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DISCLAIMER

INNOVATIVE TECHNOLOGIES AND VADOSE ZONE TREATMENT OF CHLORINATED VOLATILE ORGANIC COMPOUNDS – CASE STUDY

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Abstract

Over the last 10 years a mix of innovative and conventional characterization techniques has been used to assess the contamination of vadose zone sediments beneath the pilot-scale test facility known as TNX at the Savannah River Site (SRS) in South Carolina. Shallow soils and groundwater beneath the TNX facility are contaminated with chlorinated volatile organic compounds (CVOCs), trichloroethylene (TCE), carbon tetrachloride (CCl_4), perchloroethylene (PCE), and chloroform ($CHCl_3$). An interim pump and treat remediation system was placed in operation in 1996 to provide hydraulic containment of groundwater containing greater than 500 ug/L dissolved TCE.

In 1994, a vadose zone study was initiated to determine the degree and extent of CVOC contamination above the contaminated groundwater. Headspace sampling and analysis, acoustic infra-red spectroscopy, cone penetrometry, and vadose zone pumping tests were used to determine contaminant concentrations and physical properties related to soil vapor extraction. In 2001, soil vapor extraction (SVE), a presumptive remedy for CVOCs in soils similar to those present beneath TNX, was selected to treat the CVOC contamination. Cone Penetrometer Testing (CPT) with soil vapor sampling provided a detailed understanding of the subsurface geology and CVOC distribution which was essential for proper well design and placement. Twelve SVE wells were installed using direct push technology (DPT) and were tested to determine specific capacity and CVOC concentrations. This information was then used to develop a strategy for operating the SVE system. Based on the results of the baseline testing and previous studies, sets of 2 to 3 extraction wells will be treated using SVE at one-month intervals. This will allow continuous operation of the SVE system and give individual wells up to 3 months for rebound between treatments. This method of operation is intended to

maximize contaminant recovery from individual wells and reduce the overall capital investment and operating cost of the SVE system.

Background

For approximately 40 years the Savannah River Site produced nuclear material for use in national defense, space, and medical programs in the United States. Pilot-scale tests of chemical processes used in the Defense Waste Processing Facility, Separations Area, and fuel and target manufacturing areas were conducted in the TNX Area of SRS. Non-radioactive waste generated at TNX was disposed in unlined excavations and basins resulting in contamination of the vadose zone and shallow groundwater.

The SRS began monitoring groundwater quality at TNX in 1981 and detected several contaminants in groundwater. Since that time many innovative and emerging characterization and remediation technologies have been demonstrated. Primary contaminants in the shallow groundwater and vadose zone sediments beneath the TNX Area are *dissolved* and *residual* CVOCs such as trichloroethylene (TCE), carbon tetrachloride (CCl_4), perchloroethylene (PCE), and chloroform ($CHCl_3$).

In November 1994, an Interim Record of Decision was agreed to and signed by the U. S. Department of Energy (DOE), the U. S. Environmental Protection Agency (EPA), and the South Carolina Department of Health & Environmental Control (SCDHEC). The Interim Record of Decision required the installation of a hybrid groundwater corrective action to stabilize the plume of groundwater contamination by capturing and containing the dissolved contamination that was greater than 500 ug/L TCE (Westinghouse Savannah River Company [WSRC], 1994). In 2001, the Interim Record of Decision was modified to incorporate the use of SVE to treat soil contaminated with CVOCs (WSRC, 2001a). This paper presents a case study of innovative and conventional techniques to select and deploy a treatment for the contaminated vadose zone soils at TNX.

Geologic Setting

The TNX Area is located in South Carolina on a terrace adjacent to the Savannah River in the southwest portion of the SRS, (Figure 1). The vadose zone is approximately 15 meters (49 ft.) thick at TNX and is composed of fluvial sediments in the Savannah River valley and underlying Coastal Plain sediments consisting of sand, clayey sand, sandy clay and clay layers with several zones containing quartz pebbles and cobbles. The sands are yellow, red and orange and range from poorly to well sorted quartz sand. They have characteristics of fluvial and shallow marine, lagoon or marsh depositional environments (Wyatt and Harris, 2004).

TNX is underlain by two aquifer systems - a deep aquifer system and a shallow aquifer system. The aquifer systems are separated by a thick layer of clay and silt with thin sand lenses (Figure 2). There is an upward gradient between the deep and shallow aquifer system equal to about 17 meters (56 ft.) of water (24 psi). The upward gradient results in upward groundwater flow from the deep aquifer system to the shallow aquifer system. Lateral groundwater flow in the shallow aquifers beneath TNX is to the west-southwest towards the Savannah River (Nichols, 1993).

The shallow aquifer system is comprised of an unconfined aquifer and a semi-confined aquifer. Depth to the water table varies from zero to 15.25 m (50 feet) in the area of groundwater contamination. The unconfined aquifer outcrops in the swamp adjacent to the Savannah River.

Previous Investigations and Studies

The first groundwater monitoring wells at TNX were installed and sampled in 1980. Several constituents including CVOCs, TCE, PCE, CCL_4, and $CHCl_3$ were detected in concentrations that exceeded maximum concentration levels (MCLs) for drinking water (Nichols, 1993). Initial characterization efforts were concentrated on groundwater activities. Vadose zone characterization began in the mid 1990s.

The first contaminant profiles were prepared in 1995 using results from the headspace analysis of soil samples collected from areas of known CVOC disposal and overlying groundwater concentrations, greater than 500 ug/L dissolved TCE (Figure 3). The analysis was performed on sediment samples collected in sealed vials using a gas chromatograph. The gas chromatograph was equipped with an auto sampler, an electron capture detector (ECD) and a flame ionization detector (FID). The use of dual detectors provided excellent sensitivity and a large dynamic range in the analysis of CVOCs. This technique allowed depth discrete sampling to become a routine method because it was efficient and cost-effective. This technique is similar to Method 5021 that was later published by the EPA (EPA, 1996).

The headspace sampling results were used to finalize the design to test air-lift recirculation well treatment groundwater technology (ARW). Water table wells and vadose zone piezometers installed as part of the ARW test were pump tested to estimate the permeability of vadose zone sediments (WSRC, 1999) and to determine the zone of influence (ZoI). Data from the pumping tests were analyzed using techniques similar for groundwater pumping tests analysis by correcting for viscosity and density differences as reported by Massman (Massman and Madden, 1994). Figure 4 shows typical results for a vadose zone pumping test at TNX.

