	5-7 January 1998		18-19 December 1997
	20-21 October 1997		23-25 September 1997
	18 September 1997 (Methane only)		
Hydraulic Conductivity			
17 December 1997	22 September 1997	22 December 1997	22 September 1997
4 March 1999	12 March 1999	6 March 1999	18 March 1999

DISCUSSION AND RESULTS

With the exception of water table measurements, the analysis of the data and the presentation of the results are as follows. The data were transformed and then analyzed by normal distribution statistical methods; the detailed results are provided in Appendix G. In this section, a cross-plot of the direct-push measurement versus the conventional well measurement is provided to illustrate the variation and trend of the data. The results of the statistical analysis are summarized and used to explain and draw conclusions concerning the trends and variations (or lack thereof) observed.

The statistical analyses were generally performed without consideration of the physics and geologic conditions that could influence the results; that is, variables (or factors) and combinations of variables (or factors) were statistically analyzed simply because the analysis was possible. In other words, the analysis is strictly statistical. It is up the hydrogeologist and engineer to interpret whether a statistical observation has any physical relevance and draw conclusions.

The general methodology for the statistical analysis of the data included the following: a transformation of the data so adequate weight can could be given to the range of measurements (larger values did not swamp smaller values), a probability analysis to determine if the statistics of normal distributions were applicable (the transformation was chosen so that the normal distribution was obtained), and the use of General Linear Modeling (R.Littell, et. al., 1991) to determine if factors or combinations of factors might influence the results. In all cases, the transformation produced a normal distribution of the measurements to be statistically analyzed.

The general linear model (GLM) is much like applying a simple regression analysis (y = ax+b). In a simple regression (least-squares) analysis of normally distributed data, a straight line is fit to the data and the "goodness of fit" is tested with the correlation coefficient (R^2) and the significance of the correlation is generally tested with an F-test. The GLM is simply a multi-variable fit of the data that determines if the chosen variables (or factors) might result in differences among the measurements. For example, the obvious variables in this study are: the Site (or City), the Well, and the Well-type (direct-push or conventional). Combinations of these variables were considered; such as the effect that one type of well at a particular site may have on the results. With the GLM, many variables and combination of variables can be included. Also, the use of the GLM shows highlights or eliminates factors other than the well-type that could confound the analysis that, in effect, allows the well-type comparison to be performed on a larger data set.

The GLM generally had a correlation coefficient of greater than 0.75, indicating that the model explained the variability of the data or alternatively, "it was a very good fit," with the exception of the geochemistry data. The F-test values were generally large when the well-type was found to be insignificant. If the correlation coefficient and F-Test values are relatively high, this indicates a conclusive result that well-type did not affect the result.

Comparison of Water Level Measurements

The groundwater elevation determinations in the conventional and direct-push wells from data taken prior to the four sampling events are plotted in Figure 1 and shown to be nearly identical. A linear regression of the entire data set had a correlation coefficient of 0.9942 that is exceptionally high and shows the results to be independent of the type of well.

Figure 1: Water Table Elevation Measured in Direct-Push vs Conventional Monitoring Wells

$$\text{DP Elev} = 1.0157\ \text{Conv Elev} - 1.2571;\quad R^2 = 0.9942$$
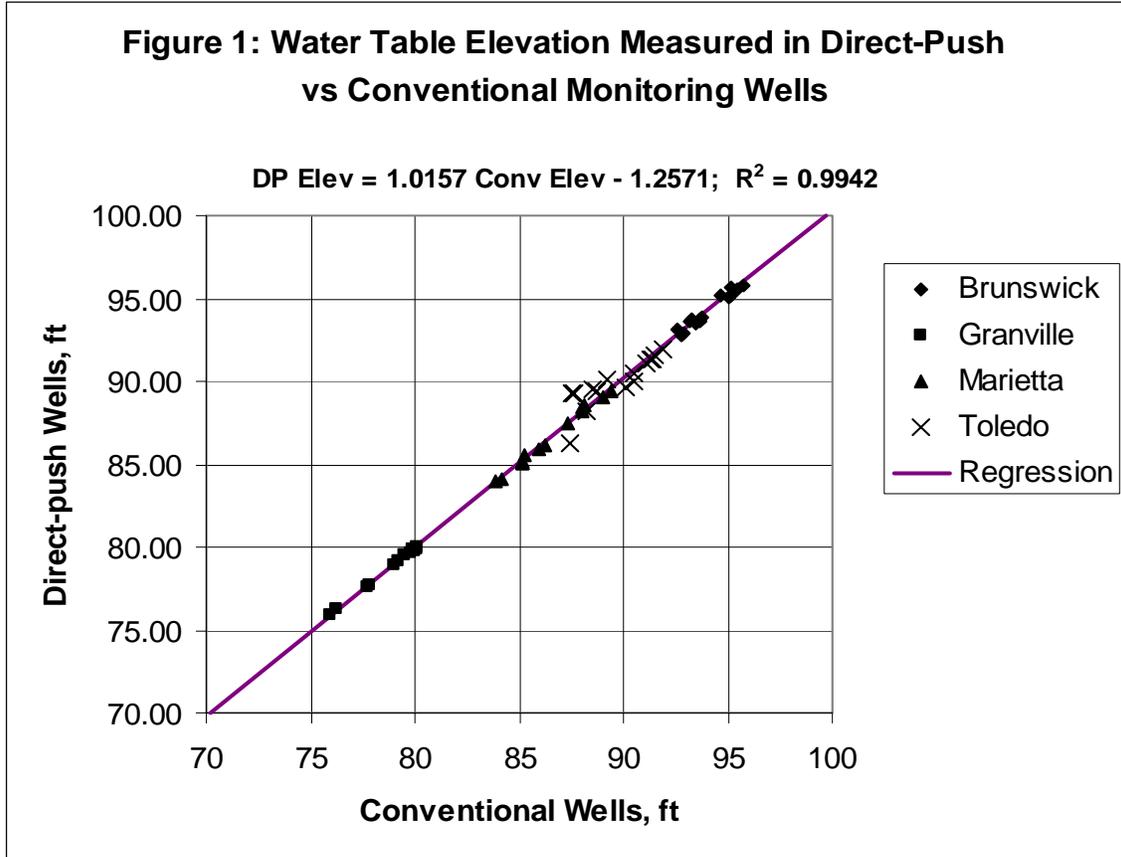
Comparison of Hydraulic Conductivity Measurements

Rising head tests were performed in the conventional and direct-push monitoring wells at the four study sites in order to compare hydraulic conductivity measurements. All of the wells were screened across the water table. Hydraulic conductivity data was analyzed by two methods: Hvorslev (1951) and Bouwer & Rice (1976). The results from the two types of wells are presented in Figure 2.

Figure 2: Hydraulic Conductivity Determined by Hvsorlev and Bower-Rice Methods
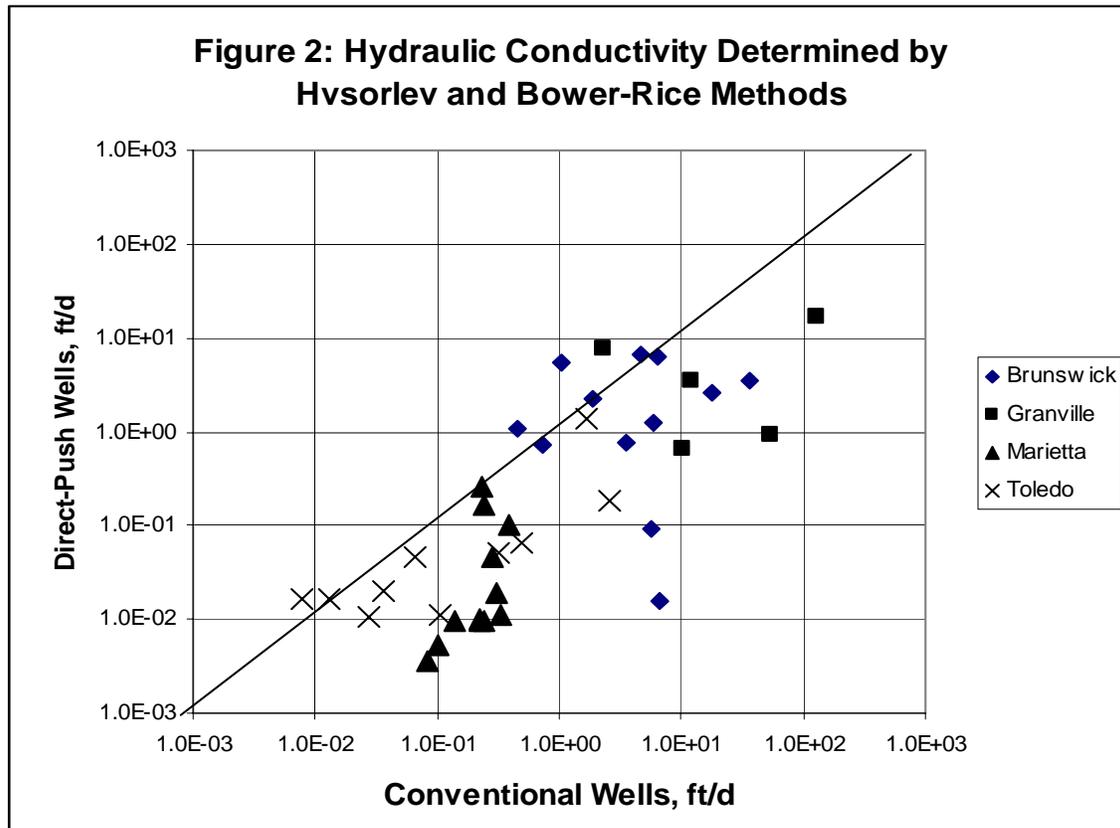
It is apparent that the conductivity values from the conventional wells are below the "equal value line" which means that they are generally greater than those determined from the direct-push wells suggesting a systematic error or problem. Based on the mean values, the hydraulic conductivity is approximately 4.4 times larger for the conventional wells than for the direct-push wells. The statistical analysis also shows this quite clearly (Appendix G, Part III).

Recently, Henebry and Robbins (2000) studied the influence of skin effects on the hydraulic conductivity of direct-push wells without filter packs. They concluded that undeveloped wells had hydraulic conductivities 3.2-9.6 times lower than those that were developed using a minisurge block tool. The direct-push wells in this study were developed by purging. Thus, it can be concluded that the direct-push wells in this study were probably not developed completely. It is also important to note that Henebry and Robbins concluded that properly developed direct-push wells yielded comparable results to conventional monitoring wells.

It should be noted that the Toledo and Marietta soils have conductivities 1-2 orders of magnitude lower than those studied by Henebry and Robbins (2000).

Comparison of Total Suspended Solids (TSS) Concentration Data

The groundwater samples from the direct-push wells had significantly higher concentrations of TSS than those from the conventional wells. This is evident by the cross-plot in Figure 3, and it was a result of the statistical analysis. As with the hydraulic conductivity data, it appears that there is a systematic error or problem. A filter pack is meant to reduce or eliminate fines in a well, so the lack of a filter pack in the direct-push wells is likely the cause for the higher TSS concentrations. It is also possible that the incomplete well development also contributed.

The statistical analysis of the data (Appendix G, Part II) also showed that there is a significant difference between the sites. This might be reflective of different degrees of development at the sites and/or the geologies. It was also noticed in the statistical analysis that the TSS data collected in the December, 1997 sampling event had a mean TSS concentration in the conventional wells greater than the mean in the direct-push wells (see two outlying points in the lower right-hand corner of Figure 3). This is directly opposite the data collected in the other sampling periods. The reason is unknown. The statistical analysis also indicates a large sampling and measurement error that could possibly be due to mislabeling a few samples or results.

Figure 3: TSS Concentrations From Direct-Push and Conventional Monitoring Wells
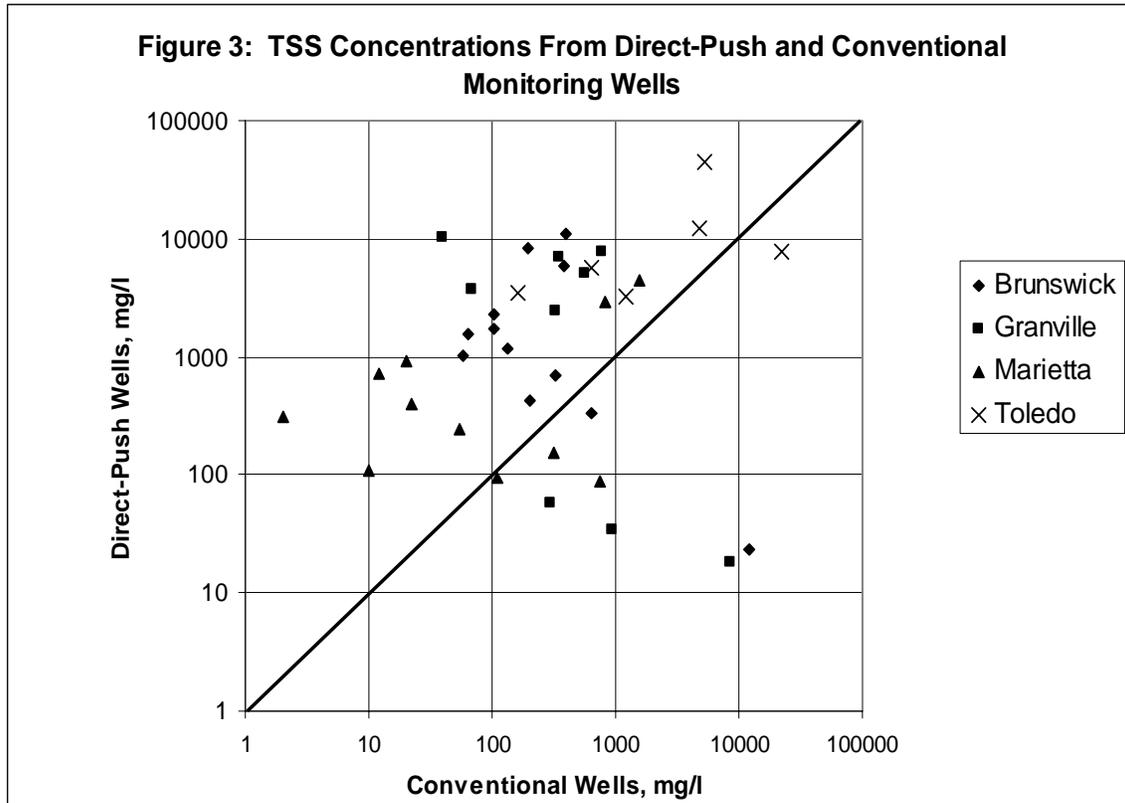
Comparison of MTBE Concentration Data

The MTBE concentration data is plotted in Figure 4. The log of the concentration data was taken prior to statistical analysis. Although there is scatter exhibited in the data, the statistical analysis exhibited a normal distribution and no bias (data generally scattered proportionately about the equal value line) toward any site or type of well. The correlation coefficient (R^2) was 0.76 indicating a very good fit. The statistical analysis conclusively showed that MTBE concentrations were equivalent in samples from the conventional and direct-push monitoring wells. For further discussion of the statistical methods, refer to Appendix G, Part I.

It is interesting that a skin effect or well development does not appear to have an affect on the MTBE concentrations. Perhaps this is due the low absorbance of MTBE. This is another reason for collecting organic carbon content so we might test such possibilities.

Figure 4: MTBE Concentrations Measured in Direct-Push vs Conventional Wells
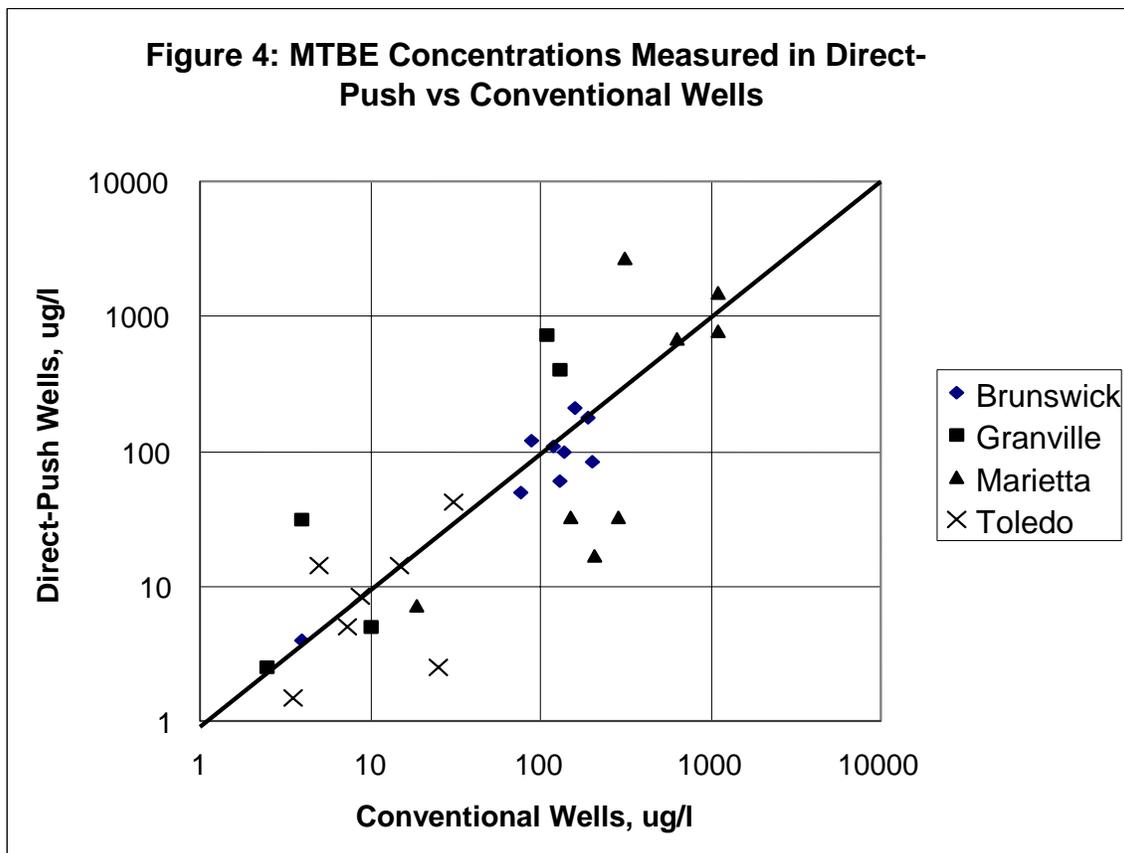
Comparison of BTEX Concentration Data

The statistical analysis for the BTEX measurement (and also for all of the individual BTEX constituent measurement; results provided in Appendix G, Part I) conclusively showed that there was no difference between direct-push and conventional post-purging across three of the cities (Brunswick, Marietta, and Toledo). However, for Granville, the fourth city in the study, the concentrations were significantly higher for the direct-push wells; this can be readily seen in Figure 5. For further discussion of the statistical results, refer to Appendix G, Part I. It is suspected that during the installation of the direct-push well at Granville, contaminated soil from near the water table filled the screen and became a long-term source.

Figure 5: BTEX Concentrations Measured in Direct-Push vs conventional Wells
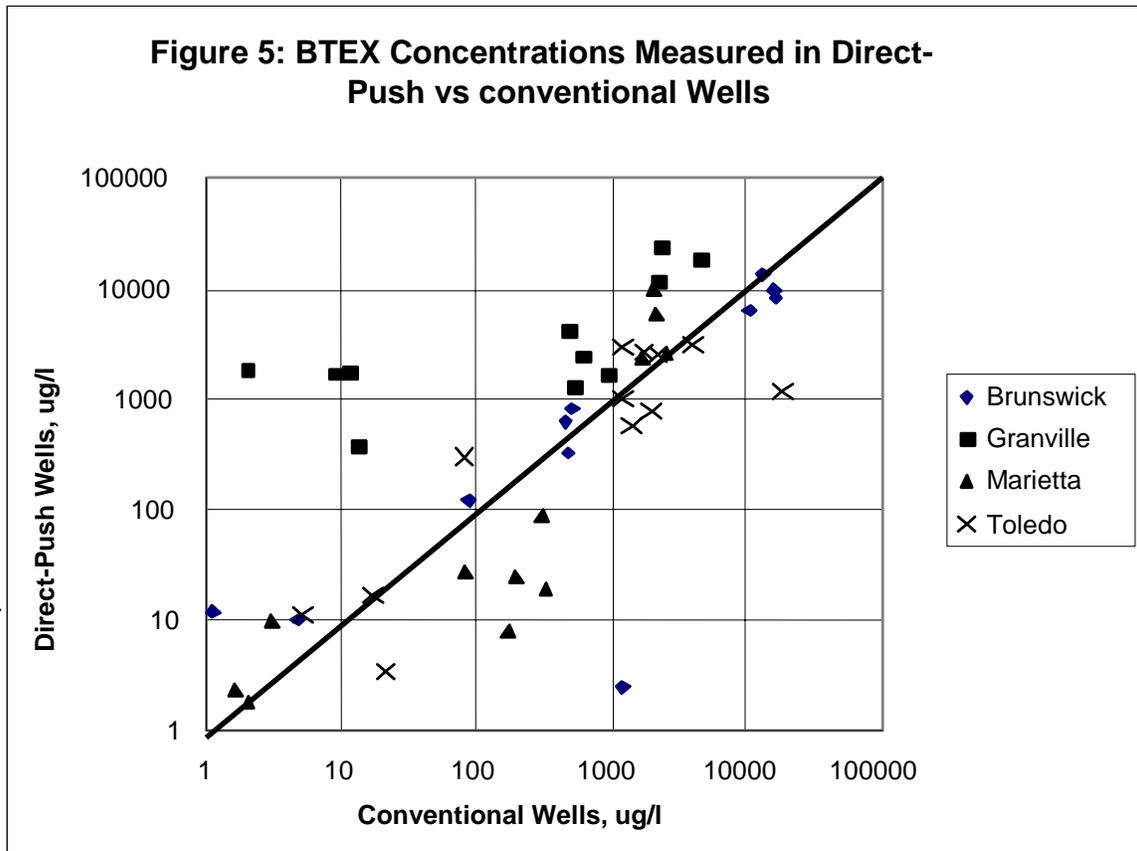
In order to investigate this possibility, direct-push well 18 was redeveloped prior to the September 2001 sampling event. All three direct-push wells used in the study were supposed to be redeveloped prior to being sampled, but the other two were dry. The results of the sampling are provided in Table 3. The fact that the concentrations in the direct-push well is decreasing with time and becoming closer in value to that in the conventional supports the possibly that the screen may have become contaminated with the clay soil during installation and that good well development may have prevented the discrepancies observed between the two types of wells.

Table 3 BTEX Concentrations At Granville Well 18		
Date	Conventional Well, ppb	Direct-Push Well, ppb
18-Dec-1997	12	1762
26-Mar-1998	2	1837
15-Jun-1998	9	1719
14-Sep-1998	13.9	366.7
27-Sep-2001	ND	75

Comparison of Naphthalene Concentrations

For naphthalene, the direct-push wells again exhibited slightly higher concentrations than those from the conventional wells, and this result was not consistent across all four sites. For Marietta, the opposite result actually was true. There was a lot more spatial variability for naphthalene across the sites than any other type of variability as is evident in Figure 6; note the significant scatter about the equal-value line. It is suspected that the higher naphthalene concentrations in the direct-push wells might be due to adsorption onto organic matter in the TSS. However, the fraction of organic carbon was not measured. Statistically, no correlation was found between naphthalene and TSS concentration. The statistical analysis can be found in Appendix G, Part II.