Following the success of the vadose zone pumping tests, a long-term pulsed SVE test was conducted to study the rate of contaminant recovery. Initially, the concentration of TCE, CCl_4, and PCE in the exhaust from the test were monitored continuously with a multi-gas, infra-red, photo-acoustic sensor. This provided a detailed record of contaminant recovery data during the early stages of the test that was analyzed to estimate several parameters such as diffusion rates and ZoI related to contaminant transport in the vadose zone (Rossabi, 2000).

After approximately 6 weeks of operation, the continuous monitoring was replaced by the collection of grab samples in Tedlar™ bags for subsequent analysis on gas chromatograph using an ECD and FID, (Figure 5). The test unit was intermittently operated for two years to study the effectiveness of SVE by monitoring the rebound of CVOC concentrations in the well (Figure 6). The test provided the necessary data for optimization of the design and operation of the full-scale SVE system.

The strategy for implementing SVE at TNX consists of pulsed pumping in sets of individual wells. The SVE system includes a portable 15 hp portable unit connected to individual clusters of SVE wells in the well network using 50 mm (2 in.) diameter flexible hose. This design facilitates pulsed operation of the unit on individual sets of wells optimizing the use of equipment by keeping it in continuous operation and decreasing the investment necessary to complete the SVE remediation. Use of a portable unit for pulsed remediation on individual set of wells also increases flexibility in use of the well network and minimizes the amount of permanent piping necessary for operation. After the contaminant recovery rate from a given set of wells has decreased significantly, the unit is removed and connected to another set of wells and the CVOC concentration in the previous set is allowed to recover. This method of operation optimizes use of energy for contaminant removal by maximizing the ratio of contaminant mass removed to energy consumed.

Full Scale Soil Vapor Extraction

Data from historical waste disposal records, groundwater contaminant plume maps, headspace soil samples, contaminant profiles, and short and long term SVE tests were analyzed to select potential well locations for the full-scale SVE system (EPA, 1991; Wisconsin Department of Natural Resources, 1993; Faybishenko, 2000). The analysis showed that the area with CVOC contamination in the vadose zone was most likely located beneath building 672-T in the central portion of TNX (Figure 7).

Selection of Extraction Zones and SVE Well Installation

The SVE well network was installed in two phases to incorporate the depth discrete nature of the design associated with well clusters having screens at different depths to address the stratified nature of CVOC contamination at the site. Cone Penetration Testing (CPT) with soil gas sampling was used to accurately locate the zones that would be used to extract contaminated soil vapors (Nichols and Noonkester, 2001). Fifteen locations were selected for the CPT investigation in the vicinity of and inside building 672-T (Figure 7). CPT was utilized because it collects detailed, high quality lithologic data, and can be used to simultaneously collect soil vapor samples, is fast and cost effective, and does not produce drilling fluids and cuttings disposal. Direct Push Technology (DPT) was used to install the SVE wells at the locations identified using CPT.

Cone Penetrometer Testing

CPT collects continuous data related to sediment behavior by measuring the mechanical response of sediments to the hydraulic advancement of a probe equipped with several sensors and a sampling port. Measurements taken include cone penetration resistance (q_c), sleeve friction (f_s), and pore pressure (u). The penetration resistance and sleeve friction are used to calculate friction ratio ($R_f = f_s/q_c$) which has been correlated to sediment texture (Lunne et. al., 1997). Typically the cone penetration resistance is high in sands and low in clays, and friction ratio is low in sands and high in clays.

The vapor sampling module is a simple screen with a sample port located approximately 0.2 m (8 in.) from the cone penetrometer tip. The cone penetrometer is pushed through the subsurface collecting soil property lithology data and displaying it in real time. When a permeable zone (typically R_f <2%) is identified, a soil gas sample is collected. Polyethylene tubing is connected to the sample port and extended through the CPT rods into the work area where samples are collected and analyzed. A vacuum pump is used to pull soil vapor through the polyethylene tubing into a Bruel & Kjaer (B&K) infra-red, photo acoustic multi-gas monitor, which continuously analyzes the soil vapor and displays the results on an LCD screen. The B&K monitor analyzed soil vapor for TCE, PCE, CCL_4, carbon dioxide ($CO_{2)}$ and soil moisture.

The sampling system was purged to assure gas samples were representative of subsurface conditions before field data and samples were collected. The system was considered purged when CO_2 concentrations stabilized and were representative of the subsurface environment. CO_2 works well for this purpose since CO_2 levels are much higher in soil vapor (2,000–40,000 ppmv) than in ambient atmospheric background (500-1,000 ppmv). After the system was purged and CO_2 stabilized, the B&K readings for TCE, PCE, and CCl_4 were considered representative of soil vapor concentrations and recorded. In addition to the B&K results, soil gas samples were collected in Tedlar™ bags from 25% of the sample zones and analyzed with gas chromatography.

Soil gas sample depths were selected using two methods. The first method has been previously described and was based on CPT data. The second method required reversing the vacuum pump flow direction so the flow direction was into the CPT sampling module. As the cone tool was advanced into the subsurface, pressure variations were observed in-situ with a pressure gauge that was connected in the system. High pressures were observed in clayey zones and low pressures in sandy zones. When the pressure dropped, the tool was stopped and the vacuum hose reversed to collect a soil gas sample. This method proved to be effective, and reliable. An additional benefit of creating a positive airflow into the screen was the prevention of smearing and clogging of the sample port screen when advancing through clayey zones. Seventy-two soil vapor samples were collected and analyzed for TCE and CCl_4 using the B&K monitor and 18 duplicates were collected in Tedlar™ bags for analysis using gas chromatography.

Sediment and soil gas data were compiled into contour maps and cross-sections for further analysis to select screen intervals for SVE wells. Figure 8 illustrates TCE concentrations at sample depths and selected screen zones in cross-sectional view. The stratigraphy was divided into four zones, Zone A (shallowest) through Zone D (deepest), Figure 8. Zones B and D were permeable enough to collect soil gas samples, while Zones A and C were too clayey to yield soil gas samples. The upper permeable zone, Zone B, varied in thickness from 3 to 5.5 meters (10 to 18 ft.) and consisted of sand with minor interbeds of silty and clayey sands. The lower permeable zone, Zone D, varied in thickness from 1.2 to 2.1 meters (4 to 7 ft.) and consisted of primarily fine grained sand and silty sand. This zone extended into the capillary fringe at several of the locations. TCE concentrations in Zones B and D are illustrated in Figure 9.

SVE wells were installed at locations with detectable CVOC concentrations and screens were placed into the permeable zones. Wells were designated as U (upper) for Zone B and L (lower) for Zone D. Well spacing was based on drawdown test results from previous SVE pumping tests and the anticipated surface seal effect of the foundation of building 672-T. More wells were screened in zone D since CVOCs were found in higher concentrations and over a wider area (Figures 9 and 10).

Well Installation

Direct Push Technology (DPT) was selected to install the SVE wells because it has been found to produce high quality and cost efficient SVE wells in unconsolidated vadose zone sediments (WRSC, 2001b). The well installation process involves pre-pushing a pilot hole using a standard DPT rod and tip to total well depth. The pilot hole is enlarged to receive the well materials by advancing a standard DPT rod with a 7.62 cm (3 in.) diameter modified "dummy" tip. After the pilot hole is completed, the well assembly begins. A solid steel tip is threaded to the first section of well material, which is usually a sump section. The steel tip provides a solid platform for the DPT rods to push against as the well is pushed to depth. The well is pushed to depth from the inside of the well casing using the DPT rods. Once the well is pushed to total depth, the DPT rods are removed (Figure 11).

SVE wells were constructed using 5.08 cm (2 in.) diameter PVC casing and stainless steel screens and sumps. Well screens were constructed of 0.254 mm (0.01 in.) slot 305 stainless steel schedule 5 shutter screen (a.k.a. louver screen) with ASTM F480 compatible flush threads (e.g. Roscoe Moss Company). Shutter screen was developed for water well installations in large diameter, deep, gravel envelope wells with the louvers facing down (Driscoll, 1986). Shutter screens were chosen because of their unique design that prevents smearing and clogging of the screen during installation when the well is pushed into the subsurface, especially in clayey sediments. The shutter screens were installed with the louvers facing up to push sediment away from the screen openings as the well is advanced (Figure 12). Grout was used to seal the annulus above the well screen to prevent short circuiting of air along the well casing. A 0.305 meter (1 ft.) long collar (grout upset), the same diameter as the pilot hole, was welded to the top of each well screen before installation to prevent grout from fouling the screen. A tag line was lowered into each well to make sure no grout had made it by the collar and contaminated the screen.

Sumps were installed on most of the wells for the purpose of collecting sediment that is pulled into the well during SVE operations, thus reducing clogging of the screen. A 1.5 meter (5 ft.) sump was installed on the shallow wells screened in Zone B. Since the DPT tool was not capable of pushing through a saturated fine-grained sand layer at approximately 15 meters (49 ft.), most of the wells installed in Zone D were not installed to the total desired depth. Sump lengths were shortened or eliminated to maximize total depth of screen zones in Zone D. Screens were extended into the water table when possible to take advantage of temporal declines in the water table that drain sediments and expose more contaminated sediment.

Baseline Testing

Baseline SVE tests were performed on all SVE wells to establish operating parameters including flow rate and CVOC concentrations. The results were used to develop a strategy for pulsed pumping of different sets of wells to allow continuous operation and maximum contaminant removal rate. The baseline tests were conducted as follows:

1. Collect pre-test soil gas sample using oil-less sampling vacuum pump and Tedlar ™ bag
2. Pump SVE well for approximately 1 day
3. Monitor flowrate with Kurz™ insertion flow transmitter
4. Monitor vacuum at wellhead
5. Collect soil gas sample at wellhead sample port after one hour of operation and after twenty-four hours.
6. Measure vacuum in the other eleven SVE wells using digital manometer immediately before terminating the test.

Well Performance

Baseline SVE testing was performed using a portable, trailer mounted SVE unit with a maximum capacity of 355 mm Hg (14 in. Hg) vacuum and flow of 3,483 standard liters per minute (slpm) (123 scfm) powered by a portable generator. A 50 mm (2 in.) diameter flexible hose was used to connect to the SVE wells. Vacuum pressure was measured from a direct reading vacuum gauge located at the well head.

Flow rates varied greatly during the baseline testing ranging from 8 slpm (<1 scfm) to 3,483 slpm (123 scfm). The average specific capacity (flowrate/applied vacuum) for Zone B wells of 23 slpm/mmHg was higher than the specific capacity for the Zone D wells, 2 slpm/mmHg (Table 1). The difference in specific capacity between the upper and lower zones can be attributed to differences in lithology, length of screened interval, and soil moisture. The deeper wells are screened through highly layered sediments in the capillary fringe and beneath the water table. As a result, the "effective length" of these well screens depends on the depth to water.

Cross-section A – A' (Figure 8) illustrates the interbedded sands and clays in the L well screen interval. The interbedding along with the variations in effective screen length, and increased soil moisture in the capillary fringe reduce specific capacity for deeper wells. The shallow wells are screened primarily in Zone B that has a more uniform thickness and is less heterogeneous than the deeper screen interval resulting in less variability in the specific capacity for the shallow wells.

Contaminant Recovery

Vapor samples were collected from each of the SVE wells during baseline testing and analyzed for CVOC using gas chromatography. Varying amounts of TCE, PCE, CCl_4, $CHCl_3$, and cis-1,2-dichloroethylene (c-DCE) were detected in the samples (Table 1). TCE and PCE concentrations were consistently less than in samples collected during the CPT with the exception of well TVX-7L. The lower CVOC concentrations from the wells can be attributed to the larger soil gas sample zone. Samples collected from wells are collected from a screen that is 3 to 6 meters (10 to 20 ft.) in length compared to the CPT soil gas sampling port length which is only 0.2 m (0.6 ft.) in length, so mixing of varying soil gas concentration occurs.

SVE well TVX-7L had the highest concentration of individual CVOCs during the baseline test, but had the lowest flow rate at 8.5 slpm (0.3 scfm). Because of the low flow rate, it will probably not be productive for contaminant removal. The higher concentration in TVX-7L may be the result of diffusion from fine grained sediments where residual CVOCs are present and it is expected that the higher concentrations will drop quickly during active SVE because of the slow diffusion rate. The baseline test for well TVX-7L lasted for only one hour due to the very low specific capacity of the well. Additional tests will be performed on TVX-7L to determine if higher flow rates can be achieved by development from pumping and if the higher concentrations can be sustained over a longer period of time.