Figure 6: Naphthalene Concentrations From Direct-Push and Conventional Monitoring Wells

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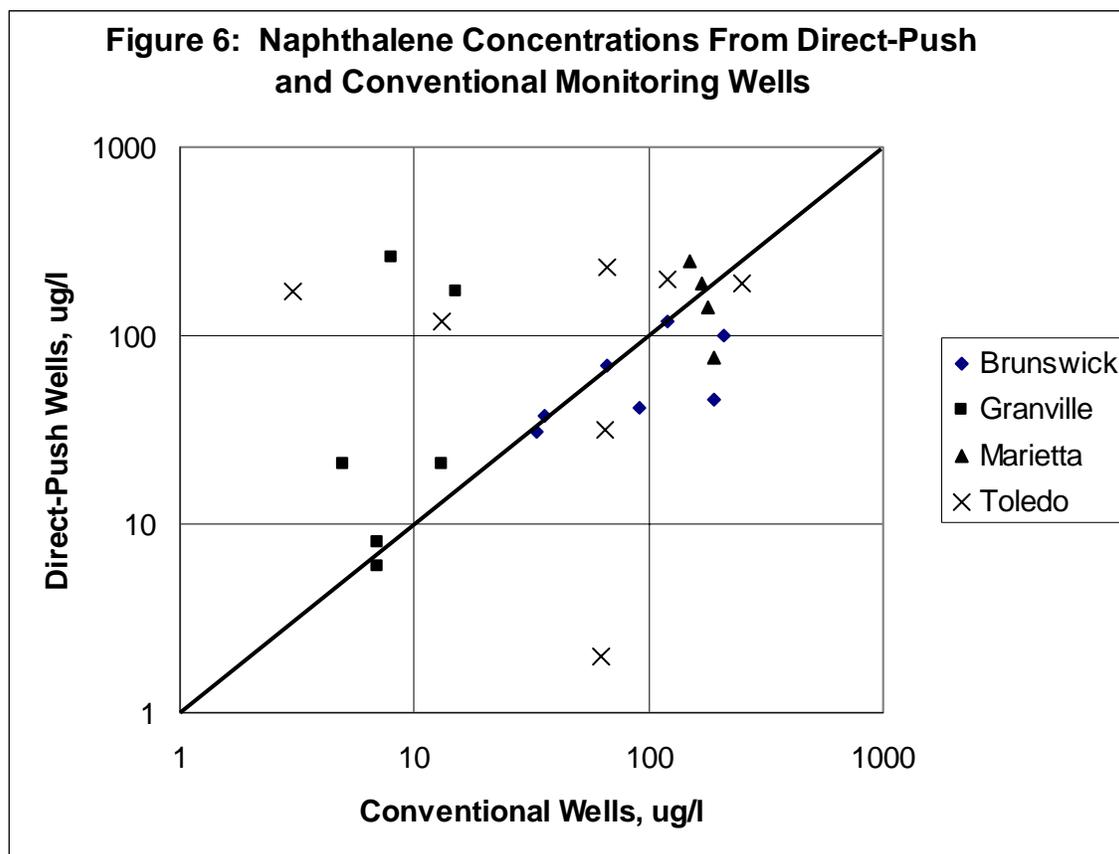
Comparison of Geochemistry Parameters

Four quarterly sets of measurements were obtained at the Marietta and Brunswick GA sites for geochemistry parameters that are generally used to indicate biodegradation of contaminants. A summary of the results of the statistical analyses is presented in Table 4. The correlation coefficient values for the fit of the GLM model to the data indicates that there is quite a bit of variability, except for the dissolved oxygen, which is not explained by the model. However, the cross plots (presented in Appendix G, Part IV) indicate that there is little bias in the data and apparently no systematic errors or problems with the possible exception of alkalinity. The variability of the data is likely related to the analytical methods, filtering of samples, and the use of field kits and the ability to perform accurate dilutions in the field. This apparently results in several concentrations reported as "greater-than", "less-than", or non-detect (See Appendix G, Part IV).

Table 4 also reports the mean values and F-Test values for each of the seven parameters by well-type and shows that there is no significant difference between the concentrations measured in the direct-push and conventional wells. On a site-by-site basis, however, there are differences noted in the nitrate, sulfate, and dissolved oxygen concentrations. Differences on a site-by-site basis should be expected. Because of the modest amount of data and the reported values, these results should be taken as indicative that direct-push wells provide concentrations equivalent to conventional wells but the results should not be considered as completely demonstrative.

Table 4: Summary of Mean Values and Statistics for the Geochemistry Parameters							
		Mean Values by Well-type			Mean Values by Site		
Parameter	Correlation Coefficient for the GLM Model	Direct-Push Well	Conventional Well	F-Test* Value on Well-type Effect	Brunswick	Marietta	F-Test* Value on Site Effect
Ferrous Iron, mg/l	0.02	1.47	0.9	0.73	0.91	1.45	0.7566
Nitrate, mg/l	0.49	2.18	2.46	0.7602	4.06	1.32	0.0178
Methane, mg/l	0.34	0.98	0.98	0.8349	2.23	0.36	0.0614
Sulfate, mg/l	0.15	2.62	8.87	0.2533	5.83	4.01	0.713
Dissolved Oxygen, mg/l	0.77	0.97	0.76	0.7745	0.43	1.28	0.0004
Carbon dioxide, mg/l	0.23	221.05	210.29	0.7164	239.75	193.89	0.1448
Alkalinity, mg/l	0.07	69.1	57.75	0.8191	85.89	46.46	0.4408

Inquiries concerning this report should be made to Vic Kremesec of Group Environmental Management Company, a BP Affiliated Company (kremesvj@bp.com) or Gilberto Alvarez, US EPA Region 5 (alvarez.gilberto@epa.gov). Mr. Alvarez is also custodian of the data.

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Bibliography

Driscoll, F. G., Groundwater and Wells, 2nd Edition, 1986, Johnson Division, pp 438-447.

Henebry, B.J., and G. A. Robbins, "Reducing the Influence of Skin Effects on Hydraulic Conductivity Determinations in Multilevel Samplers Installed with Direct Push Methods," GroundWater, 38(6) (2000):882-886.

Littell, R., R.Freund, and P.Spector, *SAS Systems for Linear Models,* 3E, SAS Institute, Cary NC, 1991

Hvsorlev, M.J., *Time Lag Soil Permeability in Groundwater Observations*, U.S. Army Corps of Eng. Waterways Experimentation Station, Bulletin 36, 1951.

Bouwer, H., and R.R. Rice, "A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely of Partially Penetrating Wells," Water Resources Research, 12 (1976):423-28.

APPENDIX A
BRUNSWICK, GEORGIA

SITE HISTORY

This facility is located at Interstate 95 and US Highway 17 in Brunswick, Georgia. At the time of the study, the site was occupied by a tractor-trailer fueling facility with a restaurant, motel and truck service center. The surrounding area is distinguished by undeveloped property, residential properties and commercial facilities. The current operations dispense diesel fuel and gasoline. The diesel fuel is stored in three 30,000-gallon capacity steel aboveground storage tanks (ASTs) located north of the service garage. The ASTs were installed in 1980. The gasoline is stored in three 10,000-gallon steel underground storage tanks (USTs) located east of the dispenser islands. The USTs were installed in 1980. A 10,000-gallon bulk oil fiberglass UST and an 8,000-gallon used oil steel UST are located adjacent to and west of the service garage. The bulk oil and used oil USTs were installed in 1993.

In May, 1991, site clean-up activities were coordinated in response to stained soil and an oil/water mixture being observed in the ditch on the western side of the property by Georgia EPD. 450 tons of petroleum hydrocarbon impacted soil were excavated and disposed. 30,000 gallons of oil/water mixture were also disposed. BTEX concentrations ranged from below detection limit to 0.22 ppm. TPH concentrations ranged from below detection limits to 6,500 ppm. Phase I and Phase II Environmental Audits were performed in 1993. Additional assessments were performed in 1994, which showed TPH concentrations in the range from below detection limits to 160 ppm. BTEX concentrations ranged from below detection limits to 13 ppm. In March, 1995, further assessments focused on defining the extent of petroleum hydrocarbons in soil and groundwater.

SITE GEOLOGY

The site is situated in an area of low relief in an estuarine environment between the Little Satilla River and the South Brunswick River. The site elevation is approximately 16-feet above mean sea level. Moderate temperatures prevail. The annual mean temperature in January is 49 degrees F and the annual mean July temperature is 80 degrees F. Average annual rainfall is 48 inches.

The site is located in the Georgia Coastal Plain in the Southeast Georgia Embayment. The embayment is a shallow, broad basin, which appears to have subsided relative to the surrounding regional structures. Subsidence appears to be episodic since deposits of the Miocene are exceptionally thick and deposits of the Plio-Pleistocene show no evidence of differential thickening across the embayment. The Pliocene to recent deposits are interbedded locally with fossiliferous clays and coquina limestone and are underlain by the Miocene Hawthorn Group consisting of feldspathic phosphatic sand and dolomitic, phosphatic, fossiliferous limestone. The Floridan aquifer, the Brunswick upper and lower aquifer and the surficial aquifer are the three-aquifer systems in Southern Glynn County. The water bearing layers of the surficial aquifer consists of permeable silty and clayey, fine to medium sands. The thickness of the aquifer is estimated to reach as much as 170-feet. The aquifer is recharged by rainfall infiltration. The shallow subsurface consists of fine to coarse grained, dark brown to white, sand with some shell fragments. Bedrock was not encountered in any soil borings. A soil boring log is shown in Figure A1.

SOIL BORING LOG

Earth Systems

Project #: 87H03CA

LOCATION: I-95 & U.S. 17, Brunswick, GA

BORING/WELL ID #: TA-7

COMPLETED: 3/8/95

PREPARED FOR:
BP Oil Company
Former Site #01043

DEPTH (ft)	SAMPLING METHOD	BLOW COUNTS	WELL CONSTRUCTION	DESCRIPTION	LITH SYMBOL	OVA-FID Headspace Measurement (ppm) UNFILTERED	FILTERED	DEPTH (ft)
0				ASPHALT				0
				SAND: Shelly, fine to coarse, compacted, light grey, dry		7	0	
						0	NM	
	PH	NA				0	NM	
				SAND: Shelly, organic, coarse, brown, moist				
5								5
	SS	4,4 6,5		SAND: Slightly silty, fine well sorted, very dense, light brown, wet @ 7 ft bls a 0.5 ft thick layer of coarse shell fragments				
	SS	4,5 6,9						
10	SS	1,4 4,4		SAND: Same as above, light grey				10
	SS	3,3 4,4		SAND: Silty, micaceous with dark minerals, fine, very dense, greenish grey				
	SS	1,1 1,1		SAND: Slightly clayey, silty, micaceous, dark minerals, very dense, cohesive, green-grey @ 15 ft bls a 0.5 ft thick coarse shell fragments				
15								15
	SS	1,1 1,4						
				Total Depth = 17.5 ft bls				
20								20

SAMPLING METHOD
SS - Split Spoon
PH - Posthole
HA - Hand Auger
GS - Machine Auger Grab Sample
MR - Mud Rotary Cuttings
ST - Shelby Tube

WELL CONSTRUCTION
GROUT: Type I Portland Cement
BENTONITE: Pellets
FILTER PACK: Graded Silica Sand

Figure A1: Brunswick Soil Boring Log

SITE HYDROGEOLOGY

Ground water zones were encountered through the drilling activities at depths in the range of 4.5 to 8.4 feet below the top of casing elevations. No separate phase liquids were identified. Ground water flows in a south-southwest direction, at gradients ranging from 0.0006 to 0.0014 feet vertical per feet horizontal.

CONVENTIONAL WELL INSTALLATION

Six monitoring wells, TA-1 through TA-6 were installed at the site on August 23 to August 25, 1993. One monitoring well, TA-100 was installed on March 27, 1994. Seven monitoring wells, TA-7 through TA-13 were installed on March 6 through March 9, 1995. The monitoring wells were installed at the locations shown in Figure A-1.

The shallow monitoring wells were installed with 4-inch Schedule-40 PVC casing and 15-feet of screen (0.010-inch slots) with flush threaded joints. Once the screen was properly positioned, the sand pack, bentonite seal, and cement grout were installed into the annular space. A lockable watertight cap and flush mounted steel-vault were installed at the surface to ensure the integrity of the well and preclude infiltration of surface runoff.

SITE MAPS

Figure A2 shows the site map for the Brunswick site.
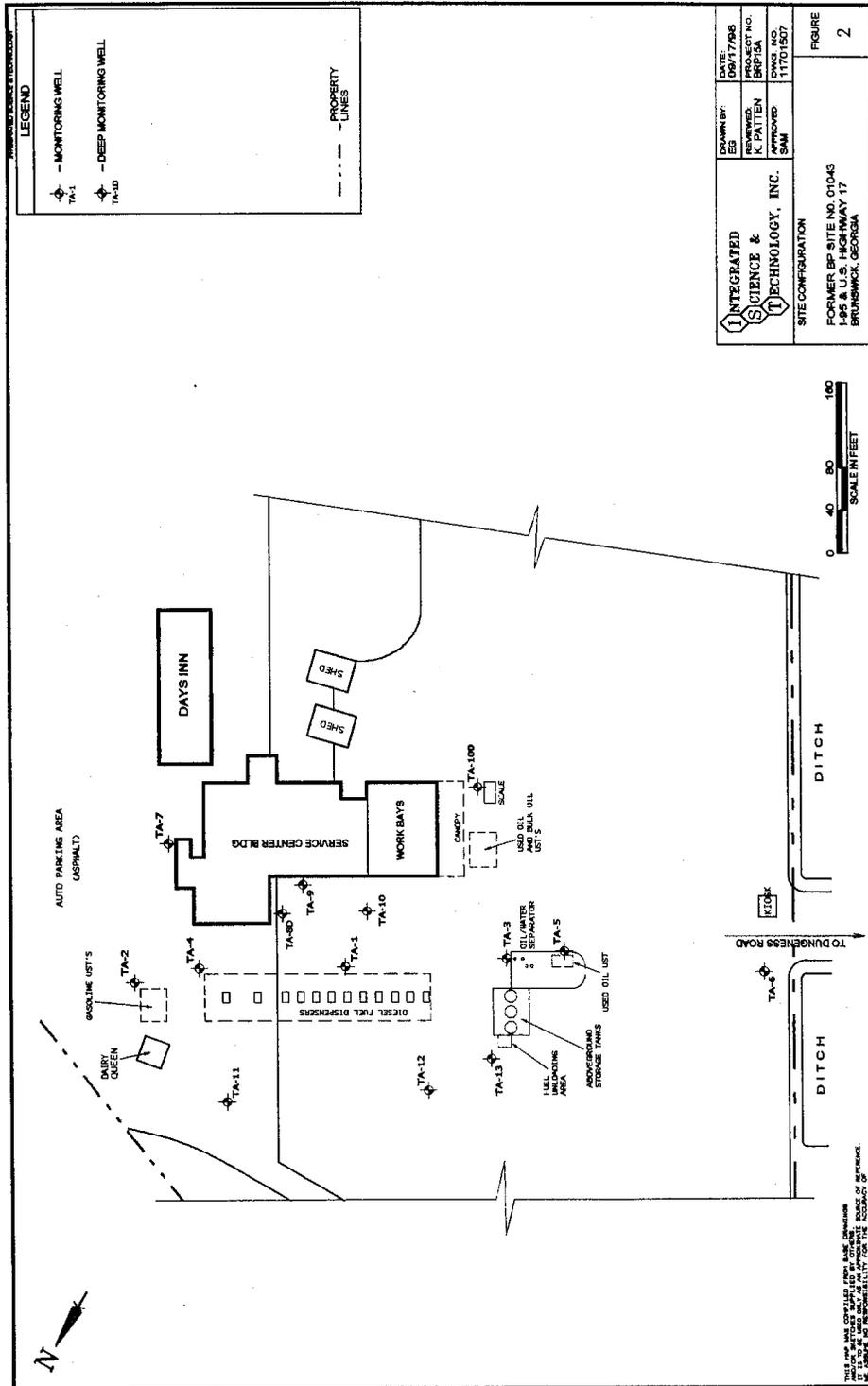
Figure A2: Brunswick Site Map

APPENDIX B
MARIETTA, GEORGIA

SITE HISTORY

The Marietta site formerly contained four underground storage tanks (USTs). Two new UST areas consist of a total of seven USTs presently containing diesel and unleaded gasoline. The surrounding area is dominated by commercial businesses including restaurants and retail shops. Residential areas exist farther to the south. No basements were evident within the immediate vicinity of the site. An extended site assessment was prepared after discovery of hydrocarbon contamination in preexisting monitoring wells.

SITE GEOLOGY

The Marietta site is located in the Central Uplands District of the Piedmont Physiographic Province. Most of the surrounding area is a broad rolling upland or plateau that generally contains the same topography throughout. The plateau is inclined to the southeast from higher elevations in the northwest. The elevations in the northwest are about 1,200 feet mean sea level and the elevation in the southeast are about 700 feet mean sea level. The area is underlain by fine-grained soils and saprolite that mantle bedrock. The site is underlain by muscovite, sillimanite, and quartz schists locally interlayered with thick beds of graywacke, quartzite, and other rocks. Garnet, graphite, and biotite are common accessory minerals. Site soils are weathered in place from this formation and consist of residual soil with black fine sandy silt and clay saprolite. Groundwater can be found in two separate zones in the Piedmont. A shallow water-bearing zone typically occurs within the soils which mantle bedrock. A deeper water-bearing zone also occurs within the crystalline bedrock. Groundwater flow in the shallow zone is controlled by local topography. Recharge of the shallow zone occurs in upland areas and discharge occurs in local drainage features. Recharge of the shallow zone is generally through the infiltration of precipitation. Groundwater flow in the deeper zone is controlled by the amount and interconnection of fractures and open spaces in the bedrock. Groundwater flow direction in the deeper zone is generally controlled by local discharge features such as large creeks or rivers. Recharge of the deeper zone is generally from the shallow zone. Groundwater encountered in monitoring wells on the site is from the shallow water-bearing zone. A soil boring log is shown in Figure B1.

ADVANCED ENVIRONMENTAL MANAGEMENT, INC.
1798 MONTREAL CIRCLE, SUITE A
TUCKER, GA 30084
(404) 908-0809   FAX (404) 908-8802

CONTRACTED WITH: BP Oil   WELL NO.: MW-4
PROJECT NAME: BP Johnson Ferry   JOB NO.: 176   DATE: 9/28/94
DRILLER: Brian Titshaw   RIG: Acker   LOGGED BY: P. Gagen

DESCRIPTION	DEPTH (FEET)	#	BLOWS/6"	PID/NOTES	WELL COMPLETION REPORT
2.0" Asphalt Cover.					Street grade 8" Manhole Cover
Sand (SM) Orange silty fine sand fill, some clay.	0				Locking Watertight Cap 2.0' x 2.0' Concrete Pad
					Top of Bentonite Grout 1.0 ' BLS.
Sand (SM) dark brown clayey fine sand, aluvial, organics.	5	1	3-3-3	475 ppm	4" O.D. Schedule 40 PVC Riser and Screen ASTM NSF-Rated
Sand (SM) Tan to white fine clayey sand, some silt, Residual.	10	2	9-14-14	80 ppm	Top of Bentonite: 7.0' BLS
	15	3	6-13-13	390 ppm	Top of Sand:8.0' BLS
	20	4			Top of Screen: 10.0' BLS 10.0' Total 0.01 Slot
					Borehole Diameter:10.5"
Boring Terminated @ 20.5 ft' BLS.	25	5			
	30	6			Bottom of Screen: 20.0' BLS
					Bottom of Well: 20.5' BLS
					Bottom of Boring: 20.5' BLS
	35	7			
	40	8			1.0 Bags of Bentonite (50 Lb. Bags) Placement: gravity
					8.0 Bags of Sand NSF-Rated (50 Lb. Bags) Placement: gravity
	45	9			

Figure B1: Marietta Soil Boring Log

SITE HYDROGEOLOGY

Groundwater exists at a depth of approximately 13-15 feet below the land surface under unconfined water table conditions. The hydraulic gradient at the site was calculated to be 0.016 ft/ft. The relatively low permeability of the surficial aquifer produces groundwater flow velocities in the range of 10 to 100 feet per year. Groundwater flows in a westerly direction towards an unnamed creek approximately 600 feet off site.

CONVENTIONAL WELL INSTALLATION

Type II monitoring wells were installed in 1990, 1993, and 1995. They were constructed using 2-inch diameter, schedule 40-PVC casing with flush threaded couplings. The well screen consisted of PVC pipe with factory-installed slots, which extend above and below the water table except in the case of deep wells. After the casing was installed, the annulus around the well screen was filled with clean graded sand to above the top of the screen. Bentonite pellets were then placed on top of the sand and hydrated to form a seal. A cement-grout seal was then placed in the annulus from the bentonite seal up to the surface. The top of the PVC well heads were set in either a flush mounted traffic rated box at grade with an internal metal locking cover or a stand up steel casing with a water tight locking cover.

The wells were developed by hand bailing or pumping. Groundwater was allowed to stabilize for a day or more prior to purging the well of three casing volumes and collecting groundwater samples.

SITE MAP

Figure B2 shows the site map for the Marietta site.
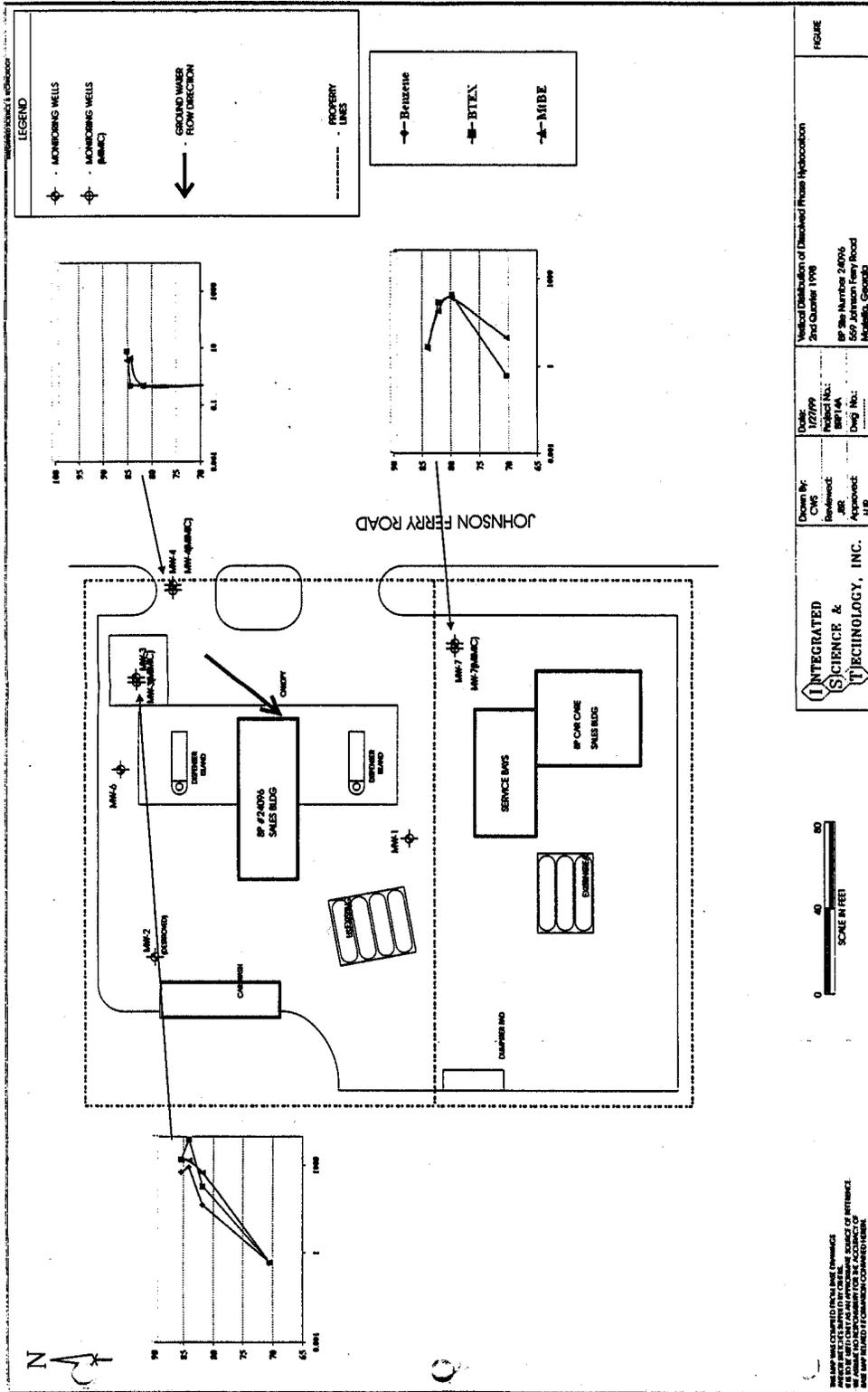
Figure B2: Marietta Site Map

APPENDIX C
GRANVILLE, OHIO

SITE HISTORY

At the time of the study, the site was operating as a retail facility with a combined sales and automotive service building with two service bays, three fiberglass gasoline underground storage tanks (USTs), one 4,000 gallon and two 8,000 gallons, one 550 gallon used oil UST, one 550 gallon heating oil UST and three gasoline dispensers. In 1989 a gasoline inventory loss was documented and found to be related to a hole that had formed in one of the 8,000 gallon USTs. The volume of gasoline released was likely on the order of 100 gallons.

SITE GEOLOGY

The site is located in Licking County within the glaciated portion of the Allegheny Plateau physiographic province. The topography is comprised of low, rolling hills separated by broad, terraced stream valleys, with topographic elevations ranging from 900 to 1200 feet USGS. Surface drainage discharges into Raccoon Creek, which is located approximately 300 feet north of the site. The regional geology includes three major units: Mississippian bedrock, unconsolidated Pleistocene (Wisconsin and Illinoisan) glacial deposits, and Quaternary alluvial deposits. Bedrock is formed by the Logan Formation and the Black Hand Member of the Cuyahoga Formation that are comprised of sandstone, siltstone, and shale. Glacial deposits generally cover bedrock everywhere except along the eastern edge of the county. The glacial deposit consists mostly of silty clay tills forming ground and end moraines in upland areas and sand and gravel outwash deposits forming terraces along streams and rivers. Alluvial deposits are comprised of thin stratified layers of silt and clay with lesser amounts of sand, which overlie the glacial deposits and bedrock in floodplain areas. Both bedrock and the sand and gravel outwash form water supply aquifers. A soil boring log is shown in Figure C1.