Zone of Influence

Estimating the ZoI produced by an SVE well network is a common method for designing vapor extraction systems. The ZoI is the volume of soils that is subjected to a vacuum that exceeds a predetermined critical vacuum to ensure containment of contaminated vapors. A critical vacuum is established by monitoring subsurface gas pressure to determine the nominal magnitude of natural variations resulting from diurnal changes in atmospheric pressure. Results from previous studies at TNX show that natural diurnal variations in subsurface pressure are approximately 2 to 3 cm H_2O (0.8 to 1.2 in. H2O), (Nichols, 1997). Based on this result and presence of highly interbedded sands and clays, particularly in zone D, a conservative critical vacuum of 25 cm H_2O (9.8 in H2O) was selected. Contour maps were constructed to show the ZoI for each well. Baseline test data for TVX-5U and TVX-5L are shown as examples of vacuum drawdown maps (Figure 13). A digital manometer vented to the atmosphere was used to measure vacuum in surrounding SVE wells during each test to measure individual well vacuum drawdown (Table 2). In general, the shallow wells have larger zones of influence than the deeper wells as would be expected based on the average specific capacities and lithologic characteristics.

An alternative method to design an SVE well field is to determine the Zone of Capture (ZOC). The ZOC is based on pore-gas velocity calculations using permeability test data. The critical pore-gas velocity can be defined as the minimum pore-gas velocity necessary to produce timely remediation (Digiulio and Varadham 2001). If vapor containment is the objective, a ZoI based approach is sufficient; however if vapor collection is the objective, a ZOC approach may be more appropriate.

Vacuum drawdown results (Table 2) indicate the ZoI propagates across zone C, which is a confining unit separating zones B and D. The propagation of vacuum across zone C does not necessary result in soil vapor flow across zone C. High vacuum in fine grain sediment as found in zone C will only produce low soil vapor flow at best while even a low vacuum in course gain sediment can produce high soil vapor flow. This exemplifies why it is important to have a through understanding of the stratigraphy when designing an SVE system.

The concrete foundation of Building 672-T which lies in the center of the area of contamination, acts as a surface seal to prevent short circuiting of atmospheric gas into the subsurface. Test results for TVX-5U and TVX-5L are shown in Figure 12. Testing on well TVX-5U demonstrates the positive effect that a surface seal has on the ZoI. TVX-5L, which is in the much less permeable zone D, has a much smaller ZOI. Results from the other baseline tests show the same relationship between shallow and deeper wells during individual well tests (Table 2). Based on the results of the baseline testing and previous studies, sets of 2 to 3 extraction wells will be treated with SVE on one month intervals. This will allow continuous operation of the SVE and give individual wells up to 3 months to rebound between treatments. This method of operation is intended to maximize contaminant recovery from individual wells and reduce the overall capital investment and operating cost for the system.

Summary and Conclusions

The TNX SVE case study is an example of integrating innovative and baseline characterization for cost effective remedial SVE testing. An understanding of the subsurface geology in Coastal Plain sediments and the associated heterogeneities in the sands and clays is the first step to an effective system design. Understanding the vadose zone soil properties allowed proper well design and construction materials that would minimize clogging and smearing of the well screen and maximize vapor recovery. Combining knowledge of the subsurface with depth discrete headspace sample data and soil vapor sample data minimized the size of the SVE well network and associated equipment. Understanding the specific capacities and relationships between the shallow and deeper wells assisted in delineating the areal and vertical extent of ZoI and the distribution of CVOCs concentrations in the subsurface. This study provides an example of the importance of integration of geology and engineering for designing and testing a successful remedial system. The overall remedial strategy combined with cost effective implementation has produced an effective and simplified system both technically and financially.

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Figure 1: Location of the TNX facility at the Savannah River Site

Figure 2: Hydrostratigraphic section for the shallow groundwater system at TNX

Figure 3: Typical contaminant profile beneath the TNX facility

Figure 4: Results from a vadose zone pumping test performed at TNX

Figure 5: Results from real-time sensor (B&K) and grab samples from SVE emissions

Figure 6: Rebound test results for TCE in SVE well TVM-1U and TVM-4U

Figure 7: CPT Soil Gas Locations and Location of Cross-Sections A-A’

Figure 8: Cross-section A-A’ with CPT soil gas TCE results and SVE screen zones. Location of Cross-Section A–A’ shown on Figure 7

Figure 9: TCE Concentration Contour Map

Figure 10: Location of Soil Vapor Extraction Wells

Figure 11: SVE Well Installation using Direct Push Technology

Figure 12: Shutter (Louver) screen used for SVE wells to prevent clogging and smearing during installation

Figure 13: Contour Map of Zone of Influence during Baseline Test at TVX-5L and TVX-5U

Table 1: Flow rate, vacuum, specific capacity and contaminant concentrations from baseline tests

Table 2: Vacuum (cm H_2O) recorded during baseline testing to determine Zone of Influence for each SVE well

Fig. 1

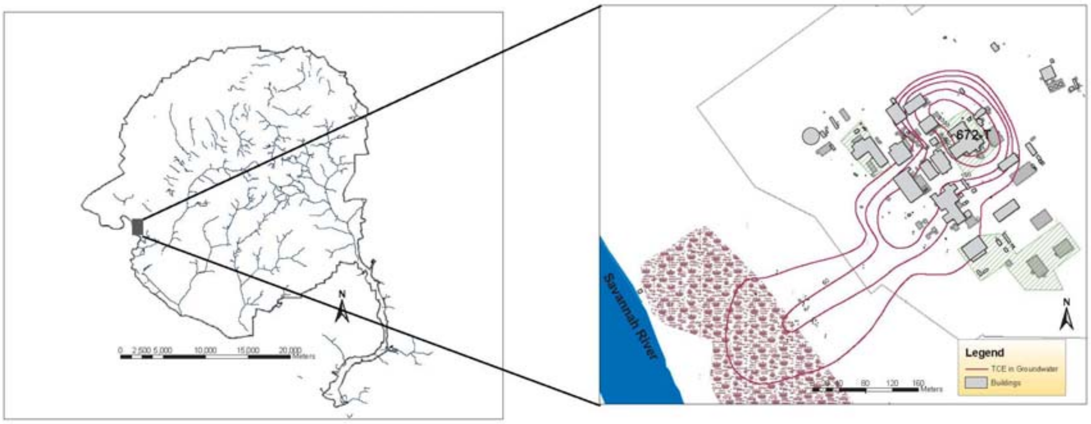

N
0 2,500 5,000 10,000 15,000 20,000
Meters
672-T
Savannah River
N
Legend
TCE in Groundwater
Buildings
40 80 120 160
Meters