STRATIGRAPHIC AND INSTRUMENTATION LOG

PROJECT _BP OIL SITE #08032_ JOB NO. _BPO-5_ HOLE NO _MW-3_

CLIENT _BP OIL COMPANY_ STARTING DATE/TIME _7/20/88_

LOCATION _STATE RT 16 & CHERRY, GRANVILLE, OHIO_ COMPLETION DATE/TIME _7/20/88_

CONTRACTOR _Belsaco_ DRILL METH _H.S. AUGER_ GEOLOGIST/HYDROGEOLOGIST _Ron Wells_

BOREHOLE TYPE _MONITORING WELL_ BOREHOLE Ø _9"_ COMPLETION INFORMATION

FORMATION SAMPLING METHOD _SPLIT SPOON_ _Monitoring well completed in fill_

GROUND ELEVATION _96.0'_ MEASURING ELEV _96'_

STATIC WATER DEPTH _14.3'_ GROUND WATER EL _81.7'_

ELEV. FT AMSL	STRATIGRAPHY / MATERIAL DESCRIPTION	LITH OL OGY	DEEP (FT)	INSTALLATION DESCRIPTION	WELL CONST	FORM. SAMP. NO.	LAB	PENETR. TIP/HNU	BLOWS /0.5ft
			0	Road Box					
95				Grout					
				Bentonite Seal					
90	S.I. 5.0-7.0 Recovery: 1.9 1.9 Dark Greyish Brown Silty Clay; Some Medium Sand; Trace Rock Fragments; Stiff To Very Stiff; Damp		5	Quartz Filter Sand		1	no	10.6	6-6-6
85	S.I. 10.0-12.0 Recovery: 1.7 0.7 Brown Silty Clay; Some Rock Fragments; Firm; Wet 0.3 Brown Rock Fragments; Some Silty Clay; Very Stiff; Damp 0.2 Tan Silty Clay; Stiff; And Rock Fragments; Loose; Dry		10	#10 Slot 4" Diameter PVC Screen		2	Wet	222	9-10--9

PAGE 1 OF 2

IEP Inc.
ENVIRONMENTAL SCIENTI
PLANNERS ENGINEERS

Figure C1: Granville Soil Boring Log

SITE HYDROGEOLOGY

Soils underlying the site include the following in order of occurrence with respect to depth: fill material, silty clay till, sandy silt, and sand and gravel outwash. The fill material ranges from 5 to 10 feet. This is underlain by silty clay till ranging from 10 to 20 feet thick. Up to 8 feet of sandy silt underlies the till, and the sandy silt is underlain by a sand and gravel outwash layer that is at least 40 feet thick. Groundwater levels generally vary between 15 and 20 feet below ground surface. Groundwater flow is towards the north, and the hydraulic gradient is estimated to be 0.002 feet/foot. The estimated hydraulic conductivity of the outwash aquifer varies between 4.5 x 10^{-5} to 5.0 x 10^{-3} cm/sec.

CONVENTIONAL WELL INSTALLATION

Monitoring wells were installed in September 1990. All four monitoring wells were constructed using flush joint, thread coupled, four-inch diameter, schedule 40 PVC riser and 15 feet of 0.01 inch slot PVC screen. The annular space around the well was filled with #5 washed quartz sand to a height of one to two feet above the top of the screen, sand pack, and a bentonite based grout to approximately one half foot from land surface. An expanding locking cap was placed at the top of the PVC riser. All wells were developed by removing three well casing volumes of water and using dedicated disposable polyethylene bailers. During development, water temperature, pH and hydraulic conductivity were monitored to verify that the two final readings stabilized within 10%. No free product was observed in any well during development.

SITE MAP

Figure C2 shows the site map for the Granville site.
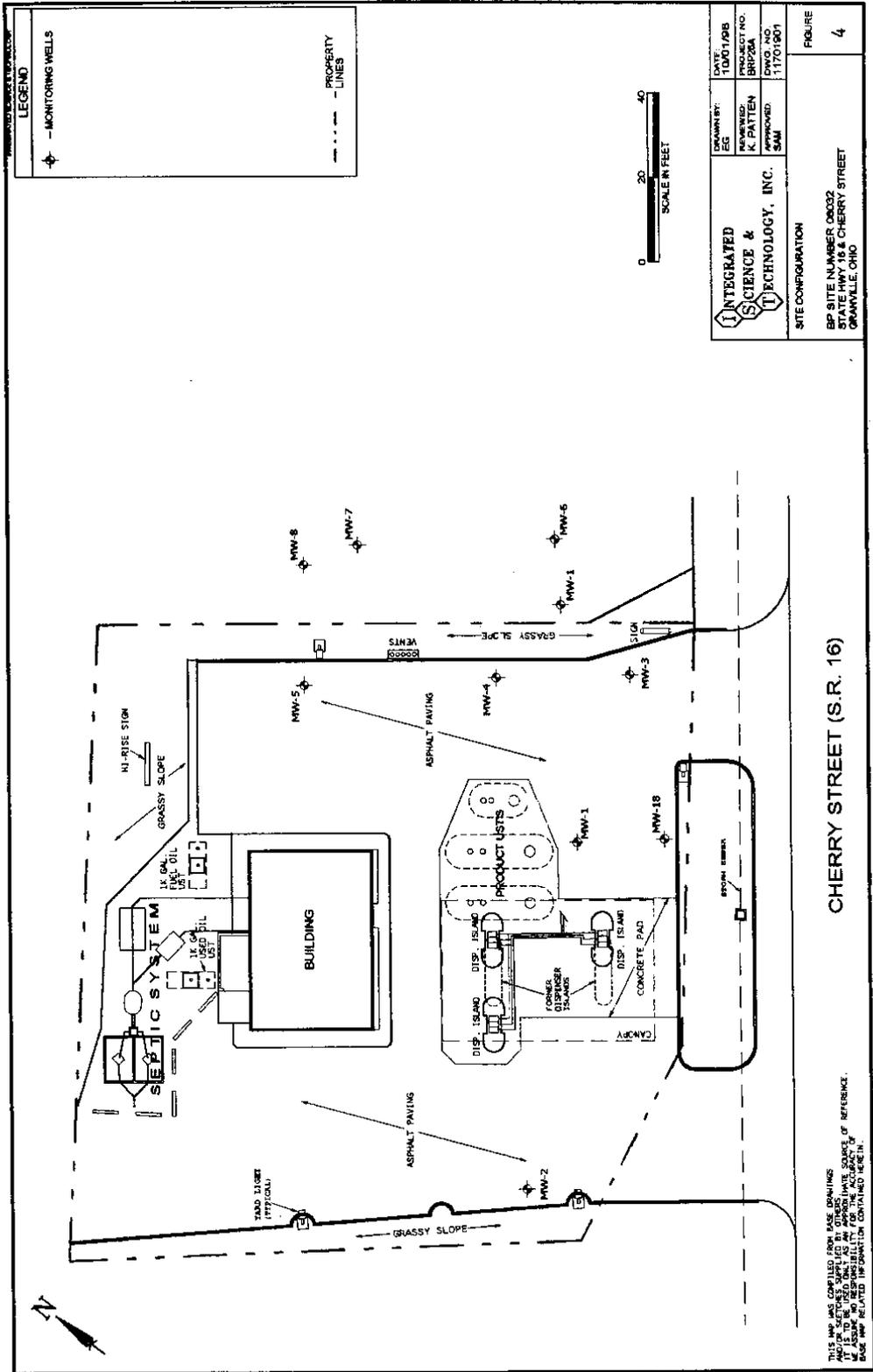
Figure C2: Granville Site Map

APPENDIX D
TOLEDO, OHIO

SITE HISTORY

The site is an operating retail facility. Four 8,000-gallon fiberglass gasoline USTs were installed in 1978 and are still in use at the site. In the fall of 1996 the site was temporarily closed to allow for modifications to the UST system, predominantly dispenser removal and the addition of new dispensers in a relocated area, and the construction of a new sales building and carwash. Prior to the fall 1996 construction activities, a pre-construction site assessment was conducted to investigate conditions and note the potential presence of petroleum hydrocarbons in the soil and groundwater. The results of this assessment were indicative that residual hydrocarbons were present in both soil and groundwater and a release was reported to the state in May 1996. A file review did not indicate any reportable releases prior to the pre-construction assessment. Subsequent corrective action activity has occurred since the 1996 release.

SITE GEOLOGY

The site is located in Lucas County and is primarily underlain by Silurian age dolomite bedrock overlain by Wisconsinan age ground moraines, beach ridges, and lake deposits, averaging approximately 100 feet or more in thickness in the vicinity of the site. The ground moraines typically consist of clay-rich tills and the lake deposits are comprised of fine sand and clayey silt. The beach ridge deposit trends northeast-southwest form Sylvania through Holland, Ohio and southwest to Neapolis and consists of silty fine sand to medium sand. The region is characterized by relatively flat topography that gently slopes northeastward toward Lake Erie. Ground-water resources can be obtained from lenses of sand and gravel scattered irregularly throughout the glacial till, but most well log information obtained from the ODNR suggests that domestic wells, within the vicinity of the site produce water from the carbonate bedrock and sand and gravel deposits associated with buried valley deposits. The predominate soil type encountered in the borings consists of lacustrine deposits of clayey silt and silty clay with varying percentages of sand and gravel. The upper saturated unit is comprised of a sequence of finely laminated clayey silt with very thin and discontinuous laminae of clay encountered at a depth of six to ten feet. Bedrock was not encountered in any of the borings. A soil boring log is shown in Figure D1.

LOG OF MONITORING WELL
WELL NUMBER MW-2

PROJECT: Phase I Hydrogeologic Assessment
BORING LOCATION: West central side of Site
BORING NO.: SB-2   WELL NUMBER:. MW-2
DRILLING METHOD: 4.25" ID Hollow Stem Augers
CONTRACTOR: Summit Drilling Service
DEPTH TO WATER: 9.44'   DATE CHECKED: 11/22/96
LOGGED BY: J.W. Biehl   FIRST SATURATION: 8.0'

PROJECT NO.: BP0693
GROUND ELEV.: 99.52
TOTAL DEPTH: 14.5'
DATE START: 10/29/96
DATE END: 10/29/96
WATER ELEVATION: 90.08
TOP OF CASING: 99.22

ELEVATION / DEPTH	SOILS, UNDISTURBED/ DISTURBED SAMPLERS, AND FIELD TEST DATA	SOIL DESCRIPTIONS	REMARKS	PID (ppm)	SAMPLE NUMBER
		ASPHALT	Drilled through asphalt and sub-base, then sampled with hand auger to 5'.		
		FILL: Grey road gravel, some fines, damp.			
98		FILL: Brown fine sand, moist, loose.			
2.5		Black silty CLAY, trace of sand, trace of gravel, moist, slightly friable.	Soil sample SS-1 collected using hand auger at 2.0' to 2.5'.	32	SS-1
95.5		Greenish grey mottled brown very silty CLAY, trace of sand, moist, slightly plastic.	Soil sample SS-2 collected using hand auger from 4.0' to 4.5'.	86	SS-2
5		Same as above according to ends of Shelby tube sample (USCS: CL, USDA: silty clay loam).	Rec.=2.0' for Shelby tube ST-1. SS-3 collected from base of tube at 6.75'-7.0'.		
93		Same as above.		151	SS-3
7.5	2/6 12/12 10/6	Medium dense brown clayey SILT, saturated, faint laminations, occasional thin clay laminae (<1cm).	Rec.=1.5'for SP-1. SS-4 collected from 7.5' to 8.5'.	104	SS-4
90.5		Same as above.	Overdrill due to a shear-off of the center plug in the hole.		
10	12/6 34/12 10/6	Same as above with occasional horizontal oxidation and Dense.	Rec.=2.0' for SP-2. SS-5 collected from 10.5' to 12.5'.	174	SS-5
88					
12.5	6/6 17/12 9/6	Same as above.			
		Very stiff grey very silty CLAY, with thin (<1mm) interbedded clayey silt, very moist, very plastic.	Rec.=2.0'. SS-6 collected from 13.0' to 14.5'.	2.0	SS-6
85.5		Well Construction (2" PVC) Screen: 14.0'-8.0' Riser: 8.0'-0.5' Sand: 14.0'-7.5' Holeplug: 7.5'-5.5' Grout: 5.5'-1.0' Concrete: 1.0'-0.0'	TD Augers at 14.0'.		
15					
83					
17.5					

Elevations are referenced to a benchmark datum of 100.00 on the north bolt of the traffic light pole located at the southwest corner of Site.

SOIL SAMPLE SS-3 WAS SENT TO LABORATORY FOR ANALYSIS.

HULL & ASSOCIATES, INC.

Figure D1: Boring Log for the Toledo Site.

SITE HYDROGEOLOGY

The potentiometric surface appear to slope to the south-southwest at gradients of 0.031 feet/foot as measured from ME-3 to MW-2 and 0.033 feet/foot as measured from monitoring wells MW-3 to MW-4. Depth to water is about seven to nine feet.

CONVENTIONAL WELL INSTALLATION

Monitoring wells MW-1 through MW-7 were installed in soil borings SB-1 through SB-7, respectively. Factory wrapped well screens and riser pipes were utilized in the construction of the wells. Each well was constructed of 2-inch schedule 40 PVC riser and schedule 40 PVC 0.010 inch slotted screen installed through 4.25 inch I.D. hollow stem augers. An inert sand pack, extending approximately 0.5 feet vertically above the well screen, was placed around each well screen to serve as a filtering medium. A minimum of two feet of sodium-bentonite chips was then placed above the sand pack. The remaining annular space was grouted to within two feet of the surface with a sodium-bentonite and Portland cement slurry. Finally, each well was secured with a locking watertight cap, keyed-alike lock, and cast manhole cover.

SITE MAP

Figure D2 shows the site map for the Toledo site.
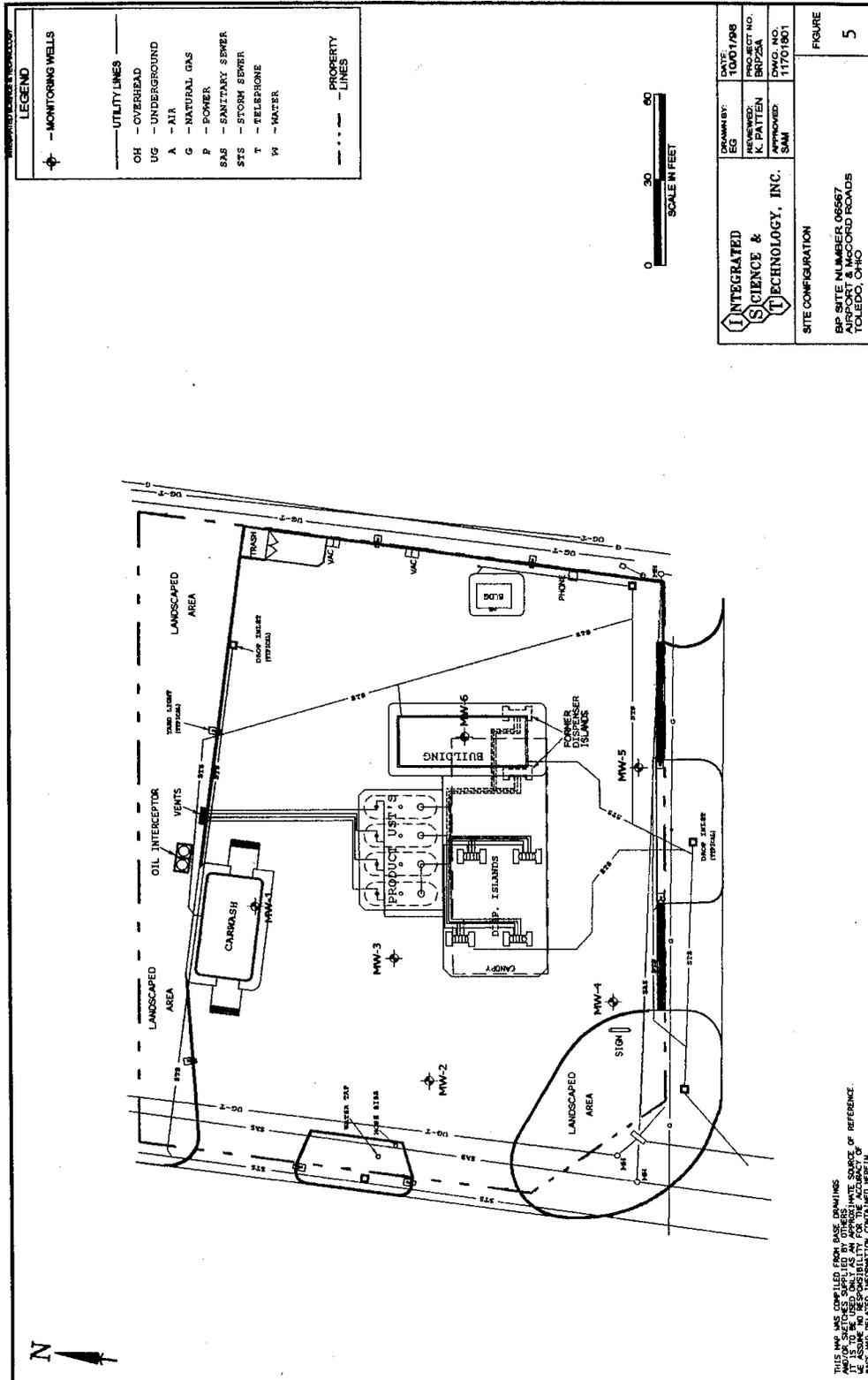
Figure D2: Toledo Site Map

APPENDIX E
STUDY PROCEDURES

DIRECT-PUSH WELL INSTALLATION

The direct-push wells were installed with a Geoprobe[R] direct-push apparatus. During drilling, soil samples were taken (procedure described in appendix F) for grain size analysis. Continuous soil samples were collected from the saturated zone that corresponded to the screened interval of the conventional well. These boring logs are available in the compendium of data available from Gilberto Alvarez.

After soil sampling was completed and the boring reached the proper depth, the Geoprobe[R] rods were extracted from the bore. A 1-in diameter, schedule 80 PVC screen and riser pipe were properly assembled and inserted into the bore. The diameter of the bore was approximately 0.2-in larger than the outer diameter of the well screen and riser, and no filter pack, bentonite, or grout was used in the annulus. The upper 2 ft of all direct-push wells was sealed at the surface with bentonite and neat cement grout. The surface finish of each of the direct-push wells consisted of a flush-mounted, 5 in diameter, traffic rated vault set in a 1 ft square concrete pad. Well construction diagrams were prepared for each direct-push well and are available in the data compendium retained by Gilberto Alvarez. After they were installed, measuring points on the direct-push wells and all existing monitoring wells at the site were surveyed to a common datum. Each Direct-push well was developed as discussed below.

Each monitoring well nest contained the conventional 4-inch monitoring well as well as five direct-push wells. The existing conventional monitoring well was designated A, the direct-push well is designated B, and the other wells located in the nest were designated C, D, E and F. The location of each type of direct-push well relative to the existing monitoring well was planned to be the same for each cluster. The B wells were all installed 2.5-feet to the west of the conventional well and had the same screen interval as the conventional well. Wells C, D and E were installed with 1-foot of screen at intervals that approximately correlated to the top, mid-point, and bottom of the water column measured in the conventional monitoring well. These wells are located 2.5-feet to the north, 2.5-feet to the south, and 2.5-feet to the east of the conventional well, respectively. The final direct-push well in each nest location, F, had a 1-foot section of 0.01-inch slotted well screen 15-feet below the bottom of the conventional well. Data for wells C-F were not analyzed in this report.

DIRECT-PUSH WELL DEVELOPMENT

Each Geoprobe[R] direct-push well was developed by purging. Development continued until the water cleared or at least five well volumes were removed. The conventional well development is provided in Appendices A-D when known.

PURGING AND SAMPLING

Once gauging was completed, groundwater samples were collected before purging from the conventional and direct-push wells in each cluster. These samples were labeled as MX-xA1 and MX-xB1 (x indicated the number of the conventional mentoring well). These samples are being analyzed as part of a no-purge study and are not used in this analysis or report. The wells were then purged and sampled in a specific order. The direct-push wells with 1-foot sections of screen (C, D, E, and F) in each cluster were purged from the shallowest, C, to the deepest, F. Well B was purged next and the conventional well A was purged last. A well was purged and sampled

completely before proceeding to the next well in the cluster. An attempt was made to purge all the wells of five well volumes using a dedicated disposable polyethylene bailer. However, due to slow recharge recovery rates at some of the sites, some of the wells were purged dry twice and a ground-water sample was collected from the well when it had recovered to at least 80 percent of its initial level.

ANALYTICAL METHODS

Each sample was analyzed to determine concentrations of benzene, toluene, ethylbenzene, total xylenes (BTEX), and methyl-*tertiary* butyl ether (MTBE) using SW-846 method 8021B and of polynuclear aromatic hydrocarbon compounds using SW-846 Method 8310. The samples were also analyzed for total suspended solids using EPA Method 160.2. The six ground-water samples collected prior to purging from the conventional and direct-push wells were only analyzed for BTEX and MTBE. Also, one equipment rinseate and six duplicate samples were collected for quality-control purposes and analyzed for BTEX and MTBE. The duplicate samples were collected from the B wells and the conventional wells in each cluster and labeled as MW-xG and MW-xH, respectively. In some cases, the wells produced insufficient water for every analysis.

Nitrate, sulfate, total iron, and dissolved iron were analyzed in the field using a HACH DREL/2000 spectrophotometer. The DREL/200 incorporated colorimetric methods with spectrophotometer capable of wavelength resolution to one nanometer. The DREL/2000 meter calibration was checked at the start and end of each day's sampling event. Dissolved iron concentrations were also determined using CHEMMets Colorimetric Test Kits (K-6010) as a screening tool to help determine when a sample needed to be diluted for analyses by the DREL/2000 meter. If dissolved iron concentrations were below 10 mg/L, then the CHEMMets was a second method to determine dissolved iron concentrations.

Methane samples were collected in 80 ml vials, preserved with three drops of 50 percent HxSO4 solution, and shipped overnight by Federal Express to the Robert S. Kerr Research Center. Methane gas analyses were performed as per RSKSOP-194, and calculations were done as per RSKSOP-175.

A Cole-Palmer waterproof pH-Tester 2 (P-59000-25) pH meter was used for pH determinations. New calibration pH standards were made for each sampling event using Micro Essential Laboratory pHydrion Buffer Capsules. Three-point calibration (4.0, 7.0, and 10.0) was used to calibrate the pH meter at the start of each day's sampling event and to check pH calibration at the end of each day.

DO concentrations were measured using an Orion DO electrode (97-08) and read with an Orion ion/concentration meter (290-A). DO was also measured by using a CHEMMets Colorimetric Test Kit (K-7512) with a 1- to 10-mg/L detection range. Calibration of the Orion DO meter was conducted prior to the sampling of each monitoring well.

Alkalinity was determined by using Titrets Titrimetric Test Kit K-9810 (10- to 100-ppm) and Test Kit K-9815 (50- to 500-ppm). Carbon dioxide was measured using Titrets Titrimetric Test Kit K-1910 (10- to 100-ppm). When carbon dioxide concentrations exceeded the range of the Titrets Titrimetric Test kit, the sample was diluted to be within the range of the test kid. To check dilution methodology, two different dilution ranges were conduced and the analytical results were compared to ensure that dilution were being carried out correctly.

APPENDIX F
GRAIN SIZE ANAYLSIS

The purpose of obtaining grain-size analysis is to provide more information on the geology versus depth at the site so ground-water flow and plume morphology might be better understood. The grain size of the sediment collected in the study is determined mainly by small-scale mechanisms operating as part of some larger-scale geological process.

Soil samples were collected during boring installation at the four sites in the study. The Marietta site is located in igneous terrane, the Brunswick site in a coastal plain, the Granville site in glacial deposits, and the Toledo site in lacustrine sediments. The specific soil-sampling approach employed a large bore, closed-piston sampler. In this approach, the sampler was lined with an acetate tube pressed onto a properly decontaminated cutting shoe. A sampling point attached to a piston shaft was passed through this tube, an adapter was installed on the proximal end, and the apparatus was fitted with a drive cap. The hydraulic cylinders of the Geoprobe[R] were used, assisted by the integral hydraulic percussion hammer, to advance the apparatus from the surface to the appropriate sample depth. Once this depth was reached, the stop pin holding the piston shaft in place was removed, allowing the piston shaft and sampling point to move up into the rods and sampler as soil entered the liner in the core barrel. The rods were advanced an additional 2 ft and soil filled the liner in the sampler. Following sample collection, the large bore, closed piston apparatus was extracted from the borehole.

 The samples were submitted for grain-size analysis using ASTM Methods D422, D2216, and D4318. Initially, the samples were separated into fractions by passing them through a set of sieves with each fraction containing grains or particles of approximately the same size. A hydrometer was used to separate the sample fraction finer than 0.074mm. The raw data consists of the weight percent of the sample in each size fraction.

Composite grain-size distribution curves were constructed for each of three clusters at the four sites by calculating the mean grain size in millimeters for each size fraction. Granville is the coarsest grained, followed by Brunswick, Marietta, and Toledo (the finest grained). Table F1 presents the grain size analysis as a function of depth and provides the soil classifications. This is useful to see the variation of geology with depth.

Table F1: Grain Size Analysis and Soil Classifications

Site ID, Well, Depth, ft	Gravel	Sand	Silt	Clay	USDA	USCS	Site ID, Well, Depth, ft	Gravel	Sand	Silt	Clay	USDA	USCS
Bru11B15	0	79.5	7.7	12.8	Sandy loam	SM	Mar3B16	1.3	56.5	30.9	11.3	Sandy loam	CL
Bru11B17	0	90.1	6.1	3.8	Sand	SP-SM	Mar3B18	1	79	14.3	5.7	Loamy sand	SM
Bru11C5	0	90.7	4.8	4.5	Sand	SP-SM	Mar3C14	3.2	78.1	4	14.7	Sandy loam	SM
Bru11F22	0	87.9	2.4	9.7	Loamy sand	SM	Mar3D16.5	0	85.6	11.4	3	Sand	SP-SM
Bru11F31	0	85.7	5.1	9.2	Loamy sand	SM	Mar3E19	0	78.6	17.7	3.7	Loamy sand	SM
Bru12B15.5	0	74.1	7.1	18.8	Loamy sand	SM	Mar3F24	1	70.4	24.2	4.4	Loamy sand	SM
Bru12C4.5	0	82.9	6.9	10.2	Loamy sand	SM	Mar3F30.9	1.5	79.9	14.5	4.1	Loamy sand	SM
Bru12D10	0	92.9	3.6	3.5	Sand	SP-SM	Mar4B14	0.6	70.3	22	7.1	Sandy loam	SM
Bru12E16	0.3	78.2	8.7	12.8	Sandy loam	SM	Mar4B16	0	61.1	28.7	10.2	Sandy loam	SC
Bru12F20	0	84.5	2.2	13.3	Loamy sand	SM	Mar4C15	0.3	68.8	21.4	9.5	Sandy loam	SM
Bru12F30.5	0	87	4.3	8.7	Loamy sand	SM	Mar4D16.5	0	65.5	27.2	7.3	Sandy loam	SM
Bru1B12	0	83.5	3.6	12.9	Loamy sand	SM	Mar4E18.7	0	74.8	20.1	5.1	Loamy sand	SM
Bru1B14	0	74.5	10.5	15	Sandy loam	SM	Mar4F26	0.5	72.9	23.3	3.3	Loamy sand	SM
Bru1C6	0	90.5	6	3.5	Sand	SP-SM	Mar4F28	0	56.6	32	11.4	Sandy loam	CL
Bru1D10	0	89.1	7.9	3	Sand	SP-SM	Mar4F30.9	5.9	75.8	14.2	4.1	Loamy sand	SM
Bru1F21	0	93.3	5.1	1.6	Sand	SP-SM	Mar4F32	0	75.8	15.9	8.3	Sandy loam	SM
Bru1F29	0	89.5	4.9	5.6	Sand	SP-SM	Mar7B16	0.4	51.5	32.3	15.8	Sandy loam	CL
							Mar7B18	0	75.2	11.3	13.5	Sandy loam	SM
Tol2B10	0	0.4	55.2	44.4	Silty clay	CH	Mar7C13.5	0.3	45.8	23.5	30.4	Sandy clay loam	CL
Tol2B12	0	0.4	92	7.6	Silt	ML	Mar7C22	16.7	62.8	14.2	6.3	Loamy sand	SM
Tol2B8	0	3.3	55.1	41.6	Silty clay	CH	Mar7D16	0.4	72.1	15	12.5	Sandy loam	SM
Tol2C9	0	0.5	66.8	32.7	Silty clay loam	CL	Mar7E18.5	2.6	67.5	21.2	8.7	Sandy loam	SM
Tol2D11.5	0	0.6	84.5	14.9	Silt loam	ML	Mar7F28	2.8	69	23.8	4.4	Loamy sand	SM
Tol2E12	0	0.5	78.8	20.7	Loam	CL							
Tol2F16	0	0.7	69.6	29.7	Silty clay loam	CL	Gra18B21	5.7	52	31.6	10.7	Silt loam	SM
Tol2F26	1	24	37.3	37.7	Clay loam	CH	Gra18B23	12.4	63.5	18.5	5.6	Loamy sand	SM
Tol3B11	0	0.5	73.2	26.3	Loam	CL	Gra18B25	29.4	56.7	10.3	3.6	Loamy sand	SM
Tol3B7	0	0.8	63.4	35.8	Silty clay loam	CL	Gra18C27	17.7	66.6	11.1	4.6	Loamy sand	SM
Tol3B9	0	0.7	64.6	34.7	Silty clay loam	CL	Gra18D21	35	41.9	18.3	4.8	Loamy sand	SM
Tol3C7	0	14.4	47	38.6	Silty clay loam	CL	Gra18D24	15.3	59.4	20.7	4.6	Loamy sand	SM
Tol3D10	0	0.7	57.6	41.7	Silty clay	CH	Gra18E27	21	62.7	12.4	3.9	Loamy sand	SM
Tol3E11	0	0.7	66.8	32.5	Silty clay loam	CL	Gra18F33	30	64.8	2.5	2.7	Sand	SP-SM
Tol3F17	0	0.2	57.5	42.3	Silty clay	CH	Gra18F37	15	76.7	5.6	2.7	Sand	SP-SM
Tol3F25	0	7.7	44.8	47.5	Silty clay	CH	Gra3B17	0	25.7	46.2	28.1	Clay loam	CL
Tol4B11	0	0.5	81.1	18.4	Silt loam	CL	Gra3B19	7	47.2	30.2	15.6	Sandy loam	CL
Tol4B13	0	0.6	65.8	33.6	Silty clay loam	CL	Gra3C17	0.6	18	56.8	24.6	Silt loam	CL
Tol4B9	0	0.4	67.8	31.8	Silty clay loam	CL	Gra3D18	15.1	42.4	29.4	13.1	Sandy loam	SC
Tol4C10	0	0.3	83.3	16.4	Silt loam	ML	Gra3E20	25.1	35.8	29.3	9.8	Sandy loam	SC
Tol4D12	0	0.9	85.1	14	Silt loam	ML	Gra8B16	0	52.7	35.2	12.1	Sandy loam	CL
Tol3E13	0	3.7	78.1	18.2	Silt loam	CL	Gra8B18	1.4	61.9	17	19.7	Sandy clay loam	SC
Tol4F25	1.1	22.5	31.8	44.6	Clay	CH	Gra8C16	9.1	21.4	59	10.5	Silt loam	ML
Tol4F16	0	0.5	49.7	49.8	Silty clay	CH	Gra8D17	18.3	70.4	4.7	6.6	Loamy sand	SM
							Gra8E19	28	43.1	19.4	9.5	Sandy loam	SM
							Gra8F28	25.3	56.2	15.9	2.6	Loamy sand	SM

APPENDIX G: STATISTICAL ANALYSIS

With the exception of water table measurements, the analysis of the data and the presentation of the results are as follows. The data were transformed and analyzed by normal distribution statistical methods and the detailed results are provided. The results of the statistical analysis are summarized and used to explain and draw conclusions concerning the trends and variations (or lack thereof) observed.

The statistical analyses were generally performed without consideration of the physics and geologic conditions that could influence the results; that is, variables (or factors) and combinations of variables (or factors) were statistically analyzed simply because the analysis was possible. In other words, the analysis is strictly statistical. It is up the hydrogeologist and engineer to interpret whether a statistical observation has any physical relevance.

The general methodology for the statistical analysis of the data included the following: a transformation of the data so adequate weight can be given to the range of measurements (larger values did not swamp smaller values), a probability analysis to determine if the statistics of normal distributions were applicable (the transformation was chosen so that the normal distribution was obtained), and the use of General Linear Modeling (R.Littell, R.Freund, P.Spector, *SAS Systems for Linear Models,* 3E, SAS Institute, Cary NC, 1991) to determine if factors or combinations of factors might influence the results. In all cases, the transformation produced a normal distribution of the measurements to be statistically analyzed.

The general linear model (GLM) is much like applying a simple regression analysis (y=mx+b). In a simple regression (least-squares) analysis of normally distributed data, a straight line is fit to the data and the "goodness of fit" is tested with the correlation coefficient (R2) and the significance of the correlation is generally tested with an F-test. The GLM is simply a multi-variable fit of the data that determines if the chosen variables (or factors) might result in differences among the measurements. For example, the obvious variables in this study are: the Site (or City), the Well (a specific well), and the Well-type (direct-push or conventional). Combinations of these variables were considered; such as the effect that one type of well at a particular site may have on the results. With the GLM, many variables and combinations of variables can be included. Also, the use of the GLM shows highlights or eliminates factors other than the well-type that could confound the analysis that, in effect, allows the well-type comparison to be performed on a larger data set. These combinations of variables are represented in the analysis as products, for example, Well-type*Site would represent a possible combination effect.

After fitting the data with the linear model, an F Test is used to determine if the variable or combination of factors is statistically significant. This is much like determining if the slope of a simple regression analysis (y = ax+b) is statistically different from zero; if it is, then the variable, x, has an effect. The GLM generally had a correlation coefficient of greater than 0.75, indicating that the model explained the variability of the data or alternatively "it was a very good fit." The exception to this was the geochemistry data. The F-test values were generally large when the well-type was found to be insignificant. If the correlation coefficient and F-test values are relatively high, this indicates a conclusive result that well-type did not affect the result.

Eric Ziegel of BP performed the statistical analyses. Physical interpretation of the results is provided by Vic Kremesec of BP.

PART I--STATISTICAL COMPARISON OF MTBE and BTEX CONSTITUTENT CONCENTRATION MEASUREMENTS

Statistical Analysis Design. The analysis followed the general methodology described above.

The natural logarithm (ln) of the concentration measurements was used in the statistical analysis of the MTBE data. Concentration measurements varied over several orders of magnitude, so the proportional variability that is represented by natural logs was appropriate for ensuring an approximately consistent level of variability across all concentration measurements. The transformation also needed to ensure that

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normal distribution statistical tests would be reasonably sound. The results below show the statistical tests and the graphs that validate the transformation that was applied. Identical considerations were used in choosing other appropriate transformations for the other analyzed concentrations.

Because the conclusions seem straightforward and unequivocal, the statistical analysis was not further complicated by using maximum likelihood estimation methods for correctly handling data with non-detects. Generally, there was not a lot of non-detects, so these were represented using their detection limit.

The variables in the GLM Model were: Site (or City), at which the study was performed, each Well, and the Well-type (direct-push or conventional).   The combinations tested were Well-type at a Site (Well-type*Site) and Well-type with a specific Well (Well-type*Well).

Results for MTBE. For MTBE the variance stabilizing, normality-inducing power transformation was ln (MTBE). Using this transformation, the statistical results of the fit of the linear model are presented in Table G1.

Table G1: GLM Model Results for MTBE

Dependent Variable: ln_MTBE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	389.44	16.93	9.16	<.0001
Error	65	120.14	1.85		
Corrected Total	88	509.59			

R-Square	Coeff Var	Root MSE	ln_MTBE Mean
0.76	49.20	1.36	2.76

Source	Degrees of Freedom	Type III SS	Mean Square	F Value	Pr > F
SITE	3	105.02	35.01	18.94	<.0001
WELL	8	261.92	32.74	17.71	<.0001
WELL-TYPE	1	0.01	0.01	0.00	0.9528
WELL-TYPE*SITE	3	5.31	1.77	0.96	0.4179
WELL-TYPE*WELL	8	15.86	1.98	1.07	0.3935

The middle section of Table G1 shows that the model provides a very good fit of the data (R-square = 0.76) and explains 76% of the variability for the natural logs of the MTBE values. The variability is apparently due to the common observation of significant fluctuation in groundwater concentration data. Statistically, this is shown by the value of the Root MSE, a percentage error when natural logarithm transformations are used, which exceeds 100%. However, the plot below shows that the variability (differences between GLM model and data) is consistent across the range of the predictions for ln(MTBE), i.e. not larger for high or low values of ln(MTBE):

```
Diff    ,                  A
        ,
        ,
  2.5 ^            A           A     A
        ,    A          AB         A
        ,  A B     A     A    A        A
        ,     B      B    B              BB        B   A
  0.0 ^     A A   D   CA   B       B     CAD   C      A   A
        ,  B B         AB   AB      A     AAB   A      A   B
        ,     D B
        ,        A          AB
 -2.5 ^               AA          A
        ,                   A
        |
       $f^fffffffffffff^fffffffffffff^fffffffffffff^fffffffffffff^ff
         0           2           4           6           8
                           Fitted ln (MTBE)
```
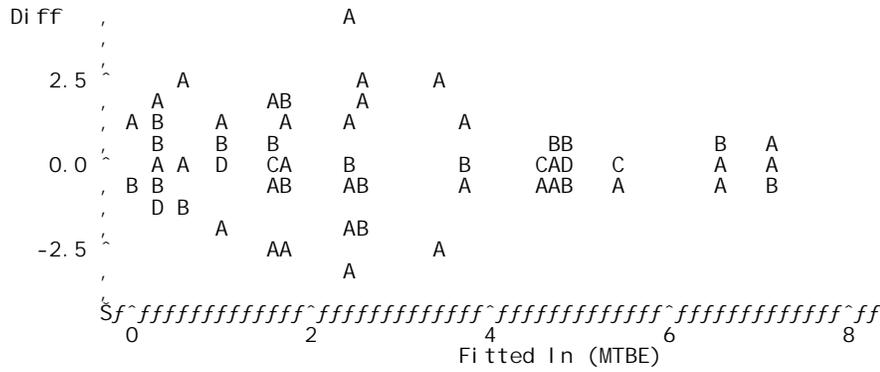
Figure G1: Differences between the GLM Model Prediction and the Measured Value for MTBE

Environmental groundwater concentration data, as much as we would like it to be otherwise, is subject to variations that make a good statistical fit of the data difficult to obtain at times. In this case, the GLM model fit the data well.

The following graph is the normal probability plot for the differences for the GLM model using the ln(MTBE) transformation. This plot validates the normal distribution assumption, and hence the use of the F Test, because all of the differences are consistent with a common straight line that represents the normal distribution for the differences.
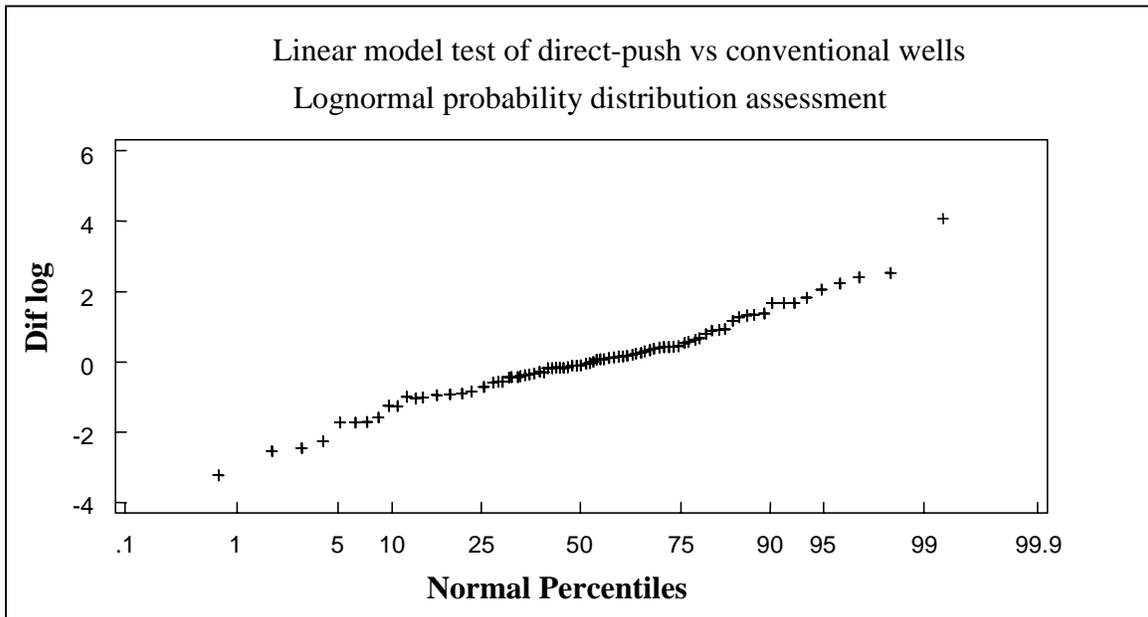
Figure G2: Normal Probability Distribution for the Difference Between the GLM and Measured MTBE Concentrations

Returning to Table G1, the important values for determining whether a variable (or factor) is significant are in the column headed by Pr>F, in the bottom section; these are the probabilities for the statistical significance of the different factors. When the probabilities are small, typically less than 0.1, then the effects are statistically significant. The probability values in the lower portion of the table show that, for the fit of the GLM model, the effects associated with the Site and the Well variables are significant; that is, they have a big effect on the model. However, Well-type does not; and hence, it can be concluded that it makes no difference if the MTBE concentration is measured in a Direct-Push well or a conventional well.

It is also clear that Well-type is not significant across Sites or individual Wells. Thus, MTBE concentrations obtained from sampling Direct-Push or conventional wells are statistically the same.

Results for BTEX. For BTEX the variance stabilizing, normality-inducing power transformation was $BTEX^{1/4}$. Using this transformation, the result for fitting the linear model is shown below:

Table G2: GLM Model Results for BTEX

Dependent Variable: qtrrt_BTEX

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	797.37	34.67	27.04	<.0001
Error	71	91.04	1.28		
Corrected Total	94	888.490			

R-Square	Coeff Var	Root MSE	qtrrt_BTEX Mean
0.90	21.65	1.13	5.23

Source	Degrees of Freedom	Type III SS	Mean Square	F Value	Pr > F
SITE	3	51.03	17.01	13.26	<.0001
WELL	8	653.74	81.72	63.73	<.0001
WELL-TYPE	1	5.68	5.68	4.43	0.0389
WELL-TYPE*SITE	3	55.51	18.50	14.43	<.0001
WELL-TYPE*WELL	8	28.49	3.56	2.78	0.0099

Unlike the model above for MTBE, the statistical results for BTEX indicate that all of the variables (lower section) have a significant effect. This is indicated by the p-value being fairly small (Pr>F <0.1). Note that the WELL-TYPE variable is significant for the BETX concentration. The confidence in the overall difference for conventional versus Direct-Push is greater than 95% (p-value=0.05). However, the large WELL-TYPE*SITE effect (Pr>F < 0.0001, a very small p-value) indicates that the difference is not consistent across all the Sites. Looking at the models for the Sites separately revealed that the difference was only significant for Granville.

To illustrate, the Table G3 shows the fitted GLM model with the Granville data excluded. In this table, the effect of the WELL-TYPE variable is not significant, and it is not significant in any of the Sites. The p-values (Pr>F) for this variable, WELL-TYPE, and combination of variables, WELL-TYPE*SITE, are not small and would not result in any effects being significant with a very high confidence level. The confidence level for the WELL-TYPE effect, for example, is less than 90%. For all the Sites except Granville, one can readily conclude that there is no difference between the two types of monitoring well.

Table G3: GLM Model Results for BTEX, Granville excluded

Dependent Variable: qtrrt_BTEX

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	17	611.11	35.95	27.93	<.0001
Error	54	69.51	1.29		
Corrected Total	71	680.62			

R-Square	Coeff Var	Root MSE	qtrrt_BTEX Mean
0.90	22.87	1.13	4.96

Source	Degrees of Freedom	Type III SS	Mean Square	F Value	Pr > F
SITE	2	28.74	14.37	11.16	<.0001
WELL	6	559.80	93.30	72.48	<.0001
WELL-TYPE	1	2.88	2.88	2.24	0.1407
WELL-TYPE*SITE	2	0.81	0.41	0.32	0.7306
WELL-TYPE*WELL	6	18.87	3.14	2.44	0.0366

The averages for the $BTEX^{1/4}$ measurements in Table G4, show that the mean averages for the two Well-types are very similar.

Table G4: Mean Value of $BTEX^{0.25}$ for the Two Well-Types

Well-type	N	Mean qtrrt_BTEX	Std Dev
Conventional	36	5.16	3.17
Direct-Push	36	4.76	3.06

Conversely, the next table shows the linear model just for Granville. Since there is only one site, there are no site variables in this model.

Table G5: GLM Model Results for BTEX at Granville

Dependent Variable: qtrrt_BTEX

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	164.41	32.88	25.97	<.0001
Error	17	21.53	1.27		
Corrected Total	22	185.94			

R-Square	Coeff Var	Root MSE	qtrrt_BTEX Mean
0.884221	18.51	1.13	6.08

Source	Degrees of Freedom	Type III SS	Mean Square	F Value	Pr > F
WELL	2	93.93	46.97	37.09	<.0001
WELL-TYPE	1	56.71	56.71	44.78	<.0001
WELL-TYPE*WELL	2	9.62	4.81	3.80	0.0433

Table G6: Mean Value of $BTEX^{0.25}$ for the Two Well-Types at Granville

Well-type	N	Mean qtrrt_BTEX	Std Dev
Conventional	12	4.52	2.33
Direct-Push	11	7.78	2.54

In Table G5, it is evident that there is a huge significant concentration difference for the Well-type. The computed means show that concentrations measured in the Direct-Push wells are much greater than those obtained from the conventional wells. Table G7 validates this result by simply displaying the actual data plus the transformation. In all three wells, it is clear that the direct-push well shows significantly higher BTEX concentrations. Note that this difference is particularly evident in the first table, which shows the results for well number 18.

Table G7: Granville BTEX Data Listing

-------------------------------- WELL=Granville18 --------------------------------

Obs	WELL	WELL-TYPE	BTEX	qtrrt_ BTEX
1	Granville 18	Conventional	13.9	1.94
2	Granville 18	Conventional	9.0	1.70
3	Granville 18	Conventional	2.0	1.19
4	Granville 18	Conventional	12.0	1.86
5	Granville 18	Direct-Push	366.7	4.37
6	Granville 18	Direct-Push	1719.0	6.44
7	Granville 18	Direct-Push	1837.0	6.55
8	Granville 18	Direct-Push	1762.0	6.48

-------------------------------- WELL=Granville 3 --------------------------------

Obs	WELL	WELL-TYPE	BTEX	Qtrrt BTEX
9	Granville 3	Conventional	805.0	5.32
10	Granville 3	Conventional	966.0	5.57
11	Granville 3	Conventional	541.7	4.82
12	Granville 3	Conventional	623.0	4.99
13	Granville 3	Direct-Push	1659.0	6.38
14	Granville 3	Direct-Push	1297.0	6.00
15	Granville 3	Direct-Push	2419.0	7.01

-------------------------------- WELL=Granville 8 --------------------------------

Obs	WELL	WELL-TYPE	BTEX	qtrrt BTEX
16	Granville 8	Conventional	2191	6.84
17	Granville 8	Conventional	4620	8.24
18	Granville 8	Conventional	2346	6.96
19	Granville 8	Conventional	494	4.71
20	Granville 8	Direct-Push	11600	10.37
21	Granville 8	Direct-Push	17900	11.56
22	Granville 8	Direct-Push	23500	12.38
23	Granville 8	Direct-Push	4240	8.07