Fig. 2

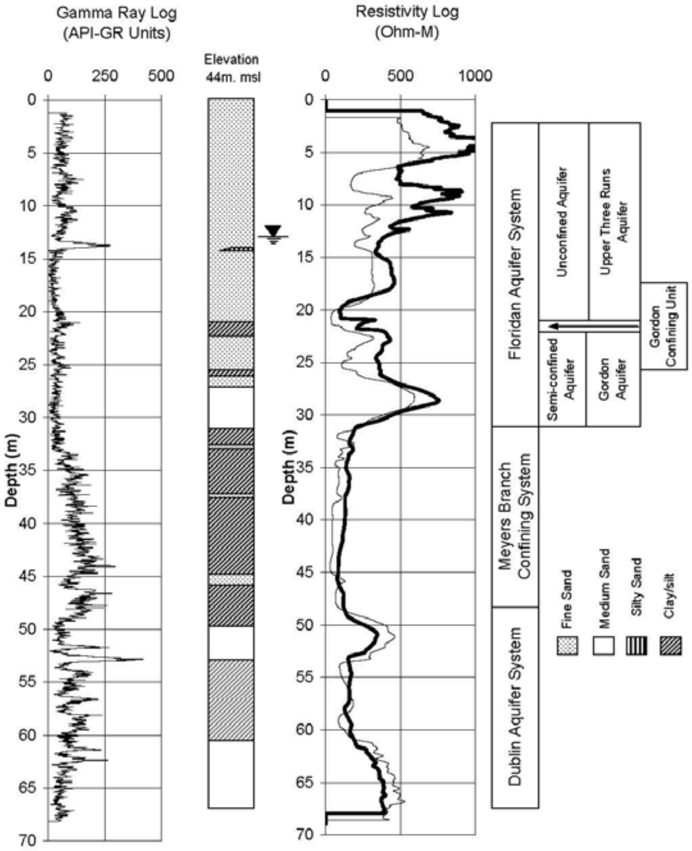
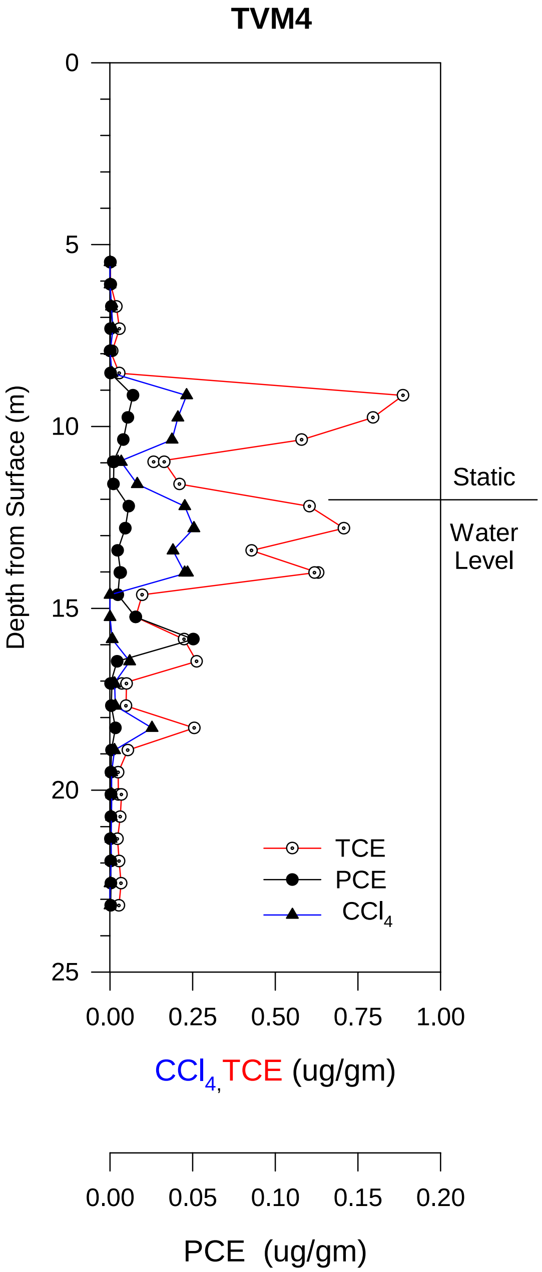

Gamma Ray Log
(API-GR Units)
0
250
500
Depth (m)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
Elevation
44m. msl
Resistivity Log
(Ohm-M)
0
500
1000
Depth (m)
Floridan Aquifer System
Unconfined Aquifer
Upper Three Runs Aquifer
Gordon Confining Unit
Semi-confined Aquifer
Gordon Aquifer
Meyers Branch Confining System
Dublin Aquifer System
Fine Sand
Medium Sand
Silty Sand
Clay/silt

Fig. 3



TVM4
Depth from Surface (m)
0
5
10
15
20
25
0.00
0.25
0.50
0.75
1.00
CCl4, TCE (ug/gm)
0.00
0.05
0.10
0.15
0.20
PCE (ug/gm)
TCE
PCE
CCl4
Static
Water
Level