Figure G3 validates the ¼ root transformation across the original linear model for all of the BTEX data. The scatter plot shows that the differences within the model are very consistent across the entire range for BTEX.

```
Diff   ^                                      A
       ,
       ,            A
       ,'
    2  ^            A                    A            A           A
       ,         A                    A   B                    
       ,         B                A                        A   A
       ,       BAA              ACA   A    C  ABB      A              B
    0  ^       AAB D             B  A  B   A  ADA                B    AA
       ,       AEA BB            A    A    A  AC
       ,            AA              AA       A     A   B A     A    A
       ,            B                        A       A A
   -2  ^                                     A
       ,                                                          A
       ,
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          0         2        4        6        8       10       12
                             fitted qtr(BTEX)
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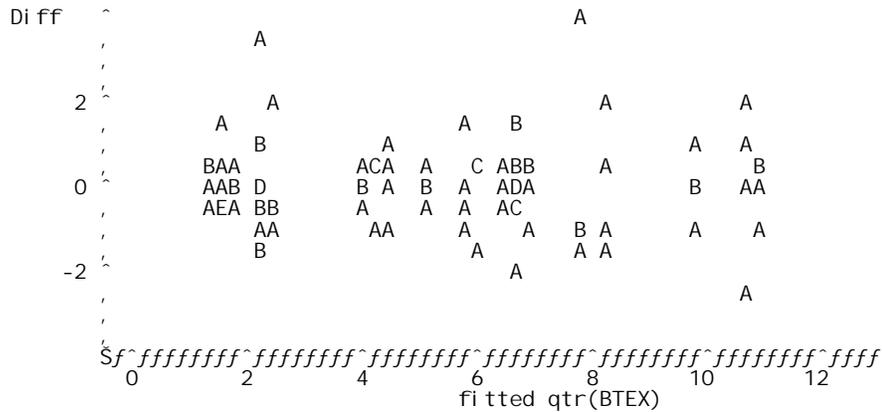
Figure G3: Differences between the GLM Model Prediction and the Measured Value for BTEX

The probability plot (Figure G4) shows that the ¼ root transformation results in differences that are very consistently represented by a normal distribution.
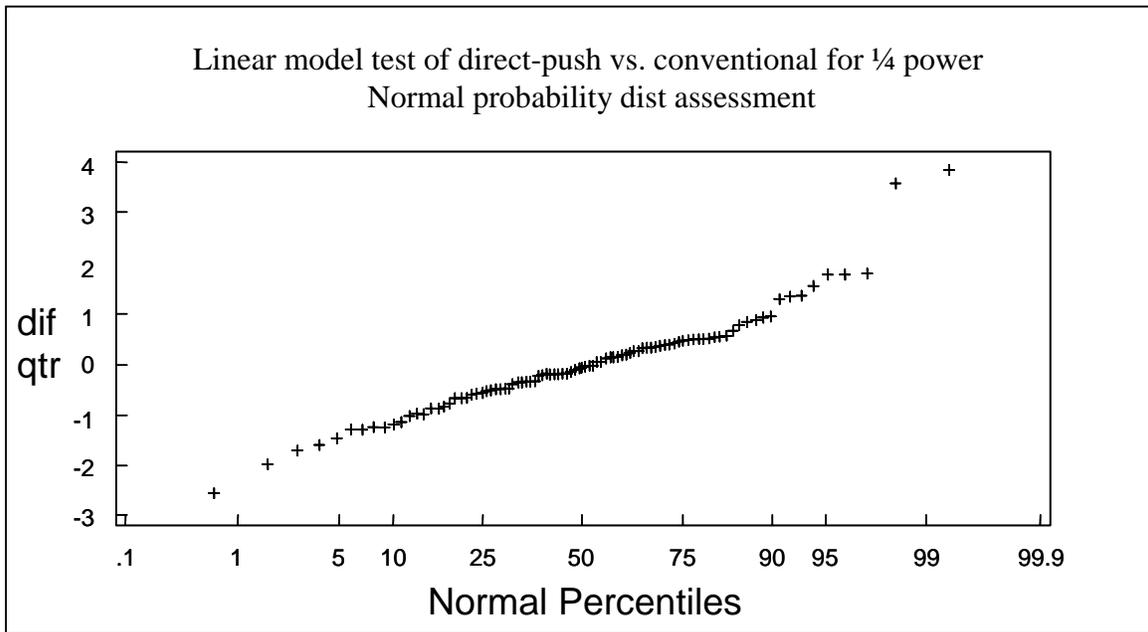
Figure G4: Normal Probability Distribution for the Difference Between the GLM and Measured BTEX Concentrations

Results for Benzene. The result for BTEX holds in varying degrees across each of the individual components that make up the BTEX measurement. For benzene the linear model is developed for SQRT(benzene):

Table G8: GLM Model Results for Benzene Concentrations

Dependent Variable: sqrt_benz

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	36877.68	1603.37	55.22	<.0001
Error	71	2061.52	29.03		
Corrected Total	94	38939.20			

R-Square	Coeff Var	Root MSE	sqrt_benz Mean
0.95	25.91	5.39	20.79

Source	Degrees of Freedom	Type III SS	Mean Square	F Value	Pr > F
SITE	3	3949.37	1316.45	45.34	<.0001
WELL	8	31751.02	3968.87	136.69	<.0001
WELL-TYPE	1	52.65	52.65	1.81	0.1824
WELL-TYPE*SITE	3	628.42	209.47	7.21	0.0003
WELL-TYPE*WELL	8	464.52	58.06	2.00	0.0588

The Well-types again are clearly significant only through the Site differences. If the Granville data are removed, then the WELL-TYPE effect is no longer significant, as shown in Table G9.

Table G9: GLM Model Results for Benzene, excluding Granville

Dependent Variable: sqrt_benz

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	17	30444.49	1790.85	93.41	<.0001
Error	54	1035.25	19.17		
Corrected Total	71	31479.74			

R-Square	Coeff Var	Root MSE	sqrt_benz Mean
0.96	21.53	4.37	20.34

Source	Degrees of Freedom	Type III SS	Mean Square	F Value	Pr > F
SITE	2	3885.33	1942.66	101.33	<.0001
WELL	6	26168.92	4361.48	227.50	<.0001
WELL-TYPE	1	30.97	30.96	1.62	0.2092
WELL-TYPE*SITE	2	85.32	42.66	2.23	0.1178
WELL-TYPE*WELL	6	273.94	45.65	2.38	0.0410

It can be seen that the means for the square root transforms of the benzene are early identical in Table G10.

Table G10: Mean Value of Benzene$^{1/2}$ for the two Well Types

WELL-TYPE	N	Mean	Std Dev
Conventional	36	20.99	22.09
Direct-Push	36	19.68	20.25

Conversely, doing the analysis just for Granville, one finds that the WELL-TYPE effect is still highly significant (Table G11):

Table G11: GLM Model Results for Benzene at Granville

Dependent Variable: sqrt_benz

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	6370.78	1274.15	21.11	<.0001
Error	17	1026.26	60.36		
Corrected Total	22	7397.04			

R-Square	Coeff Var	Root MSE	sqrt_benz Mean
0.86	34.95	7.76	22.22

Source	Degrees of Freedom	Type III SS	Mean Square	F Value	Pr > F
WELL	2	5582.10	2791.05	46.23	<.0001
WELL-TYPE	1	557.18	557.18	9.23	0.0074
WELL-TYPE*WELL	2	190.57	95.28	1.58	0.2351

Table G12: Mean Value of Benzene$^{1/2}$ for the two Well Types, excluding Granville

WELL-TYPE	N	Mean	Std Dev
Conventional	12	17.31	14.48
Direct-Push	11	27.59	21.17

The averages of the square roots are very different. The data listing for the benzene values is similarly evocative:

Table G13: Granville BTEX Data Listing

-------------------------------- WELL=Granville 18 --------------------------------

Obs	sqrt WELL	WELL-TYPE	BENZ	benz
1	Granville 18	Conventional	6.5	2.54
2	Granville 18	Conventional	2.1	1.44
3	Granville 18	Conventional	2.0	1.41
4	Granville 18	Conventional	3.3	1.81
5	Granville 18	Direct-Push	23.0	4.79
6	Granville 18	Direct-Push	62.0	7.87
7	Granville 18	Direct-Push	86.0	9.27
8	Granville 18	Direct-Push	78.0	8.83

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Table G13: Granville BTEX Data Listing (continued)

-------------------------------- WELL=Granville 3 --------------------------------

Obs	sqrt WELL	WELL-TYPE	BENZ	benz
9	Granville 3	Conventional	360	18.97
10	Granville 3	Conventional	340	18.43
11	Granville 3	Conventional	250	15.81
12	Granville 3	Conventional	240	15.49
13	Granville 3	Direct-Push	390	19.74
14	Granville 3	Direct-Push	540	23.23
15	Granville 3	Direct-Push	680	26.07

-------------------------------- WELL=Granville 8 --------------------------------

Obs	sqrt WELL	WELL-TYPE	BENZ	Benz
16	Granville 8	Conventional	1400	37.41
17	Granville 8	Conventional	1800	42.42
18	Granville 8	Conventional	1200	34.64
19	Granville 8	Conventional	300	17.32
20	Granville 8	Direct-Push	3000	54.77
21	Granville 8	Direct-Push	1900	43.58
22	Granville 8	Direct-Push	4800	69.28
23	Granville 8	Direct-Push	1300	36.05

Results for Toluene, Ethyl-benzene, and Xylenes. The following transformed variables can be used to similarly validate the conclusion for BTEX and benzene that the two post-purge methods are different for the Granville wells:

    ln(toluene)
    ln(ethyl-benzene)
    ln(xylenes)

PART II--STATISTICAL COMPARISON OF TSS AND NAPHTHALENE CONSTITUTENT CONCENTRATION MEASUREMENTS

Background. Data were collected from groundwater monitoring wells at service station sites in 4 Ohio Sites: Marietta, Granville, Toledo, and Brunswick. Quarterly samples were taken for 4 consecutive quarters, December 1997 through September 1998 for Granville and Toledo, and September 1997 through June 1998 for Marietta and Brunswick. The same three wells at each location were sampled for each of the 4 quarters. Two samples were collected after purging, one from conventional monitoring wells and the other from direct-push monitoring wells. Measurements were made for naphthalenes and total suspended solids.

Results. For total suspended solids, the groundwater sample from the Direct-Push well had significantly higher levels of TSS in the sample than that from the conventional well. For the data that was collected across all the Sites in December 1997, the opposite result actually occurred. Otherwise there was good spatial and temporal consistency in the results. There seems to be a large sampling and measurement error. For naphthalenes, again the Direct-Push method resulted in significantly higher levels in the sample. This result was not consistent across all four Sites. For Marietta, the opposite result actually was true. There was a lot more spatial variability for naphthalenes across the sites than any other type of variability.

Statistical Design. The design results from the natural constraints resulting from collecting data over time and place. Overall the design has a split plot structure. The whole plot is actually a nested design with two

nested factors. Both the different wells and the different sampling dates are specific to the Site. The sub-plot factor is the type of monitoring well. Only a single measurement was made for each combination of the four factors. However, a half dozen or so of the samples were not made for either TSS or naphthalenes. Because both measurements varied over several orders of magnitude, analysis was done for their natural logarithms. All computations are done using PROC GLM in SAS. See Littrell, et al, 1991 for more details.

Analysis for Total Suspended Solids (TSS).   Table G14 shows the complete analysis of variance (ANOVA) table for ln(TSS). SAS required the rearrangement of the model that lists "Well-Type" first.

Table G14: GLM Model Results for TSS

Dependent Variable: ln_tss

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	236.50	7.62	3.45	<.0001
Error	52	115.02	2.21		
Corrected Total	83	351.53			

R-Square	Coeff Var	Root MSE	ln_tss Mean
0.672	23.42	1.48	6.34

Source	Degrees of Freedom	Type IV SS	Mean Square	F Value	Pr > F
Well-Type	1	42.50	42.50	19.21	<.0001
Site	3*	71.19	23.73	10.73	<.0001
Well	8	39.19	4.89	2.21	0.0411
Date	8	25.831	3.22	1.46	0.1948
Site*Well-Type	3	0.14	0.04	0.02	0.9954
Date*Well-Type	4	38.25	9.56	4.32	0.0043

In the statistical model, where there were no repeated experiments, the error for statistical tests is the accumulation of the interaction effects between wells and time and between wells and type of monitoring well. It is presumed that the temporal effects on TSS measurements are consistent across the wells for a particular site, and that the TSS measurements overall are not biased by unique effects arising from the particular combination of the type of monitoring well with a specific well.   The large value for Root MSE, the estimate of the standard deviation for the differences between the ln(TSS) values and the model, and the relatively small value for the model indicate that there is a lot of variability that is not temporal or spatial. This would be due to sampling and measurement and other random factors.

The difference between the two types of monitoring wells is a highly significant difference. There is also a large difference among the Sites. The monitoring well difference was consistent across the Sites but not across the different sampling periods. Across both Well-types, neither the sampling periods nor the well-to-well differences within a Site were statistically significant. The overall means for the monitoring well types are shown below:

Table G15: Mean Value of ln(TSS) for the two well types

Mean	N	Well-Type
7.02	38	Direct-Push
5.79	46	Conventional

Direct-push monitoring wells exhibit a considerably higher measurement for TSS. The median value for TSS from direct-push is about 1130, while the median value for TSS from conventional purging is about 330. The type of monitoring well has an effect on TSS.

The difference among the sites is shown in the next table:

Table G16: Mean Value of ln(TSS) by Site

Alpha	0.05
Error Degrees of Freedom	52
Error Mean Square	2.21
Harmonic Mean of Cell Sizes	20.76

NOTE: Cell sizes are not equal.

Number of Means	2	3	4
Critical Range	0.926	0.974	1.006

Mean	N	Site
7.93	18	Toledo
6.31	24	Brunswick
6.31	20	Granville
5.11	22	Marietta

It can be seen that TSS was higher in Toledo and lower in Marietta. This would be expected due to different geologies.

The following set of table explores how the differences varied for the five sampling periods. Samples were taken in only two of the four sites in September 1997 and in September 1998, one or the other depending on the site.

Table G17: GLM Model Results for TSS, Sept, 1997

Dependent Variable: ln_tss

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	38.67	6.44	4.18	0.0689
Error	5	7.70	1.54		
Corrected Total	11	46.38			

R-Square	Coeff Var	Root MSE	ln_tss Mean
0.83	20.70	1.24	5.99

Source	Degrees of Freedom	Type IV SS	Mean Square	F Value	Pr > F
Well-Type	1	22.35	22.35	14.51	0.0125
Site	1	13.20	13.20	8.57	0.0328
Well	4	3.12	0.78	0.51	0.7352

Mean	N	Well-Type
7.36	6	Direct-Push
4.63	6	Conventional

Table G18: GLM Model Results for TSS, Dec, 1997

Dependent Variable: ln_tss

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	65.00	5.90	0.89	0.5784
Error	9	59.65	6.62		
Corrected Total	20	124.66			

R-Square	Coeff Var	Root MSE	ln_tss Mean
0.52	39.33	2.57	6.54

Source	Degrees of Freedom	Type IV SS	Mean Square	F Value	Pr > F
Well-Type	1	4.60	4.60	0.70	0.4259
Site	3	42.18	14.06	2.12	0.1677
Well	7	6.510	0.93	0.14	0.9916

Mean	N	Well-Type
7.05	11	Conventional
5.98	10	Direct-Push

Table G19: GLM Model Results for TSS, March, 1998

Dependent Variable: ln_tss

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	12	92.94	7.74	7.01	0.0022
Error	10	11.056	1.10		
Corrected Total	22	104.00			

R-Square	Coeff Var	Root MSE	ln_tss Mean
0.89	16.26	1.05	6.46

Source	Degrees of Freedom	Type IV SS	Mean Square	F Value	Pr > F
Well-Type	1	39.29	39.29	35.54	0.0001
Site	3	32.99	10.99	9.95	0.0024
Well	8	26.80	3.35	3.03	0.0520

Mean	N	Well-Type
7.7320	11	Direct-Push
5.3057	12	Conventional

Table G20: GLM Model Results for TSS, June, 1998

Dependent Variable: ln_tss

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	12	39.91	3.32	2.86	0.0720
Error	8	9.31	1.16		
Corrected Total	20	49.22			

R-Square	Coeff Var	Root MSE	ln_tss Mean
0.81	17.60	1.07	6.12

Source	Degrees of Freedom	Type IV SS	Mean Square	F Value	Pr > F
Well-Type	1	10.42	10.42	8.96	0.0172
Site	3	14.46	4.82	4.14	0.0479
Well	8	19.74	2.46	2.12	0.1540

Mean	N	Well-Type
6.7732	9	Direct-Push
5.6408	12	Conventional

Note that there was not enough data to do the analysis separately for September, 1998 since the two labs that were scheduled to have results for that month did not get all of their samples. The interaction that was noted above occurred because the differences between the means for the two types of monitoring wells differed across the months. This situation occurred because in December, 1997 the average result overall that Direct-Push gave higher TSS than conventional monitoring wells was completely contradicted. In December 1997, conventional monitoring wells resulted in a higher value for TSS than Direct-Push. The reason is unknown but it appears that only a few samples show this and they may have been mislabeled.

The natural log transformation and the analysis of variance model are adequately validated by the plots that follow on the next page. First, the scatter plot for the differences between ln(TSS) and the ANOVA model fitted values for ln(TSS) versus the fitted values for ln(TSS) show no bias versus the fitted values. Second, the consistency of the ANOVA model versus the data is represented by the normal probability plot of the same differences. The differences clearly are consistent with the normal distribution that would be represented by a straight line appropriately fitted to the data.
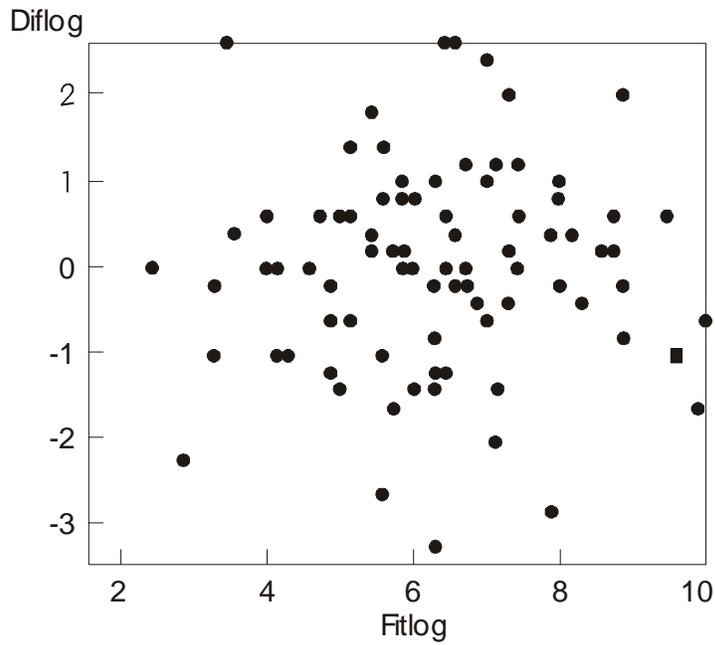
Figure G5: Differences between the GLM Model Prediction and Measured Values for TSS
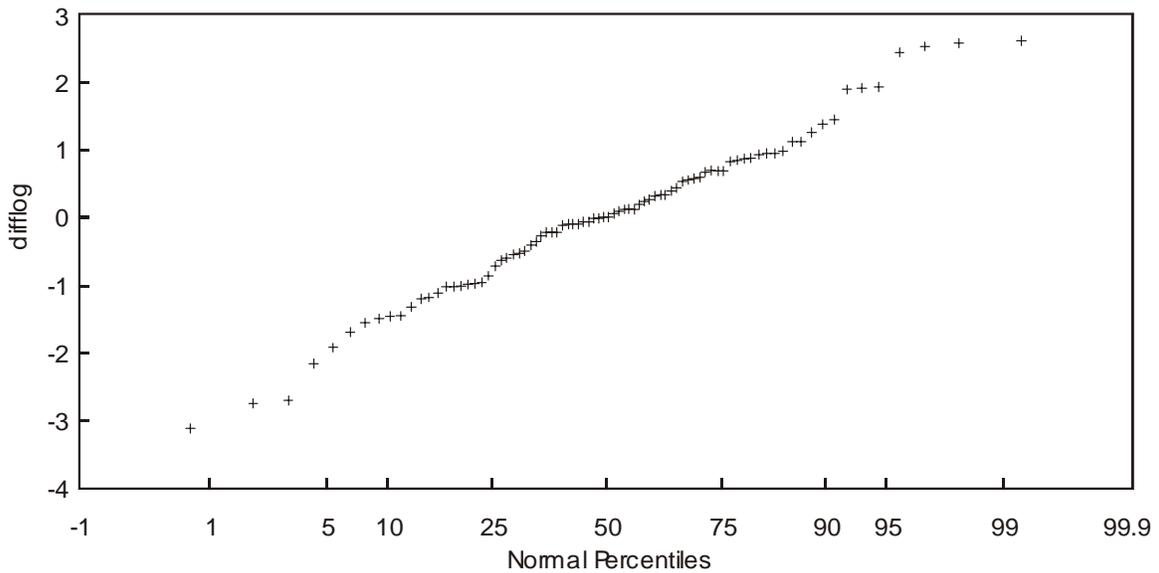
Figure G6: Normal Probability Distribution for the Difference Between the GLM and Measured TSS

Analysis for Naphthalenes.   Below is shown the complete ANOVA for ln(naphthalene).

Table G21: GLM Model Results for Naphthalene

Dependent Variable: ln_naph

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	747.91	24.12	16.03	<.0001
Error	55	82.78	1.50		
Corrected Total	86	830.70			

R-Square	Coeff Var	Root MSE	ln_naph Mean
0.90	72.84	1.22	1.68

Source	Degrees of Freedom	Type IV SS	Mean Square	F Value	Pr > F
Well-Type	1	7.61	7.61	5.06	0.0286
Site	3*	61.77	20.59	13.68	<.0001
Well	8	592.96	74.12	49.24	<.0001
Date	8	15.95	1.99	1.33	0.2507
Site*Well-Type	3	16.89	5.63	3.74	0.0161
Date*Well-Type	4	4.97	1.24	0.83	0.5138

The difference between Direct-Push and conventional monitoring wells is moderately significant. The difference also is not consistent across the four sites. The sites are different but that should be expected. In addition, there was a lot of spatial difference across the four Sites but the wells were chosen so there were large differences. This model explains 90% of the variability in ln(naphthalene). Below are the averages for ln(naphthalene):

Table G22: Mean Values for ln_naphthalene

Mean	N	Well-Type
2.0028	41	Direct-Push
1.4005	46	Conventional

Direct-push wells exhibited a significantly higher result for naphthalene. Using anti-log for the results, the median for direct-push is about 7.4, while the median for conventional monitoring wells is 4.0. Note that if the result for direct-push was 0.7, then the result for conventional would be 0.4. Similarly if the result for direct-push was 70, then the result for conventional would be 40. The next table shows the comparison of the sites:

Table G23: Duncan's Multiple Range Test for ln_naph

Alpha	0.05
Error Degrees of Freedom	55
Error Mean Square	.50
Harmonic Mean of Cell Sizes	21.60

NOTE: Cell sizes are not equal.

Number of Means	2	3	4
Critical Range	.74	.78	.81

Mean	N	Site
2.91	20	Toledo
1.95	24	Brunswick
1.85	20	Granville
0.17	23	Marietta

Again Toledo gives a higher result, and Marietta gives a lower result, but different means for the sites should be expected.

The following set of tables explores the consistency of the Direct-Push versus conventional well differences across the four sites:

Table G24: GLM Model Results for Brunswick

Dependent Variable: ln_naph

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	201.24	22.36	20.78	<.0001
Error	14	15.065	1.07		
Corrected Total	23	216.31			

R-Square	Coeff Var	Root MSE	ln_naph Mean
0.93	52.99	1.03	1.95

Source	Degrees of Freedom	Type IV SS	Mean Square	F Value	Pr > F
Well-Type	1	0.65	0.65	0.61	0.4490
Well	2	192.07	96.03	89.25	<.0001
Date	3	6.33	2.11	1.96	0.1661
Date*Well-Type	3	2.18	0.72	0.68	0.5802

Mean	N	Well-Type
2.12	12	Direct-Push
1.79	12	Conventional

Table G25: GLM Model Results for Granville

Dependent Variable: ln_naph

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	62.11	6.90	2.86	0.0584
Error	10	24.10	2.41		
Corrected Total	19	86.22			

R-Square	Coeff Var	Root MSE	ln_naph Mean
0.72	83.53	1.55	1.85

Source	Degrees of Freedom	Type IV SS	Mean Square	F Value	Pr > F
Well-Type	1	21.18	21.18	8.79	0.0142
Well	2	23.19	11.59	4.81	0.0344
Date	3	2.42	0.80	0.34	0.8001
Date*Well-Type	3	2.60	0.86	0.36	0.7835

Mean	N	Well-Type
3.18	9	Direct-Push
0.77	11	Conventional

Table G26: GLM Model Results for Marietta

Dependent Variable: ln_naph

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	304.33	33.81	93.67	<.0001
Error	13	4.69	0.36		
Corrected Total	22	309.03			

R-Square	Coeff Var	Root MSE	ln_naph Mean
0.98	345.61	0.60	0.17

Source	Degrees of Freedom	Type IV SS	Mean Square	F Value	Pr > F
Well-Type	1	1.16	1.16	3.22	0.0958
Well	2	298.64	149.32	413.63	<.0001
Date	3	1.22	0.40	1.13	0.3714
Date*Well-Type	3	1.30	0.43	1.20	0.3470

Mean	N	Well-Type
0.50	11	Conventional
-0.13	12	Direct-Push

Table G27: GLM Model Results for Toledo

Dependent Variable: ln_naph

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	105.40	11.71	4.13	0.0186
Error	10	28.346	2.83		
Corrected Total	19	133.75			

R-Square	Coeff Var	Root MSE	ln_naph Mean
0.78	57.66	1.68	2.91

Source	Degrees of Freedom	Type IV SS	Mean Square	F Value	Pr > F
Well-Type	1	4.82	4.82	1.70	0.2214
Well	2	70.14	35.07	12.37	0.0020
Date	3	10.36	3.45	1.22	0.3530
Date*Well-Type	3	9.45	3.15	1.11	0.389

Mean	N	Well-Type
3.69	8	Direct-Push
2.40	12	Conventional

Note that the differences are not consistent for Marietta, where the conventional method actually resulted in a higher value for naphthalenes than the Direct-Push method.

The log transformation and the analysis of variance model are adequately validated by the plots that follow on the next page. First, the scatter plot for the differences between ln(naphthalenes) and the ANOVA model fitted values for ln(naphthalenes) versus the fitted values for ln(naphthalenes) show no bias versus

the fitted values. The impact of considering possible nondetects as quantifications is not readily apparent from the scatter plot.

 Second, the consistency of the ANOVA model versus the data is represented by the normal probability plot of the same differences. The differences clearly are consistent with the normal distribution that would be represented by a straight line appropriately fitted to the data.
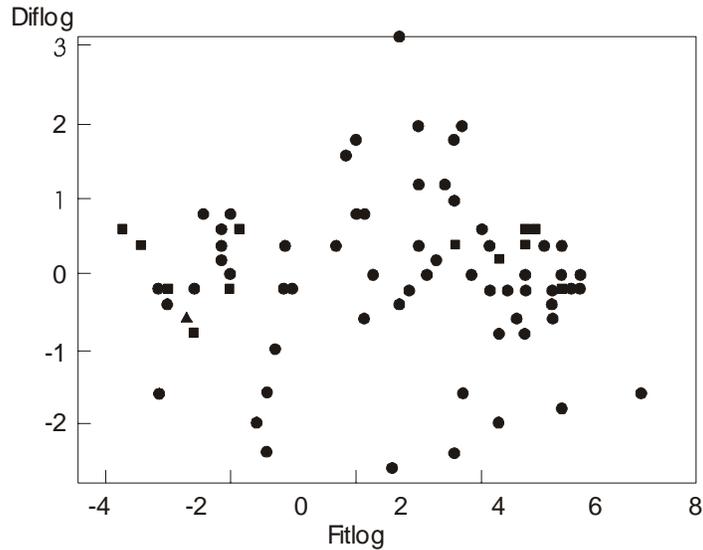
Figure G7: Differences between the GLM Model Prediction and the Measured Value for Naphthalene
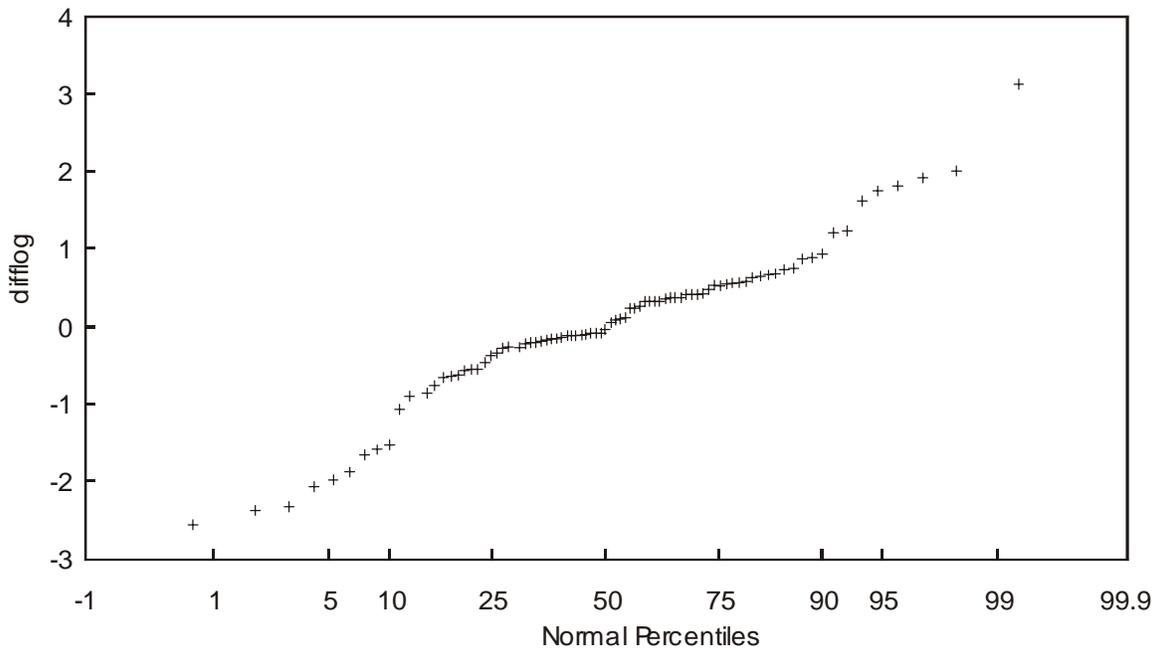
Figure G8: Normal Probability Distribution for the Difference Between the GLM and Measured
Naphthalene Concentrations

PART III--STATISTICAL COMPARISON OF HYDRAULIC CONDUCTIVITY MEASUREMENTS

RESULTS

Data was collected at four sites: Toledo, Granville, Marietta, and Brunswick. There were three different wells at each site. Data collection was done in 1997 and in March of 1999. Hydraulic conductivity data was analyzed by two different methods: Hvorslev and Bouwer & Rice. Units for hydraulic conductivity were feet/day. Results were obtained in the conventional and Direct-Push wells. It was obvious from the data that the conventional wells generally exhibited higher hydraulic conductivity measurements than the ones that were measured in the direct-push wells. The statistical comparison looked at the possible statistical significance of Well-type, analysis method, Site (or site), date, and well on the measured hydraulic conductivity.

DATA ANALYSIS

The general methodology for the statistical analysis of the data included the following: a log transformation of the data so that variability would be consistent across the range of concentrations measured, probability analysis to determine if the statistics of a lognormal distribution is applicable, and the use of General Linear Modeling (R.Littell, R.Freund, P.Spector, *SAS Systems for Linear Models,* 3E, SAS Institute, Cary NC, 1991) to determine if factors or combinations of factors might influence the results.

The general linear model (GLM) is simply a multi-variable fit of the data that determines if the following factors might result in differences among the measurements:

    Site
    Well Pair (specific to Site)
    Date
    Analysis type
    Well-type

In addition to these primary factors, combinations of factors was evaluated:

- Measurement dates for the different Sites
- Measurement dates for the individual wells
- Measurement dates for the different Well-types
- Hydraulic conductivity procedure for the different Sites
- Hydraulic conductivity procedure for the different Measurement dates
- Hydraulic conductivity procedure for the different Well-type
- Well-types for the different Sites

Combinations of factors are accounted for as products, for example, SITE*DATE would represent the first effect.

The natural logarithm (ln) of the hydraulic conductivity measurements was used in the statistical analysis. Hydraulic conductivity measurements varied over several orders of magnitude, so the proportional variability that is represented by logs was appropriate for ensuring an approximately consistent level of variability across all hydraulic conductivity measurements. This is a necessary assumption for effective application of statistical tests within the GLM framework.

A preliminary screening of all of the data versus the model described above revealed one anomaly in the data that can be seen in the following figure. This figure is a normal probability plot of the differences between the log of the measured conductivities and the log of the model predicted values. The differences on the y-axis are plotted versus normal probability on the x-axis. The differences should lie along one

straight line. The anomaly is the unusually large negative value that does not appear to be consistent with the other measurements. The inconsistency can be attributed to one of the measurements that was made at the Granville site. This is evident in Figure G10.
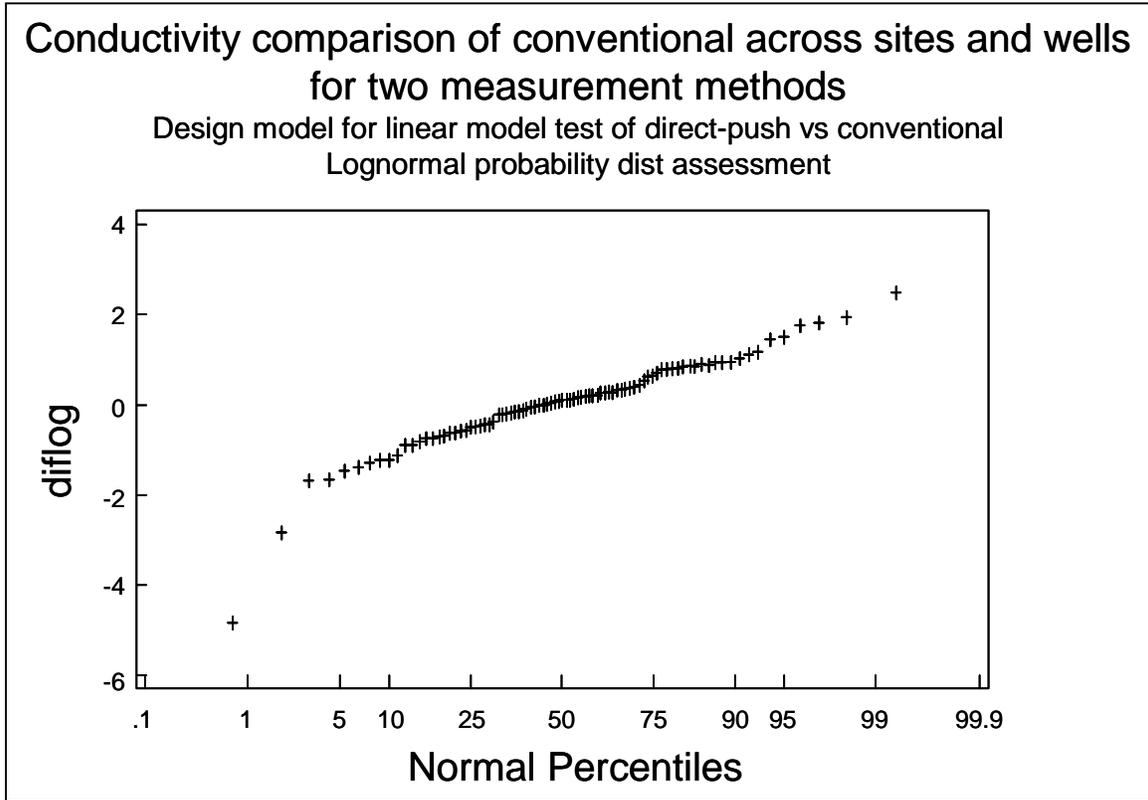
Figure G9: Normal Probability Distribution for the Differences between the GLM and Measured Hydraulic Conductivity Values