Fig. 4

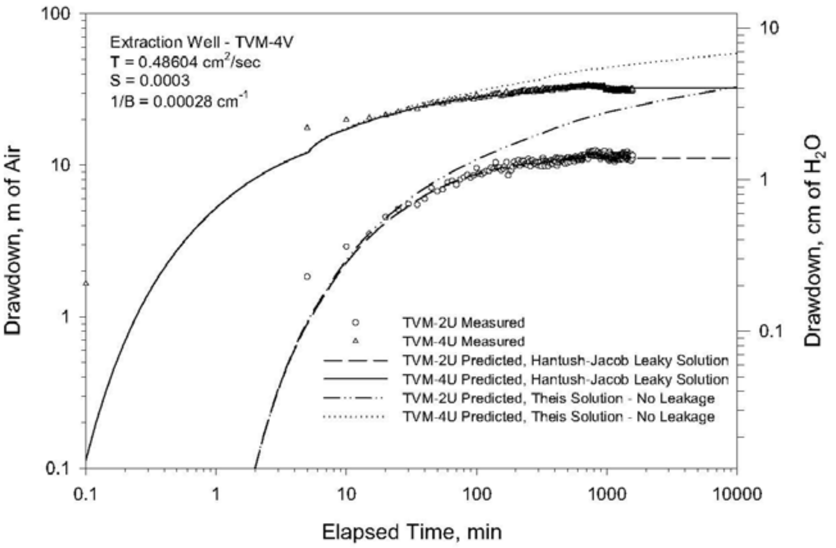
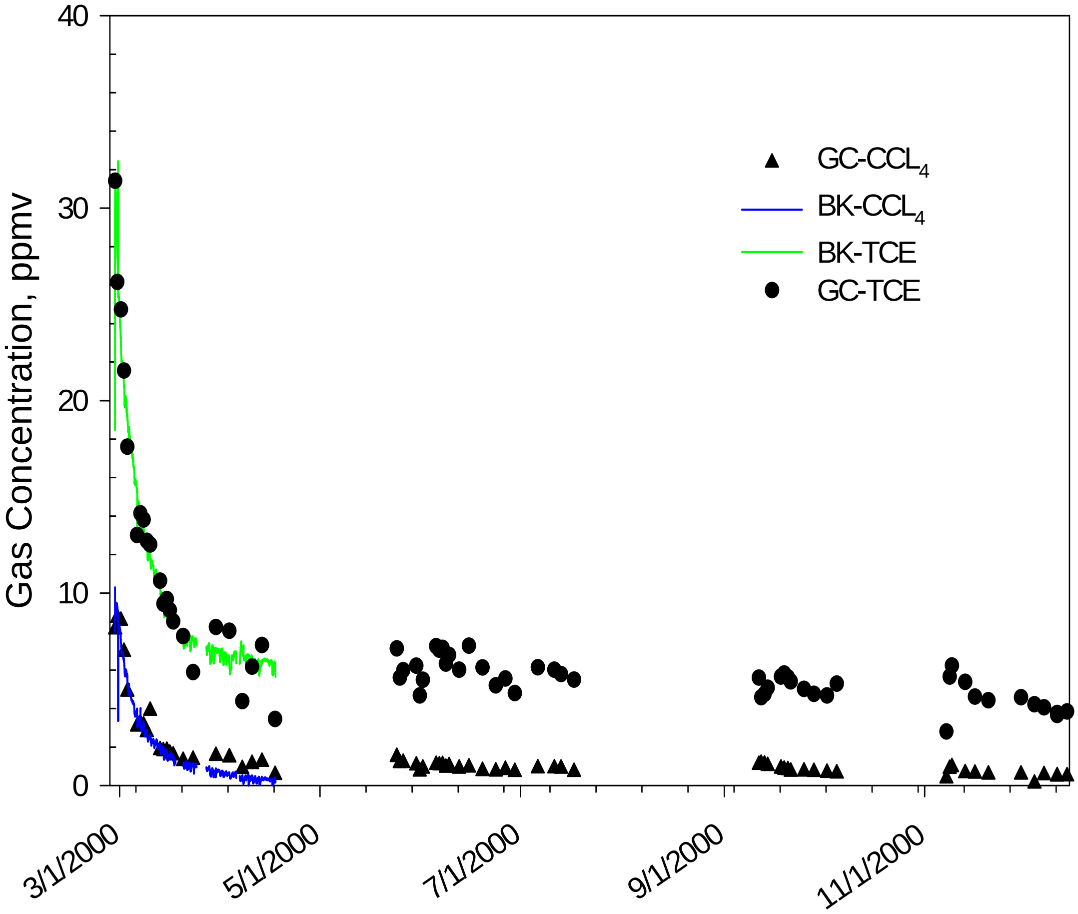
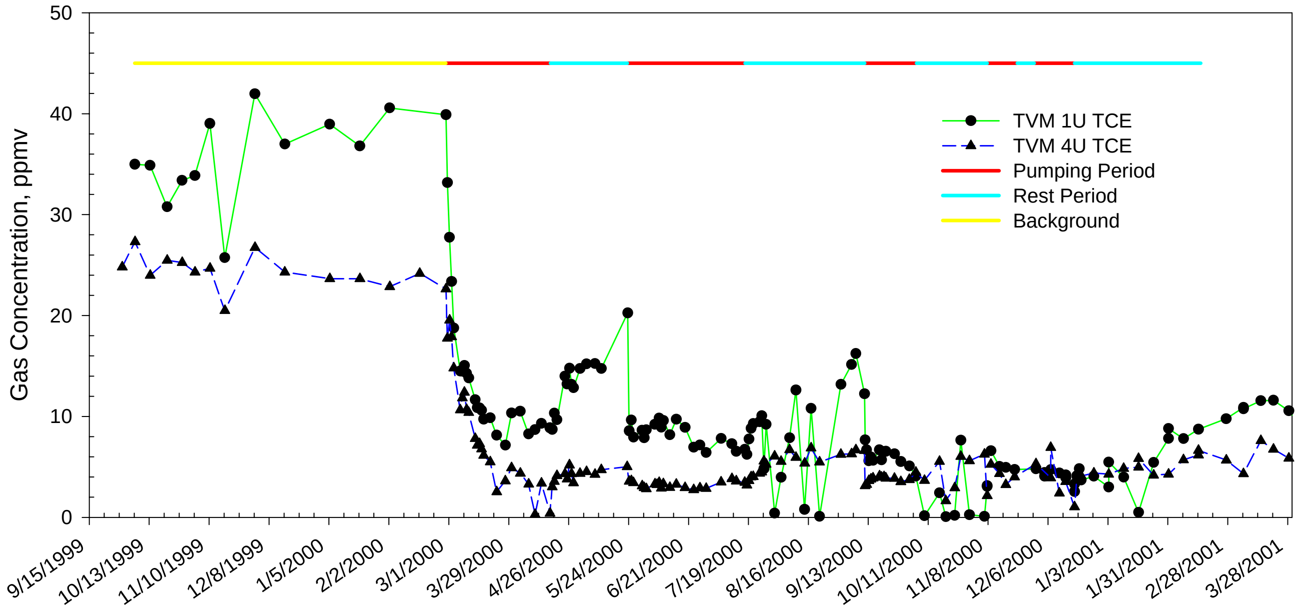

Extraction Well - TVM-4V
T = 0.48604 cm²/sec
S = 0.0003
1/B = 0.00028 cm⁻¹
Drawdown, m of Air
Drawdown, cm of H₂O
Elapsed Time, min
100
10
1
0.1
0.1
1
10
100
1000
10000
TVM-2U Measured
TVM-4U Measured
TVM-2U Predicted, Hantush-Jacob Leaky Solution
TVM-4U Predicted, Hantush-Jacob Leaky Solution
TVM-2U Predicted, Theis Solution - No Leakage
TVM-4U Predicted, Theis Solution - No Leakage

Fig. 5



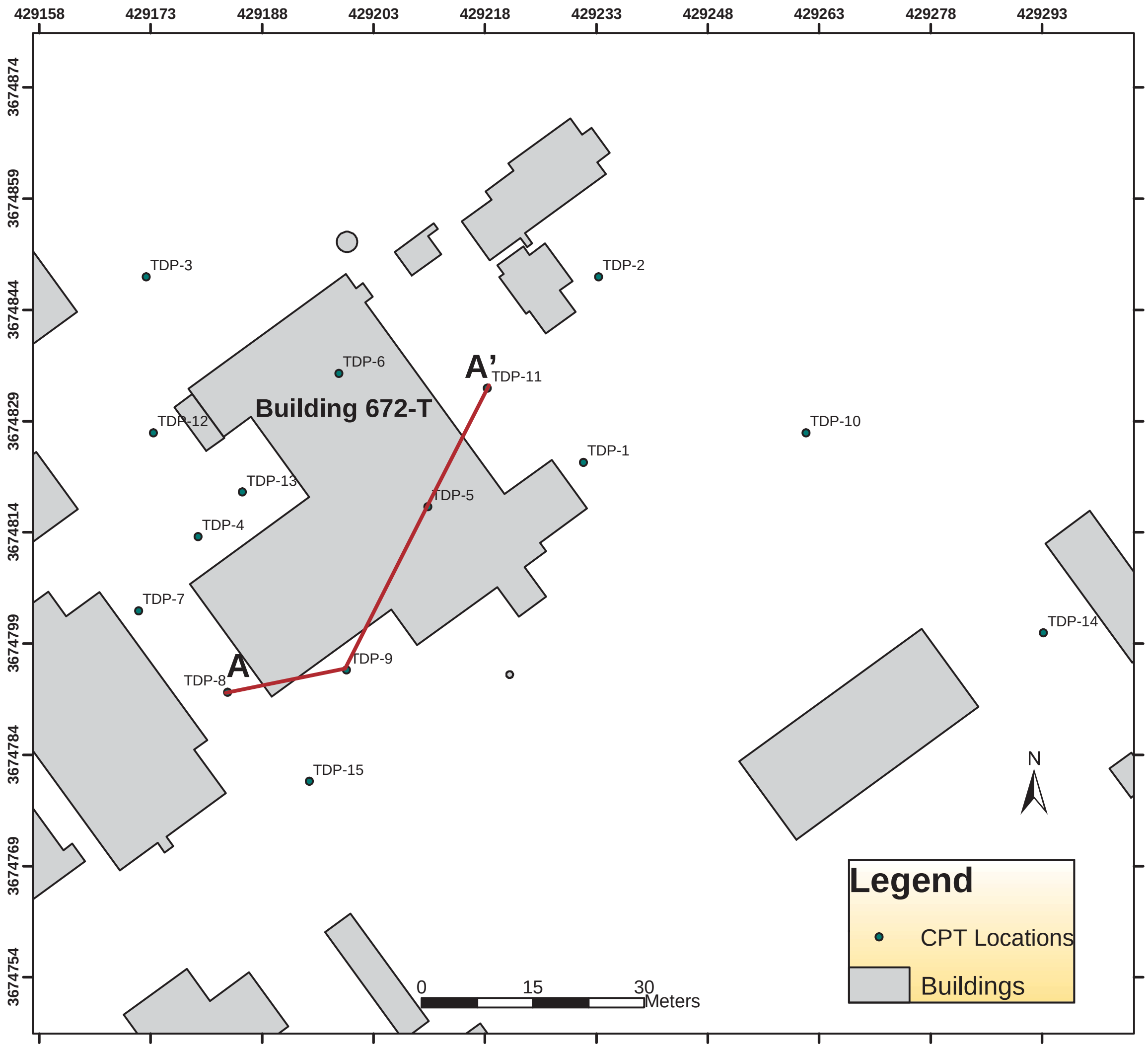
Gas Concentration, ppmv
0
10
20
30
40
3/1/2000
5/1/2000
7/1/2000
9/1/2000
11/1/2000
▲ GC-CCL_4
BK-CCL_4
BK-TCE
● GC-TCE

Fig. 6



Gas Concentration, ppmv
0
10
20
30
40
50
9/15/1999
10/13/1999
11/10/1999
12/8/1999
1/5/2000
2/2/2000
3/1/2000
3/29/2000
4/26/2000
5/24/2000
6/21/2000
7/19/2000
8/16/2000
9/13/2000
10/11/2000
11/8/2000
12/6/2000
1/3/2001
1/31/2001
2/28/2001
3/28/2001
TVM 1U TCE
TVM 4U TCE
Pumping Period
Rest Period
Background

Fig. 7



429158
429173
429188
429203
429218
429233
429248
429263
429278
429293
3674874
3674859
3674844
3674829
3674814
3674799
3674784
3674769
3674754
TDP-3
TDP-2
TDP-6
A'
TDP-11
Building 672-T
TDP-12
TDP-10
TDP-1
TDP-13
TDP-5
TDP-4
TDP-7
TDP-14
A
TDP-9
TDP-8
TDP-15
N
Legend
CPT Locations
Buildings
0
15
30
Meters