```
          '
        ,'                             x
     2 '^
        ,    x                      x
d       ,    x
i       ,    x                                    x
f       ,    x              x                      x                          x
f       ,    x                                     x                          x
e       ,    x              x                      x                          x
r    0 ^ffffffffffffffffffffxffffffffffffffffffffxfffffffffffffffffffffxff
e       ,    x              x                      x                          x
n       ,    x                                     x
c       ,                                          x
e       ,    x                                     x
(       ,    x                                                                x
l                           x
o    -2 '^
g       ,    x
s       ,
)       ,    x              x
        ,'
        ,'
   -4 '^
        ,'
        ,'                   x
        ,
        S ff^ffffffffffffffff^ffffffffffffffff^ffffffffffffffff^ff
        Brunswick          Granville          Marietta          Toledo

                              Site
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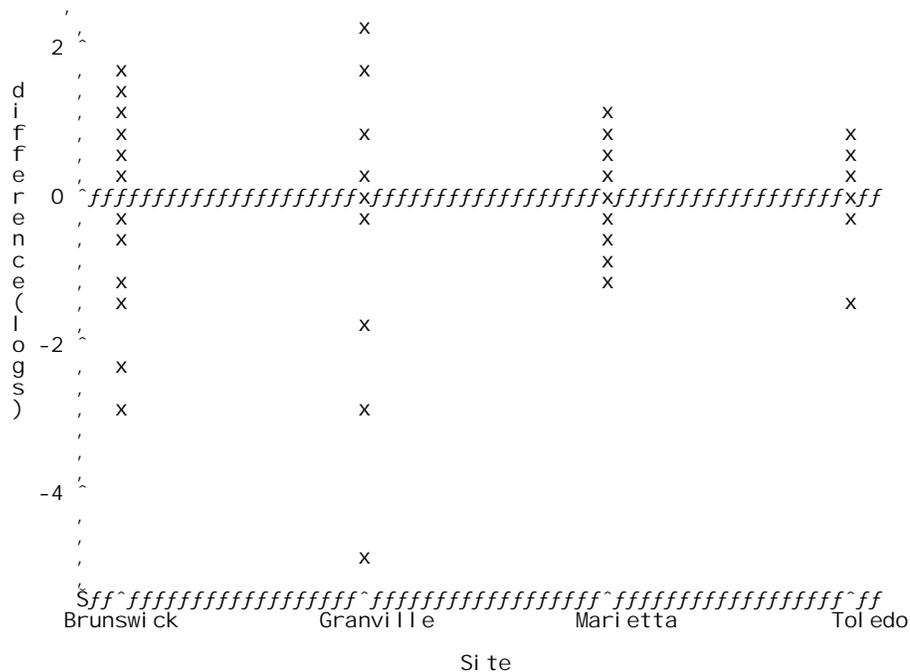
Figure G10: Difference between the GLM Model Prediction and the Measured Hydraulic Conductivity by Site

It is apparent that the large negative difference is inconsistent with the other differences. Generally there seems to be more variability across Granville than across the other locations

An investigation of the data shows that the difference results from the model's failure to accommodate the very low value, 8.56E-03, for the hydraulic conductivity measured in conventional well MW-3 using the Bower-Rice method at Granville. This hydraulic conductivity measurement is more than two orders of magnitude smaller than any other measurement that is reported for either date, either type of well, and either analysis method at Granville. It seems reasonable to conclude that the very low value is not a very plausible measurement at Granville and should be excluded.

The low measurement was eliminated from the data that was used for the statistical analysis, and the fitting of the GLM to all of the rest of the data was performed again. The plot in Figure G11 indicates that the model provides a consistent representation for all of the data when the point is excluded.

```
   2 ^
     ,
     ,    x
     ,    x
     ,                    x
     ,    x
     ,    x                              x
   1 ^    x
     ,    x              x                              x
d    ,    x              x              x
i    ,                   x              x               x
f    ,    x              x              x               x
f    ,    x              x              x               x
e    ,    x                             x               x
r  0 ^ffffffffffffffffffffffxffffffffffffffffffffffxffffffffffffffffffffffxff
e    ,                   x              x               x
n    ,                   x              x               x
c    ,    x                             x               x
e    ,    x              x              x
(    ,    x                             x
l    ,                                  x
o -1 ^    x                             x
g    ,    x                             x
s    ,                   x                              x
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  -3 ^
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      Sffˆffffffffffffffffffffˆffffffffffffffffffffˆffffffffffffffffffffˆff
      Brunswick         Granville        Marietta           Toledo
                              Site
```
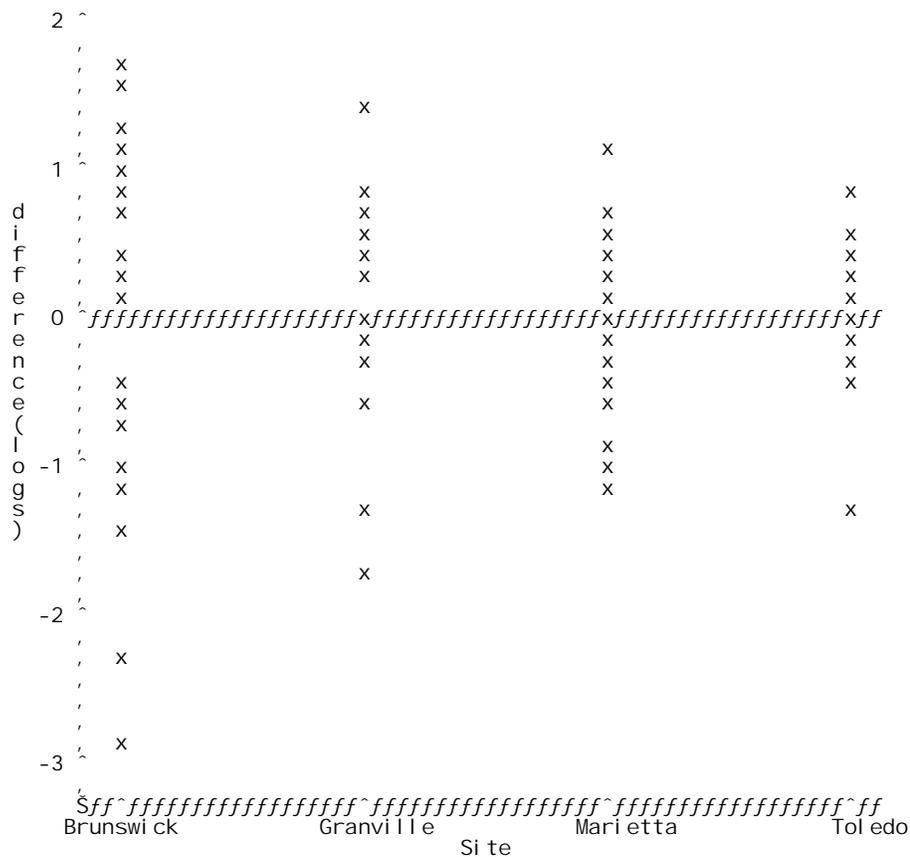
Figure G11: Differences between the GLM Model Prediction and the Measured Conductivities by Site Excluding the One Granville Measurement

The summary of the GLM results including the one Granville point appears in the next two Tables. Table G28 is the statistical summary for the fit of the model to the data by the GLM procedure:

Table G28: GLM Model Results for Hydraulic Conductivity

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	36	444.89	12.36	6.58	<.0001
Error	51	95.75	1.88		
Corrected Total	87	540.64			

R-Square	Coeff Var	Root MSE	ln_cond Mean
0.82	-141.41	1.37	-0.97

In the table above, the two key statistics are the value for R-square, 0.82, which shows that the GLM fits the logs of the conductivities very well, and the Root MSE that shows that there is a large variability between the model and the data for the conductivities. The variability is apparently due to the common observation of significant differences in hydraulic conductivity data. However, Figure G11 showed that the variability (differences between GLM model and data) is consistent across the range of the predictions. In other words, this implies that hydraulic conductivity measurements are not particularly precise which is a common observation.

Table G29: Results for the GLM Variables for Hydraulic Conductivity

Source	Degrees of Freedom	Type IV SS	Mean Square	F Value	Pr > F
SITE	2	1.92	0.96	0.51	0.6022
WELL Pair (SITE	1	23.42	23042	12.47	0.0009
DATE	2	0.35	0.18	0.09	0.9102
SITE*DATE	1	0.04	0.04	0.02	0.8919
WELL*DATE	8	19.54	2.44	1.30	0.2643
--					
Well-Type	1	30.44	30.44	16.21	0.0002
SITE*Well-Type	3	3.77	1.26	0.67	0.5744
DATE*Well-Type	2	3.17	1.59	0.85	0.4353
method	1	0.29	0.29	0.16	0.6942
SITE*method	3	7.26	2.42	1.29	0.2884
DATE*method	2	0.42	0.21	0.11	0.8954
method*Well-Type	1	0.56	0.56	0.30	0.5883

In this table, the important numbers are the values in the column headed by (Pr>F). These are the probabilities for the statistical significance of the different effects. When the probabilities are small, typically less than 0.1, then the effects are statistically significant. A primary observation for this table is that the only statistically significant variable is well-type.

The next two tables show the result of fitting a GLM with the one Granville point excluded. Table G30 shows that there was little impact on the overall fit of the conductivities by the GLM.

Table G30: GLM Model Results for Hydraulic Conductivity, excluding the Granville Point

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	35	470.60	13.07	11.78	<.0001
Error	50	55.50	1.11		
Corrected Total	86	526.10			

R-Square	Coeff Var	Root MSE	ln_cond Mean
0.89	-113.85	1.05	-0.93

The R-square value is increased from the fit of the larger GLM, so the smaller GLM fits the data better. The Root MSE is somewhat smaller so there is slightly less variability, but it is still large. Table G31 provides the same result as shown in Table G29; that is, only the well type is significant.

Table G31: OLM Model Results for the Hydraulic Conductivity, excluding the Granville Point

Source	Degrees of Freedom	Type IV SS	Mean Square	F Value	Pr > F
SITE	2	6.01	3.01	2.71	0.0764
WELL	1	23.42	23.42	21.10	<.0001
DATE	2	0.35	0.18	0.16	0.8531
WELL*DATE	8	13.81	1.73	1.56	0.1624
--					
Well-Type	1	45.64	45.64	41.12	<.0001
method	1	2.45	2.45	2.21	0.1434
SITE*method	3	2.58	0.86	0.78	0.5132

The two types of wells clearly do not give the same hydraulic conductivity results. The respective mean values for the logs of the conductivities are shown in the Table G33.

Table G32: Mean Values of Hydraulic Conductivity by Well-type

		-----------ln_cond----------	
Level of Well-Type	N	Mean	Std Dev
Conventional	47	-0.24	2.22
Direct Push	40	-1.73	2.53

Since these measurements are in natural logarithms, comparison of the mean values is approximately multiplicative. The conductivities for conventional wells in sampling groundwater from the wells are about four times as large compared to the conductivities from using the Direct-Push method for wells.

Table G33 displays all the data with the conductivities for conventional (C) and direct-push (D) wells shown side by side. The dominance of the conductivities measured in the conventional wells is obvious.

Table G33: Hydraulic Conductivity Values for all Sites

Well	Site	Date	C Hvorslev K (ft/day)	D Hvorslev K (ft/day)	C Bouwer & Rice K (ft/day)	D Bouwer & Rice K (ft/day)
MW-2	Toledo	17-Dec-97	1.32E-02	1.65E-02	6.54E-02	4.71E-02
MW-2	Toledo	04-Mar-99	2.09E-02	.	9.73E-02	.
MW-3	Toledo	17-Dec-97	3.19E-01	5.05E-02	1.67E+00	1.37E+00
MW-3	Toledo	04-Mar-99	4.95E-01	6.39E-02	2.53E+00	1.87E-01
MW-4	Toledo	17-Dec-97	7.92E-03	1.68E-02	3.66E-02	1.99E-02
MW-4	Toledo	04-Mar-99	2.73E-02	1.05E-02	1.06E-01	1.14E-02
MW-3	Granville	22-Dec-97	2.25E+00	7.63E+00	8.56E-03	3.22E+00
MW-3	Granville	06-Mar-99	1.95E+00	.	2.97E+00	.
MW-8	Granville	22-Dec-97	1.04E+01	6.53E-01	1.20E+01	3.42E+00
MW-8	Granville	06-Mar-99	4.49E+00	.	3.94E+00	.
MW-18	Granville	22-Dec-97	5.41E+01	9.33E-01	1.28E+02	1.71E+01
MW-18	Granville	06-Mar-99	8.86E-01	.	8.05E-01	.
MW-3	Marietta	22-Sep-97	3.01E-01	1.90E-02	2.20E-01	9.38E-03
MW-3	Marietta	12-Mar-99	1.40E-01	9.78E-03	8.21E-02	3.67E-03
MW-4	Marietta	22-Sep-97	3.86E-01	1.00E-01	2.86E-01	4.68E-02
MW-4	Marietta	12-Mar-99	2.34E-01	2.61E-01	2.43E-01	1.64E-01
MW-7	Marietta	22-Sep-97	3.28E-01	1.10E-02	2.19E-01	1.02E-02
MW-7	Marietta	23-Mar-99	1.02E-01	5.35E-03	2.43E-01	9.76E-03
MW-1	Brunswick	22-Sep-97	4.67E+00	6.70E+00	6.52E+00	6.39E+00
MW-1	Brunswick	18-Mar-99	6.01E+00	1.27E+00	3.67E+01	3.50E+00
MW-11	Brunswick	22-Sep-97	3.57E+00	7.64E-01	6.55E+00	1.57E-02
MW-11	Brunswick	18-Mar-99	1.78E+01	2.65E+00	5.66E+00	9.07E-02
MW-12	Brunswick	22-Sep-97	1.02E+00	5.50E+00	1.86E+00	2.27E+00
MW-12	Brunswick	18-Mar-99	4.63E-01	1.09E+00	7.29E-01	7.17E-01

PART IV--STATISTICAL COMPARISON OF GEOCHEMICAL PARAMETERS

BACKGROUND

This report examines the potential statistical differences in concentrations between samples of seven geochemical constituents obtained from adjacent Direct-Push and conventional monitoring wells. The seven geochemical constituents are: ferrous iron, nitrate, sulfate, dissolved iron, carbon dioxide, methane, and alkalinity. The analysis shows that the concentrations are the same for seven different geochemical constituents in the adjacent Direct-Push and conventionally constructed monitoring wells.

A summary of the results of the statistical analyses is presented in Table G35. The squared multiple correlation coefficient values for the fit of the GLM model to the data indicates that there is quite a bit of variability, except for the dissolved oxygen, which is not explained by the model. However, the cross plots (Figures G12-G18, near the end of the Appendix) indicate that there is little bias in the data or apparently no systematic errors or problems with the possible exception of alkalinity. The variability of the data is possibility related to the analytical methods, filtering of samples, and the use of field kits and the ability to perform accurate dilutions in the field. This apparently results in several concentrations report as "greater-than", "less-than", or non-detect (See Table G36). The models that were used did not account for the censoring of any of the measurement values.

Table G35 also reports the mean values and probability values for the F-Tests for each of the seven parameters by well-type and shows that there is no significance difference between the concentrations measured in the direct-push and conventional wells. On a site-by-site basis, however, there are differences represented by small probability values for the nitrate, sulfate, and dissolved oxygen concentrations. Differences on a site-by-site basis should be expected. Because of the modest amount of data and the reported values, these results should be taken as indicative that direct-push wells provide concentrations equivalent to convention wells but the results should not be considered as completely demonstrative.

The detailed methodology of the statistical analysis is discussed below for ferrous iron. The results for the other constituents are repeated without discussion, since all the methods and conclusions are the same.

Table G35: Summary of Mean Values and Statistics for the Geochemistry Parameters							
		Mean Values by Well-type			Mean Values by Site		
Parameter	Squared Multiple Correlation Coefficient for the GLM Model	Direct-Push Well	Conventional Well	Probability Value for F-Test on Well-type Effect	Brunswick	Marietta	Probability Value for F-Test on Site Effect
Ferrous Iron, mg/l	0.02	1.47	0.90	0.7300	0.91	1.45	0.7566
Nitrate, mg/l	0.49	2.18	2.46	0.7602	4.06	1.32	0.0178
Methane, mg/l	0.34	0.98	0.98	0.8349	2.23	0.36	0.0614
Sulfate, mg/l	0.15	2.62	8.87	0.2533	5.83	4.01	0.7130
Dissolved Oxygen, mg/l	0.77	0.97	0.76	0.7745	0.43	1.28	0.0004
Carbon dioxide, mg/l	0.23	221.05	210.29	0.7164	239.75	193.89	0.1448
Alkalinity, mg/l	0.07	69.10	57.75	0.8191	85.89	46.46	0.4408

Table G36--Geochemical Parameters Indicative of Natural Attenuation

Conventional Monitoring Well MW-3A: Marietta GA

Sampling Event	Dissolved Oxygen Meter (mg/l)	Dissolved Oxygen Color (mg/l)	pH	CO_2 (mg/l)	Alkalinity (mg/l)	Iron by color (mg/l)	Ferrous Iron (mg/l)	Total Iron (mg/l)	Nitrate (mg/l)	Sulfate (mg/l)	Methane (mg/l)
10/20/97	0.6	<1	-	210	-	-	13.6	26.5	1.3	9	4.06
01/05/98	0.5	<1	6.0	100	70	>10	7.4	19.3	1.3	9	1.14
03/25/98	1.1	1.0	6.7	200	210	>10	13.9	27.6	1.3	9	2.61
06/25/98	1.2	1.0	6.5	200	260	>10	20.8	44.0	1.3	9	3.11

Direct-Push Monitoring Well MW-3B- Marietta Ga.

Sampling Event	Dissolved Oxygen Meter (mg/l)	Dissolved Oxygen Color (mg/l)	pH	CO_2 (mg/l)	Alkalinity (mg/l)	Iron by color (mg/l)	Ferrous Iron (mg/l)	Total Iron (mg/l)	Nitrate (mg/l)	Sulfate (mg/l)	Methane (mg/l)
10/20/97	0.8	1.0	-	>100	-	-	6.5	8.4	0.0	0	3.70
01/06/98	1.2	1.5	-	140	200	>10	9.1	8.4	1.3	2	3.18
03/25/98	0.6	<1	6.6	160	250	>10	16.0	8.4	1.5	0	2.27
06/25/98	0.9	<1	6.5	200	270	>10	23.7	8.4	1.1	0	3.26

Conventional Monitoring Well MW-4A: Marietta Ga.

Sampling Event	Dissolved Oxygen Meter (mg/l)	Dissolved Oxygen Color (mg/l)	pH	CO2 (mg/l)	Alkalinity (mg/l)	Iron by color (mg/l)	Ferrous Iron (mg/l)	Total Iron (mg/l)	Nitrate (mg/l)	Sulfate (mg/l)	Methane (mg/l)
10/21/97	0.7	<1	6.1	200	-	-	14.2	22.7	1.8	3	0.05
01/05/98	2.3	2.5	5.3	90	<10	0.2	0.1	0.1	0.8	0	0.00
03/26/98	1.0	<1	5.5	90	<10	5.0	2.3	4.4	1.1	15	0.04
06/25/98	0.9	1.5	5.6	220	45	>10	9.0	12.2	1.6	15	0.05

Direct-Push Monitoring Well MW-4B: Marietta Ga.

Sampling Event	Dissolved Oxygen Meter (mg/l)	Dissolved Oxygen Color (mg/l)	pH	CO2 (mg/l)	Alkalinity (mg/l)	Iron by color (mg/l)	Ferrous Iron (mg/l)	Total Iron (mg/l)	Nitrate (mg/l)	Sulfate (mg/l)	Methane (mg/l)
10/20/97	1.3	2.0	-	100	-	-	2.2	3.2	0.8	2	0.15
01/06/98	1.4	1.5	4.9	160	<10	0.4	0.3	0.4	0.7	0	0.08
03/26/98	2.1	2.5	5.1	100	<10	0.1	0.1	0.2	0.7	1	0.08
06/25/98	1.3	1.5	5.1	220	<10	0.2	0.1	0.1	0.8	2	0.07

Conventional Monitoring Well MW-7A: Marietta Ga.

Sampling Event	Dissolved Oxygen Meter (mg/l)	Dissolved Oxygen Color (mg/l)	pH	CO2 (mg/l)	Alkalinity (mg/l)	Iron by color (mg/l)	Ferrous Iron (mg/l)	Total Iron (mg/l)	Nitrate (mg/l)	Sulfate (mg/l)	Methane (mg/l)
10/21/97	1	2	5.7	280	-	-	7.3	9.9	1.2	1	0.363
01/06/98	1.6	1.5	5.3	140	18	0.1	0.06	0.09	0.7	0	0.003
03/26/98	3	3	5.2	220	25	0.1	0	0.02	0.9	2	0.591
06/26/98	1.56	1.5	5.3	260	21	0.2	0.08	0.08	0.9	2	0.65

Table G36--Geochemical Parameters Indicative of Natural Attenuation (continued)

Direct-Push Monitoring Well MW-7: Marietta Ga.

Sampling Event	Dissolved Oxygen Meter (mg/l)	Dissolved Oxygen Color (mg/l)	pH	CO2 (mg/l)	Alkalinity (mg/l)	Iron by color (mg/l)	Ferrous Iron (mg/l)	Total Iron (mg/l)	Nitrate (mg/l)	Sulfate (mg/l)	Methane (mg/l)
10/21/97	1.4	1.5	5.6	100	-	-	3.01	3.26	0	0	0.762
01/07/98	1.2	2	5.4	100	40	>10	5.15	7.025	1.3	16	0.267
03/26/98	1.2	2	5.4	240	<10	7	4.625	6.025	1.1	17	0.27
06/26/98	1.22	1.5	5.4	200	40	7	4.85	5.7	1.2	14	0.4

Conventional Monitoring Well TA-1A: Brunswick, GA

Sampling Event	Dissolved Oxygen Meter (mg/l)	Dissolved Oxygen Color (mg/l)	pH	CO2 (mg/l)	Alkalinity (mg/l)	Iron by color (mg/l)	Ferrous Iron (mg/l)	Total Iron (mg/l)	Nitrate (mg/l)	Sulfate (mg/l)	Methane (mg/l)
09/25/97	0.6	<1	5.1	>100	-	-	0.91	0.92	3.1	34	0.942
12/19/97	0	<1	5	180	<10	1.5	1.08	1.09	2.5	29	1.3
04/02/98	1.2	1	5.3	240	<50	1	0.94	0.94	3.1	35	1.91
06/23/98	0.4	<1	5.2	333	30	1	0.73	0.74	3.1	25	1.75

Direct-Push Monitoring Well TA-1B: Brunswick, GA

Sampling Event	Dissolved Oxygen Meter (mg/l)	Dissolved Oxygen Color (mg/l)	pH	CO2 (mg/l)	Alkalinity (mg/l)	Iron by color (mg/l)	Ferrous Iron (mg/l)	Total Iron (mg/l)	Nitrate (mg/l)	Sulfate (mg/l)	Methane (mg/l)
09/25/97	0.6	1	5.9	>100	-	-	0.17	0.18	3.2	30	2.06
12/19/97	0	<1	5.9	180	150	1.5	1.33	1.38	0.5	0	3.11
04/02/98	1.3	1	6.3	140	200	2	1.16	1.19	2.3	0	3.55
06/23/98	0.3	<1	5.8	300	130	0.2	0.15	0.14	4	19	2.73

Conventional Monitoring Well TA-11A: Brunswick, GA

Sampling Event	Dissolved Oxygen Meter (mg/l)	Dissolved Oxygen Color (mg/l)	pH	CO2 (mg/l)	Alkalinity (mg/l)	Iron by color (mg/l)	Ferrous Iron (mg/l)	Total Iron (mg/l)	Nitrate (mg/l)	Sulfate (mg/l)	Methane (mg/l)
09/24/97	0.8	2	5.2	>100	<50	-	0.97	1.05	ND	10	1.15
12/18/97	0.6	1	5.7	200	40	0.8	0.42	0.46	4	24	1.13
03/31/98	0.6	<1	5.8	150	45	0.4	0.32	0.34	6.2	18	1.05
06/22/98	0.69	<1	5.5	200	37	0.2	0.21	0.24	6.8	34	0.66

Direct-Push Monitoring Well TA-11B: Brunswick, GA

Sampling Event	Dissolved Oxygen Meter (mg/l)	Dissolved Oxygen Color (mg/l)	pH	CO2 (mg/l)	Alkalinity (mg/l)	Iron by color (mg/l)	Ferrous Iron (mg/l)	Total Iron (mg/l)	Nitrate (mg/l)	Sulfate (mg/l)	Methane (mg/l)
09/24/97	0.6	<1	4.9	>100	<50	-	1.72	1.82	8.7	34	0.999
12/18/97	0.01	1	6.1	100	130	3	1.99	2.07	5.3	34	0.734
03/31/98	1	1	6.5	160	200	0.2	0.3	0.29	4.3	26	0.921
06/22/98	0.55	<1	5.5	180	35	0.1	0.41	0.41	7.6	35	0.91

Table G36--Geochemical Parameters Indicative of Natural Attenuation (continued)

Conventional Monitoring Well TA-12A: Brunswick, GA

Sampling Event	Dissolved Oxygen Meter (mg/l)	Dissolved Oxygen Color (mg/l)	pH	CO2 (mg/l)	Alkalinity (mg/l)	Iron by color (mg/l)	Ferrous Iron (mg/l)	Total Iron (mg/l)	Nitrate (mg/l)	Sulfate (mg/l)	Methane (mg/l)
09/24/97	1.2	2	5.3	>100		-	-	6.55	7	2.3	29	2.07
12/19/97	0	<1	5.4	140		70	>10	6.175	8.15	3.7	40	3.05
04/01/98	1.7	<1	5.6	220		60	>10	7.325	8.7	3.4	42	2.77
06/23/98	0.25	<1	3	220		120	<1	1.68	2.09	2.9	0	5.46

Direct-Push Monitoring Well TA-12B: Brunswick, GA

Sampling Event	Dissolved Oxygen Meter (mg/l)	Dissolved Oxygen Color (mg/l)	pH	CO2 (mg/l)	Alkalinity (mg/l)	Iron by color (mg/l)	Ferrous Iron (mg/l)	Total Iron (mg/l)	Nitrate (mg/l)	Sulfate (mg/l)	Methane (mg/l)
09/24/97	0.5	1.5	5.3	>100	125	-	5.43	5.8	5.7	26	3
12/19/97	0	1.5	6.1	120	250	6	4.925	5.425	3.1	23	4.25
04/01/98	0.7	<1	6.2	280	350	>10	13.833	28.5	1.6	0	6.61
06/23/98	0.93	<1	5.8	300	180	10	7.9	9	2.4	1	5.1

Ferrous Iron
The methodology used for this study is called split plot analysis. It is used because the time measurements and any possible time trend were distinct for each well at each location. In addition, the methodology for handling the time trend also readily handles non-detects. The analysis of the time trends, called within-plot analysis, results in a single value, the fitted value at the most recent time, to represent each well. The between plot or whole plot analysis uses ANOVA methodology to compare the two concentrations from the two types of wells.

Below is a listing for the time data for a typical well. Ferrous iron measurements labeled #1 and #2 are identical unless the measurement is a nondetect. If the measurement is a nondetect, then the #1 measurement will be missing. If both measurements are missing, then there was no data for that date for that well. Both measurements are logarithms of the data.

Table G37: Sample Iron Data Listing

Obs	Sampling Data	Time	City	Well	Type	Fer Iron	ND	Fer Iron 1	Fer Iron 2
33	09/24/97	1	Brunswick	11A	Conventional	0.97	0	-0.03	-0.03
34	12/18/97	86	Brunswick	11A	Conventional	0.42	0	-0.86	-0.86
35	03/31/98	189	Brunswick	11A	Conventional	0.32	0	-1.13	-1.13
36	06/22/98	272	Brunswick	11A	Conventional	0.21	0	-1.56	-1.56

Next the fit of the equation for the time trend is shown in the display below. The p-value (Pr > ChiSq) is small (<0.0001), which shows that the time trend was significant. The coefficient (Estimate) is negative for time, which means that the slope was decreasing or that the ferrous iron level was becoming lower as time progressed. The logarithmic values in Table G37 clearly show that the concentration is decreasing.

TableG38: LIFEREG Model Results for Iron

Dependent Variable	fer_iron_1
Dependent Variable	fer_iron_2
Number of Observations	4
Noncensored Values	4
Left Censored Values	0
Name of Distribution	NORMAL
Ln Likelihood	2.075741233

Variable	Degrees of Freedom	Estimate	Error	Chi-Square	Pr > ChiSq
Intercept	1	-0.17	0.12	2.17	0.1402
Time	1	-0.01	0.00	56.31	<.0001
Scale	1	0.14	0.05		

The fitted values at the most recent time are used as the estimate of the geochemical level for the measurement in the well. Results for all of the wells are shown in Table G39.

Table G39: Natural Log (Iron) Data Listing

Obs	Sampling	time	d	Site	well	Well-Type	last
1	06/22/98	272	Brunswick	11A	Conventional	-1.61	
2	06/23/98	273	Brunswick	12A	Conventional	0.99	
3	06/23/98	273	Brunswick	1A	Conventional	-0.21	
4	06/25/98	275	Marietta	3A	Conventional	2.87	
5	06/25/98	275	Marietta	4A	Conventional	1.19	
6	06/26/98	276	Marietta	7A	Conventional	-3.88	
7	06/22/98	272	Brunswick	11B	Direct-Push	-1.15	
8	06/23/98	273	Brunswick	1B	Direct-Push	-0.87	
9	06/23/98	273	Brunswick	12B	Direct-Push	2.32	
10	06/25/98	275	Marietta	3B	Direct-Push	3.19	
11	06/25/98	275	Marietta	4B	Direct-Push	-2.83	
12	06/26/98	276	Marietta	7	Direct-Push	1.66	

Table G39 provides the data for comparing the two concentrations in samples obtained from the adjacent conventional and Direct-Push wells. The comparison is shown below in the ANOVA Table G40. The two wells are equivalent unless the p-value (Pr > F) for the variable (Well-Type) that represents the two wells is small. In this table, the p-value, 0.7372 is not small, so there is no difference between the conventional and direct-push wells. The same test can be applied versus the two sites.

Table G40: ANOVA Model Results for Iron

Dependent Variable: ln(Ferrous Iron)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.36	0.68	0.11	0.8962
Error	9	55.32	6.14		
Corrected Total	11	56.69			

R-Square	Coeff Var	Root MSE	last Mean
0.02	1777.22	2.47	0.13

Table G40: ANOVA Model Results for Iron (continued)

Source	Degrees of Freedom	Anova SS	Mean Square	F Value	Pr > F
Site	1	0.62	0.62	0.10	0.7566
Well-Type	1	0.73	0.73	0.12	0.7372

Below are the tables of means for both the Sites and the types of monitoring wells. These validate the conclusions that can be made from the ANOVOA table.

Table G41: Mean Value of Iron for Well Type and Site

Site	N	Mean	Std Dev
Brunswic	6	-0.09	1.49
Marietta	6	0.37	2.99

Well-Type	N	Mean	Std Dev
Conv	6	-0.10825938	2.38136249
Push	6	0.38728453	2.34957437

The following is the cross plot of the measured ferrous iron concentrations in the wells. The data is scattered generally evenly about the line except for a few very low iron concentrations in the direct-push wells at Marietta.
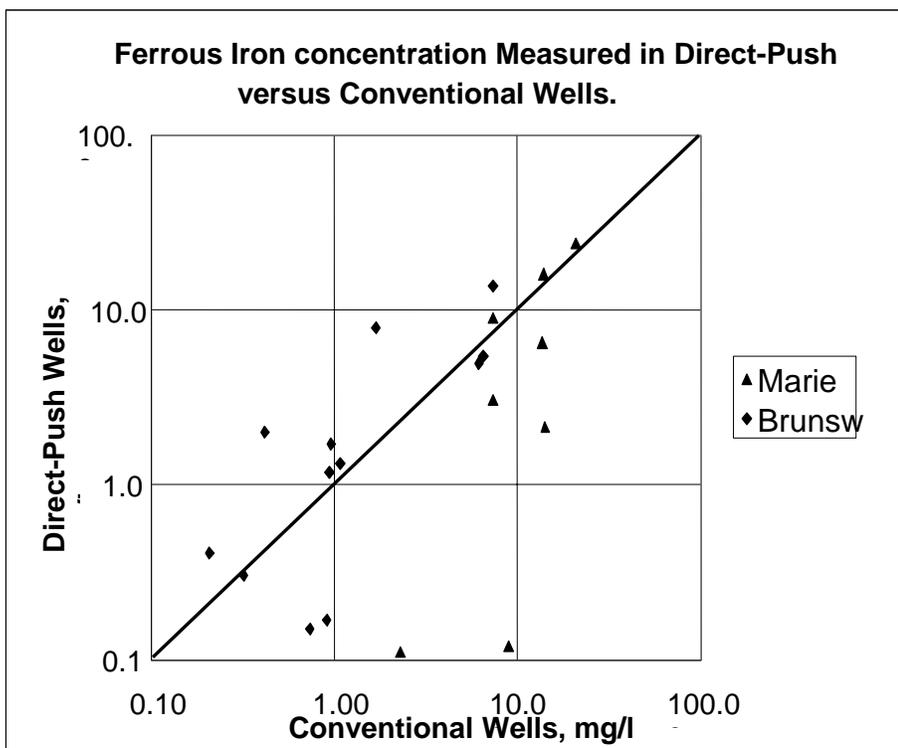
Figure G12: Ferrous Iron Concentration Measured in Direct-Push versus Conventional Wells

All the above descriptions apply generally for all the remaining geochemistry measurements

Nitrate

Table G42: Nitrate Data Listing

Obs	Sampling Data	Time	City	Well	Type	Nitrate	ND	Nitrate 1	Nitrate 2
1	09/24/97	1	Brunswick	11A	Conventional	0.1	1		-2.30
2	12/18/97	86	Brunswick	11A	Conventional	4.0	0	1.38	1.38
3	03/31/98	189	Brunswick	11A	Conventional	6.2	0	1.82	1.82
4	06/22/98	272	Brunswick	11A	Conventional	6.8	0	1.91	1.91

Table G43: LIFEREG Model Results for Nitrate

Dependent Variable	nitrate_1
Dependent Variable	nitrate_2
Number of Observations	4
Noncensored Values	3
Left Censored Values	1
Name of Distribution	NORMAL
Ln Likelihood	-5.776007261

Variable	Degrees of Freedom	Estimate	Error	Chi-Square	Pr > ChiSq	Label
Intercept	1	-1.81	1.22	2.21	0.1369	Intercept
time	1	0.01	0.01	6.21	0.0127	
Scale	1	1.24	0.54	Normal scale		

Table G43: LIFEREG Model Results for Nitrate (continued)

Obs	Sampling	time	Site	well	Well-Type	last
1	06/22/98	272	Brunswick	11A	Conventional	2.77
2	06/23/98	273	Brunswick	12A	Conventional	1.19
3	06/23/98	273	Brunswick	1A	Conventional	1.11
4	06/25/98	275	Marietta	3A	Conventional	0.26
5	06/25/98	275	Marietta	4A	Conventional	0.24
6	06/26/98	276	Marietta	7A	Conventional	-0.18
7	06/22/98	272	Brunswick	11B	Direct-Push	1.73
8	06/23/98	273	Brunswick	1B	Direct-Push	1.01
9	06/23/98	273	Brunswick	12B	Direct-Push	0.56
10	06/25/98	275	Marietta	3B	Direct-Push	0.85
11	06/25/98	275	Marietta	4B	Direct-Push	-0.28
12	06/26/98	276	Marietta	7	Direct-Push	0.78

Table G44: ANOVA Model Results for Nitrate

Dependent Variable: ln(nitrate)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	3.81	1.90	4.24	0.0505
Error	9	4.054	0.45		
Corrected Total	11	7.87			

R-Square	Coeff Var	Root MSE	last Mean
0.48	79.92	0.67	0.83

Source	Degrees of Freedom	Anova SS	Mean Square	F Value	Pr > F
Site	1	3.77	3.77	8.38	0.0178
Well-Type	1	0.04	0.04	0.10	0.7602

Site	N	Mean	Std Dev
Brunswick	6	1.40	0.77
Marietta	6	0.27	0.47

Well-Type	N	Mean	Std Dev
Conventional	6	0.90	1.06
Direct-Push	6	0.77	0.65
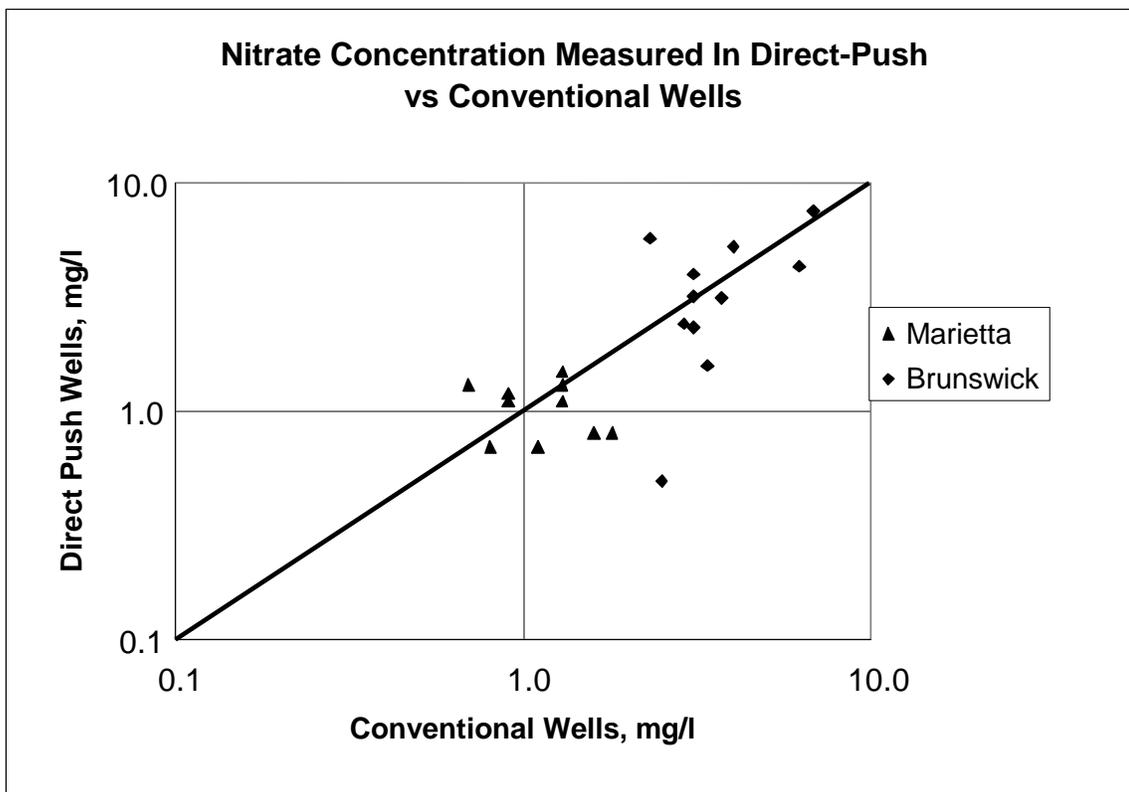
Figure G13: Nitrate Concentration Measured in Direct-Push versus Conventional Wells

Methane

Table G44: LIFEREG Model Results for Methane

Dependent Variable	methane_1
Dependent Variable	methane_2
Number of Observations	4
Noncensored Values	4
Left Censored Values	0
Interval Censored Values	0
Name of Distribution	NORMAL
Ln Likelihood	2.7567438613

Variable	Degrees of Freedom	Estimate	Error	Chi-Square	Pr > ChiSq	Label
Intercept	1	0.23	0.10	5.17	0.0229	Intercept
time	1	-0.00	0.00	10.01	0.0016	
Scale	1	0.12	0.04	Normal scale		

Table G44: LIFEREG Model Results for Methane (continued)

Obs	Sampling	time	Site	well	Well-Type	last
1	06/22/98	272	Brunswick	11A	Conventional	-0.27
2	06/23/98	273	Brunswick	12A	Conventional	1.54
3	06/23/98	273	Brunswick	1A	Conventional	0.68
4	06/25/98	275	Marietta	3A	Conventional	0.92
5	06/25/98	275	Marietta	4A	Conventional	-3.25
6	06/26/98	276	Marietta	7A	Conventional	-0.81
7	06/22/98	272	Brunswick	11B	Direct-Push	-0.12
8	06/23/98	273	Brunswick	1B	Direct-Push	1.17
9	06/23/98	273	Brunswick	12B	Direct-Push	1.82
10	06/25/98	275	Marietta	3B	Direct-Push	1.01
11	06/25/98	275	Marietta	4B	Direct-Push	-2.7
12	06/26/98	276	Marietta	7	Direct-Push	-1.23

Table G45: ANOVA Model Results for Methane

Dependent Variable: ln(methane)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	10.07	5.039	2.31	0.1555
Error	9	19.67	2.186		
Corrected Total	11	29.75			

R-Square	Coeff Var	Root MSE	last Mean
0.33	-1371.84	1.47	-0.10

Source	Degrees of Freedom	Anova SS	Mean Square	F Value	Pr > F
Site	1	9.97	9.97	4.56	0.0614
Well-Type	1	0.10	0.10	0.05	0.8349

Site	N	Mean	Std Dev
Brunswick	6	0.80	0.86
Marietta	6	-1.01	1.78

Well-Type	N	Mean	Std Dev
Conventional	6	-0.19	1.72
Direct-Push	6	-0.01	1.72
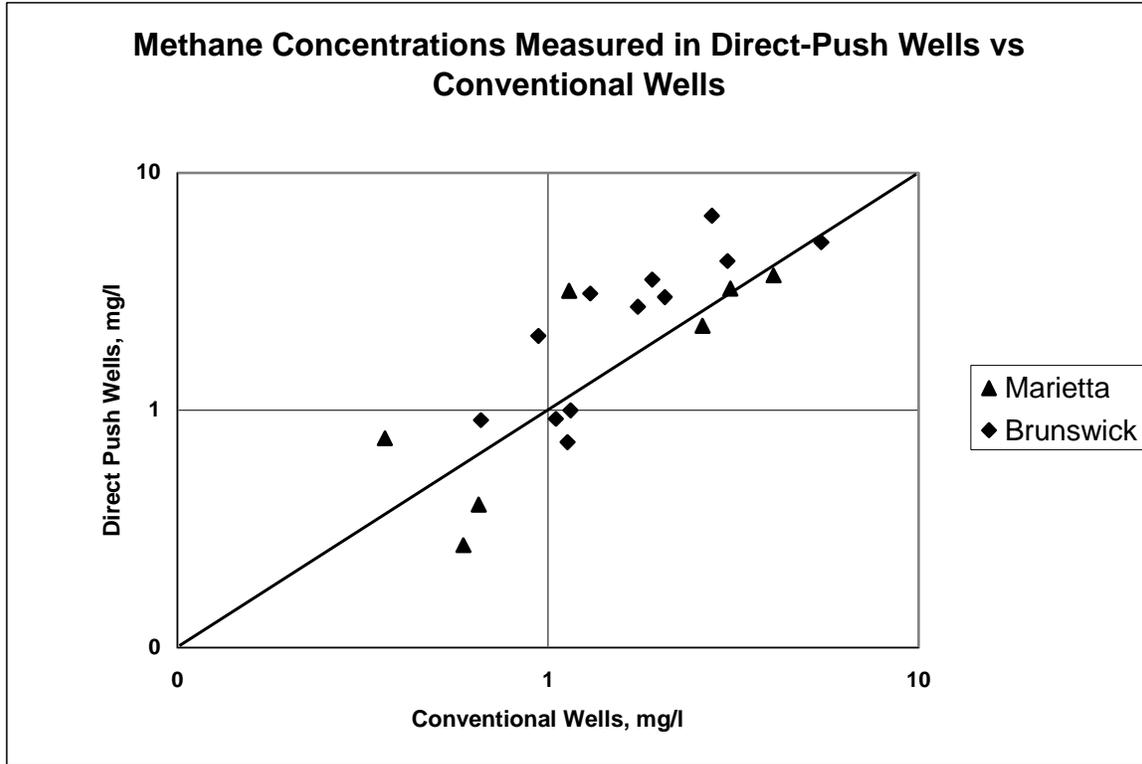
Figure G14: Methane Concentration Measured in Direct-Push versus Conventional Wells

Sulfate

Table G46: Sulfate Data Listing

Obs	Sampling	Time	City	Well	Type	Sulfate	ND	Sulfate 1	Sulfate 2
33	09/24/97	1	Brunswick	11A	Conventional	10	0	2.30	2.30
34	12/18/97	86	Brunswick	11A	Conventional	24	0	3.17	3.17
35	03/31/98	189	Brunswick	11A	Conventional	18	0	2.89	2.89
36	06/22/98	272	Brunswick	11A	Conventional	34	0	3.52	3.52

Table G47: LIFEREG Model Results for Sulfate

Dependent Variable   sulfate_1
Dependent Variable   sulfate_2
Number of Observations   4
Noncensored Values   4
Left Censored Values   0
Name of Distribution   NORMAL
Ln Likelihood   -0.217329035

Table G47: LIFEREG Model Results for Sulfate (continued)

Variable	Degrees of Freedom	Estimate	Error	Chi-Square	Pr > ChiSq	Label
Intercept	1	2.48	0.21	135.45	<.0001	Intercept
time	1	0.00	0.00	8.32	0.0039	
Scale	1	0.25	0.09			Normal scale

Obs	Sampling	time	Site	well	Well-Type	last
1	06/22/98	272	Brunswick	11A	Conventional	3.45
2	06/23/98	273	Brunswick	12A	Conventional	0.60
3	06/23/98	273	Brunswick	1A	Conventional	3.31
4	06/25/98	275	Marietta	3A	Conventional	2.19
5	06/25/98	275	Marietta	4A	Conventional	2.75
6	06/26/98	276	Marietta	7A	Conventional	0.76
7	06/22/98	272	Brunswick	11B	Direct-Push	3.43
8	06/23/98	273	Brunswick	1B	Direct-Push	0.28
9	06/23/98	273	Brunswick	12B	Direct-Push	-0.52
10	06/25/98	275	Marietta	3B	Direct-Push	-1.15
11	06/25/98	275	Marietta	4B	Direct-Push	0.33
12	06/26/98	276	Marietta	7	Direct-Push	3.40

Table G48: ANOVA Model Results for Sulfate

Dependent Variable: ln(sulfate)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	4.89	2.44	.82	0.4720
Error	9	26.94	2.99		
Corrected Total	11	31.83			

R-Square	Coeff Var	Root MSE	last Mean
0.15	109.95	1.73	1.57

Source	Degrees of Freedom	Anova SS	Mean Square	F Value	Pr > F
Site	1	0.43	0.431	0.14	0.7130
Well-Type	1	4.45	4.45	1.49	0.2533

Site	N	Mean	Std Dev
Brunswick	6	1.76	1.83
Marietta	6	.38	1.70

Well-Type	N	Mean	Std Dev
Conventional	6	2.18	1.24
Direct-Push	6	0.96	1.98
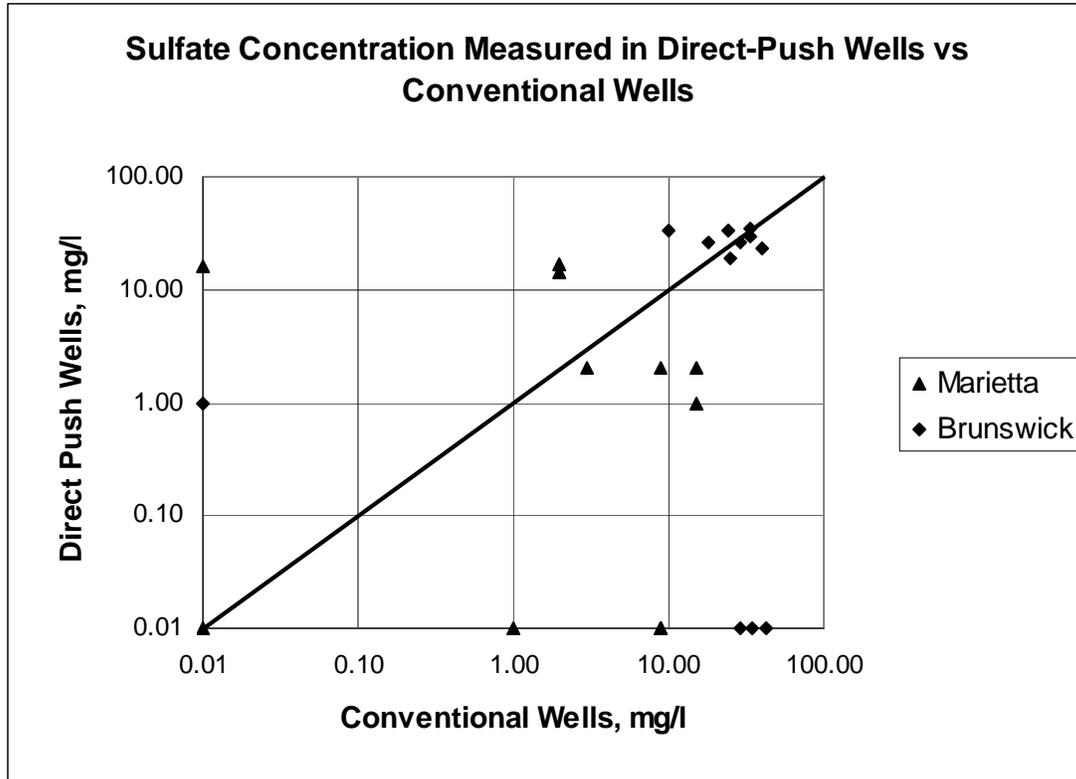
Figure G15: Sulfate Concentration Measured in Direct-Push versus Conventional Wells

Dissolved Oxygen

Table G49: Dissolved Oxygen Data Listing

Obs	Sampling	time	Site	Well Type	Dis_o2	Dis_o2_ND	dis_o2_1	dis_o2_2
25	10/20/97	27	Marietta 3A	Conventional	0.60	0	-0.51	-0.51
26	01/05/98	104	Marietta 3A	Conventional	0.50	0	-0.69	-0.69
27	03/25/98	183	Marietta 3A	Conventional	1.10	0	0.09	0.09
28	06/25/98	275	Marietta 3A	Conventional	1.20	0	0.18	0.18

Table G50: LIFEREG Model Results for Dissolved Oxygen

Dependent Variable	dis_o2_1
Dependent Variable	dis_o2_2
Number of Observations	4
Noncensored Values	4
Left Censored Values	0
Name of Distribution	NORMAL
Ln Likelihood	0.7861585911

Variable	Degrees of freedom	Estimate	Error	Chi-Square	Pr > ChiSq	Label
Intercept	1	-0.74	0.18	15.76	<.0001	Intercept
time	1	0.00	0.00	10.40	0.0013	
Scale	1	0.19	0.07			Normal scale

Obs	Sampling	time	Site	well	Well-Type	last
1	06/22/98	272	Brunswick	11A	Conventional	-0.46
2	06/23/98	273	Brunswick	12A	Conventional	-1.28
3	06/23/98	273	Brunswick	1A	Conventional	-0.95
4	06/25/98	275	Marietta	3A	Conventional	0.21
5	06/25/98	275	Marietta	4A	Conventional	0.06
6	06/26/98	276	Marietta	7A	Conventional	0.78
7	06/22/98	272	Brunswick	11B	Direct-Push	-0.71
8	06/23/98	273	Brunswick	1B	Direct-Push	-1.11
9	06/23/98	273	Brunswick	12B	Direct-Push	-0.56
10	06/25/98	275	Marietta	3B	Direct-Push	-0.21
11	06/25/98	275	Marietta	4B	Direct-Push	0.45
12	06/26/98	276	Marietta	7	Direct-Push	0.16

Table G51: ANOVA Model Results for Dissolved Oxygen

Dependent Variable: ln(dissolved oxygen)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	3.60	1.80	14.94	0.0014
Error	9	1.08	0.12		
Corrected Total	11	4.69			

R-Square	Coeff Var	Root MSE	last Mean
0.76	-115.06	0.34	-0.30

Source	Degrees of Freedom	Anova SS	Mean Square	F Value	Pr > F
Site	1	3.59	3.59	29.80	0.0004
Well-Type	1	0.01	0.01	0.09	0.7745

Site	N	Mean	Std Dev
Brunswick	6	-0.84	0.31
Marietta	6	0.245	0.342

Well-Type	N	Mean	Std Dev
Conventional	6	-0.27	0.77
Direct-Push	6	-0.33	0.58

Dissolved Oxygen Concentrations in Direct-Push vs Conventional Wells
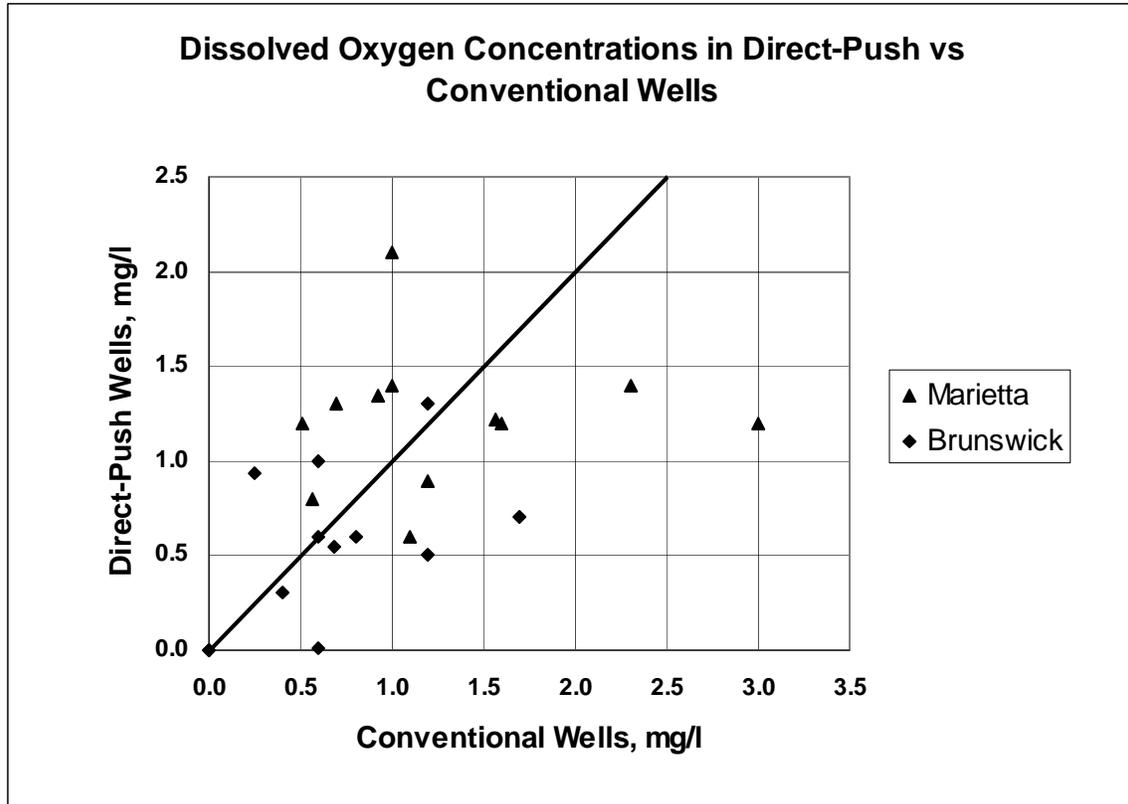
Figure G16: Dissolved Oxygen Concentration Measured in Direct-Push versus Conventional Wells

CO_2

Table G52: CO_2 Data Listing

Obs	Sampling	time	Site	Well	Type	Co2	Co2_ND	co2_1	co2_2
5	09/24/97	1	Brunswick	11B	Direct-Push	100	1	4.60	
6	12/18/97	86	Brunswick	11B	Direct-Push	100	0	4.60	4.60
7	03/31/98	189	Brunswick	11B	Direct-Push	160	0	5.07	5.07
8	06/22/98	272	Brunswick	11B	Direct-Push	80	0	5.19	5.19

Table G53: LIFEREG Model Results for CO_2

Dependent Variable	co2_1
Dependent Variable	co2_2
Number of Observations	4
Noncensored Values	3
Right Censored Values	1
Interval Censored Values	0
Name of Distribution	NORMAL
Ln Likelihood	1.622244098

Table G53: LIFEREG Model Results for CO_2 (continued)

Variable	Degrees of Freedom	Estimate	Error	Chi-Square	Pr > ChiSq	Label
Intercept	1	4.58	0.11	1736.67	<.0001	Intercept
Time	1	0.00	0.00	13.16	0.0003	
Scale	1	0.10	0.04			Normal scale

Obs	Sampling	time	Site	well	Well-Type	last
1	06/22/98	272	Brunswick	11A	Conventional	5.19
2	06/23/98	273	Brunswick	12A	Conventional	5.46
3	06/23/98	273	Brunswick	1A	Conventional	5.78
4	06/25/98	275	Marietta	3A	Conventional	5.22
5	06/25/98	275	Marietta	4A	Conventional	4.99
6	06/26/98	276	Marietta	7A	Conventional	5.42
7	06/22/98	272	Brunswick	11B	Direct-Push	5.18
8	06/23/98	273	Brunswick	1B	Direct-Push	5.47
9	06/23/98	273	Brunswick	12B	Direct-Push	5.76
10	06/25/98	275	Marietta	3B	Direct-Push	5.28
11	06/25/98	275	Marietta	4B	Direct-Push	5.22
12	06/26/98	276	Marietta	7	Direct-Push	5.44

Table G54: ANOVA Model Results for CO_2

Dependent Variable: last   ln(CO2)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.14	0.07	1.35	0.3082
Error	9	0.47	0.05		
Corrected Total	11	0.61			

R-Square	Coeff Var	Root MSE	last Mean
0.23	4.28	0.23	5.37

Source	Degrees of Freedom	Anova SS	Mean Square	F Value	Pr > F
Site	1	0.13	.13	2.55	0.1448
Well-Type	1	0.00	0.00	0.14	0.7164

Site	N	Mean	Std Dev
Brunswick	6	5.47	0.26
Marietta	6	5.26	0.16

Well-Type	N	Mean	Std Dev
Conventional	6	5.34	0.27
Direct-Push	6	5.39	0.21

CO2 Concentrations Measured in Direct-Push versus Conventional Wells
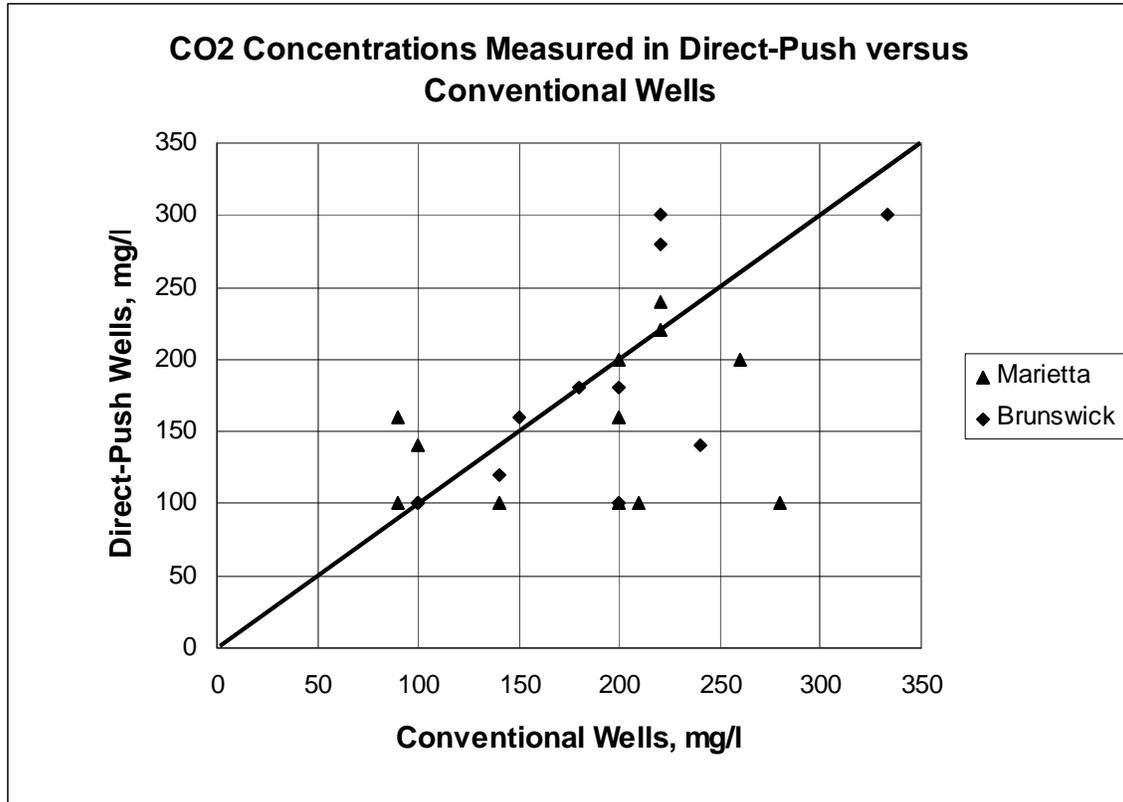
Figure G17: Dissolved Oxygen Concentration Measured in Direct-Push versus Conventional Wells

Alkalinity

Table G55: Alkalinity Data Listing

Obs	Sampling	time	Site	Well	Type	Alkalinity	Alkalinity_ ND	Alkalinity _1	Alkalinity _2
25	10/20/97	27	Marietta	3A	Conventional	.	0	.	.
26	01/05/98	104	Marietta	3A	Conventional	70	0	4.24	4.24
27	03/25/98	183	Marietta	3A	Conventional	210	0	5.34	5.34
28	06/25/98	275	Marietta	3A	Conventional	260	0	5.56	5.56

Table G56: LIFEREG Model Results for Alkalinity

Dependent Variable	alkalinity_1
Dependent Variable	alkalinity_2
Number of Observations	3
Noncensored Values	3
Left Censored Values	0
Missing Values	1
Name of Distribution	NORMAL
Ln Likelihood	0.1275942318

Table G56: LIFEREG Model Results for Alkalinity (continued)

Variable	Degrees of Freedom	Estimate	Error	Chi-Square	Pr > ChiSq
Intercept	1	3.64	0.38	90.37	<.0001
time	1	0.00	0.00	15.43	<.0001
Scale	1	0.23	0.09		

Obs	Sampling	time	Site	well	Well-Type	last
1	06/22/98	272	Brunswick	11A	Conventional	3.67
2	06/23/98	273	Brunswick	12A	Conventional	4.62
3	06/23/98	273	Brunswick	1A	Conventional	3.40
4	06/25/98	275	Marietta	3A	Conventional	5.71
5	06/25/98	275	Marietta	4A	Conventional	3.80
6	06/26/98	276	Marietta	7A	Conventional	3.12
7	06/22/98	272	Brunswick	11B	Direct-Push	4.45
8	06/23/98	273	Brunswick	1B	Direct-Push	5.00
9	06/23/98	273	Brunswick	12B	Direct-Push	5.56
10	06/25/98	275	Marietta	3B	Direct-Push	5.62
11	06/25/98	275	Marietta	4B	Direct-Push	1.66
12	06/26/98	276	Marietta	7	Direct-Push	3.10

Table G57: ANOVA Model Results for Alkalinity

Dependent Variable: ln(alkalinity)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.22	0.61	0.35	0.7120
Error	9	15.67	1.74		
Corrected Total	11	16.90			

R-Square	Coeff Var	Root MSE	last Mean
0.07	31.83	1.31	4.14

Source	Degrees of Freedom	Anova SS	Mean Square	F Value	Pr > F
Site	1	1.13	1.13	0.65	0.4408
Well-Type	1	0.09	0.09	0.06	0.8191

Site	N	Mean	Std Dev
Brunswick	6	4.45	0.81
Marietta	6	3.83	1.58

Well-Type	N	Mean	Std Dev
Conventional	6	4.05	0.95
Direct-Push	6	4.23	1.56
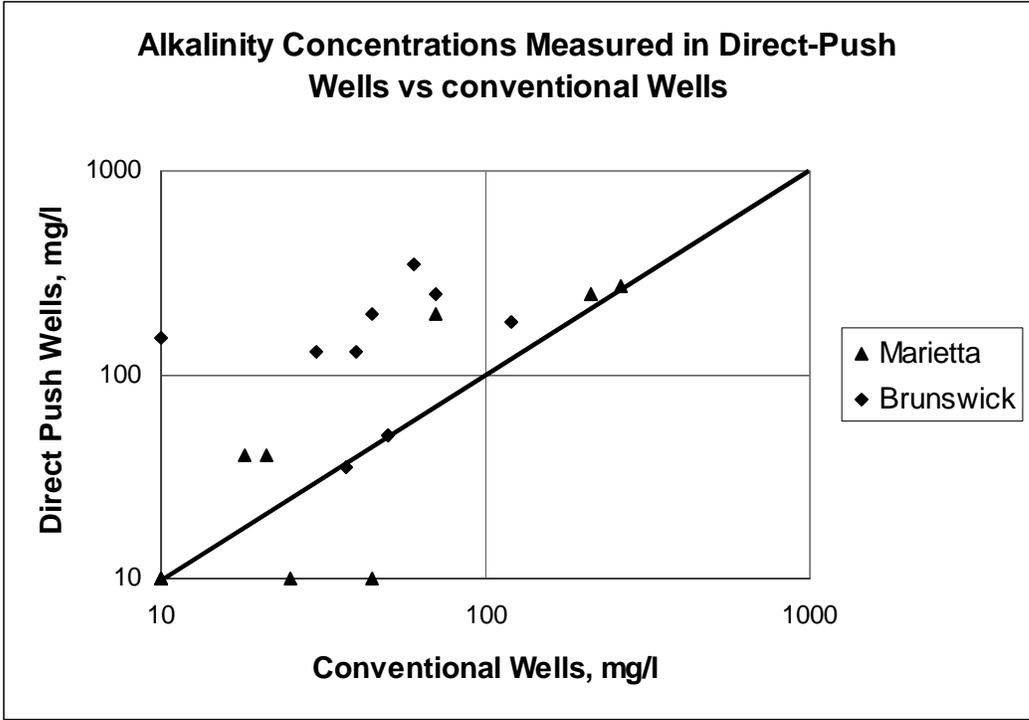
Figure G18: Alkalinity Concentration Measured in Direct-Push versus Conventional Wells