Fig. 8

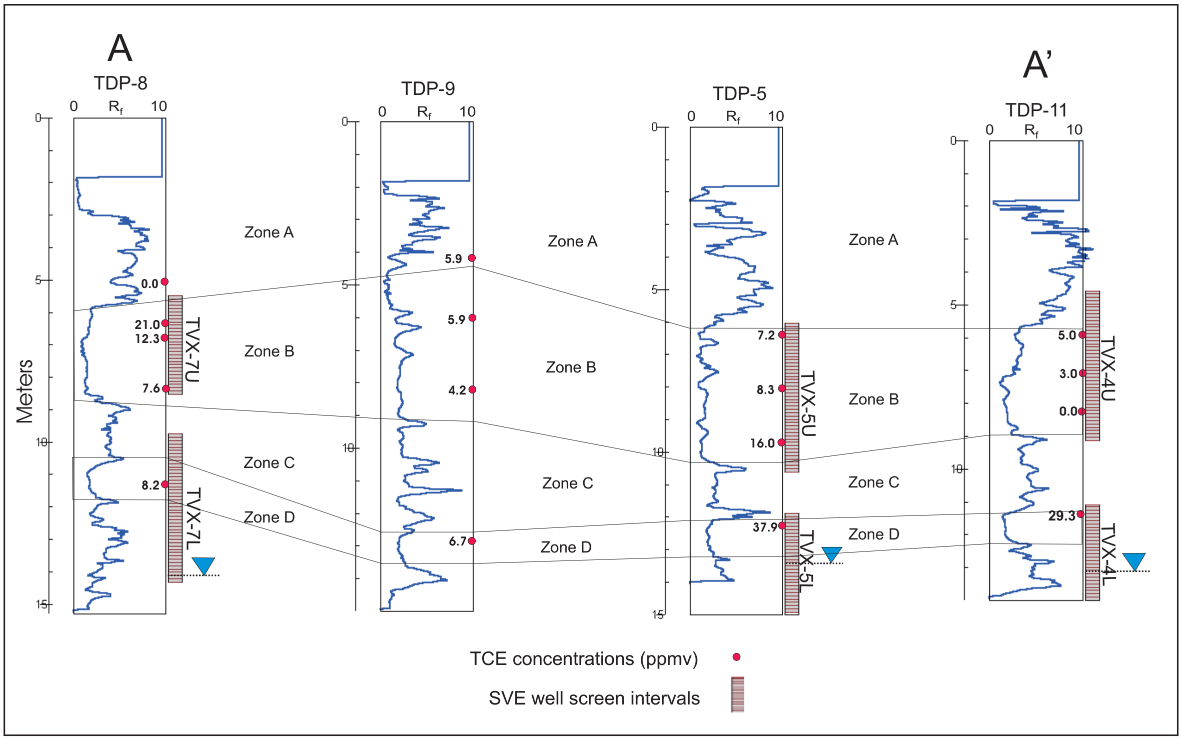

A
A’
TDP-8
TDP-9
TDP-5
TDP-11
0 Rf 10
Meters
0
5
10
15
Zone A
Zone B
Zone C
Zone D
TVX-7U
TVX-7L
TVX-5U
TVX-5L
TVX-4U
TVX-4L
0.0
21.0
12.3
7.6
8.2
5.9
5.9
4.2
6.7
7.2
8.3
16.0
37.9
5.0
3.0
0.0
29.3
TCE concentrations (ppmv) ●
SVE well screen intervals ▤

Fig. 9

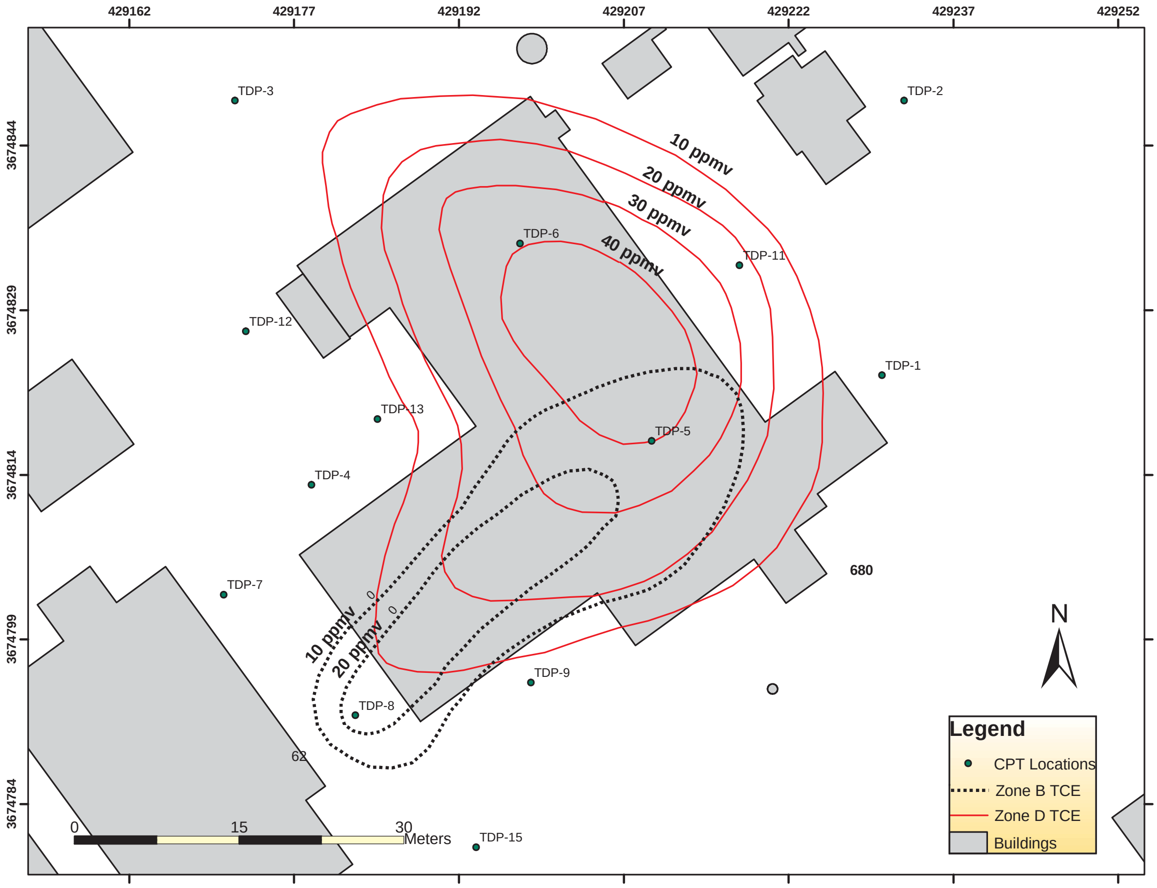

429162
429177
429192
429207
429222
429237
429252
3674844
3674829
3674814
3674799
3674784
TDP-3
TDP-2
10 ppmv
20 ppmv
30 ppmv
40 ppmv
TDP-6
TDP-11
TDP-12
TDP-1
TDP-13
TDP-5
TDP-4
680
TDP-7
0
0
10 ppmv
20 ppmv
N
TDP-9
TDP-8
62
0
15
30
Meters
TDP-15
Legend
CPT Locations
Zone B TCE
Zone D TCE
Buildings

Fig. 10

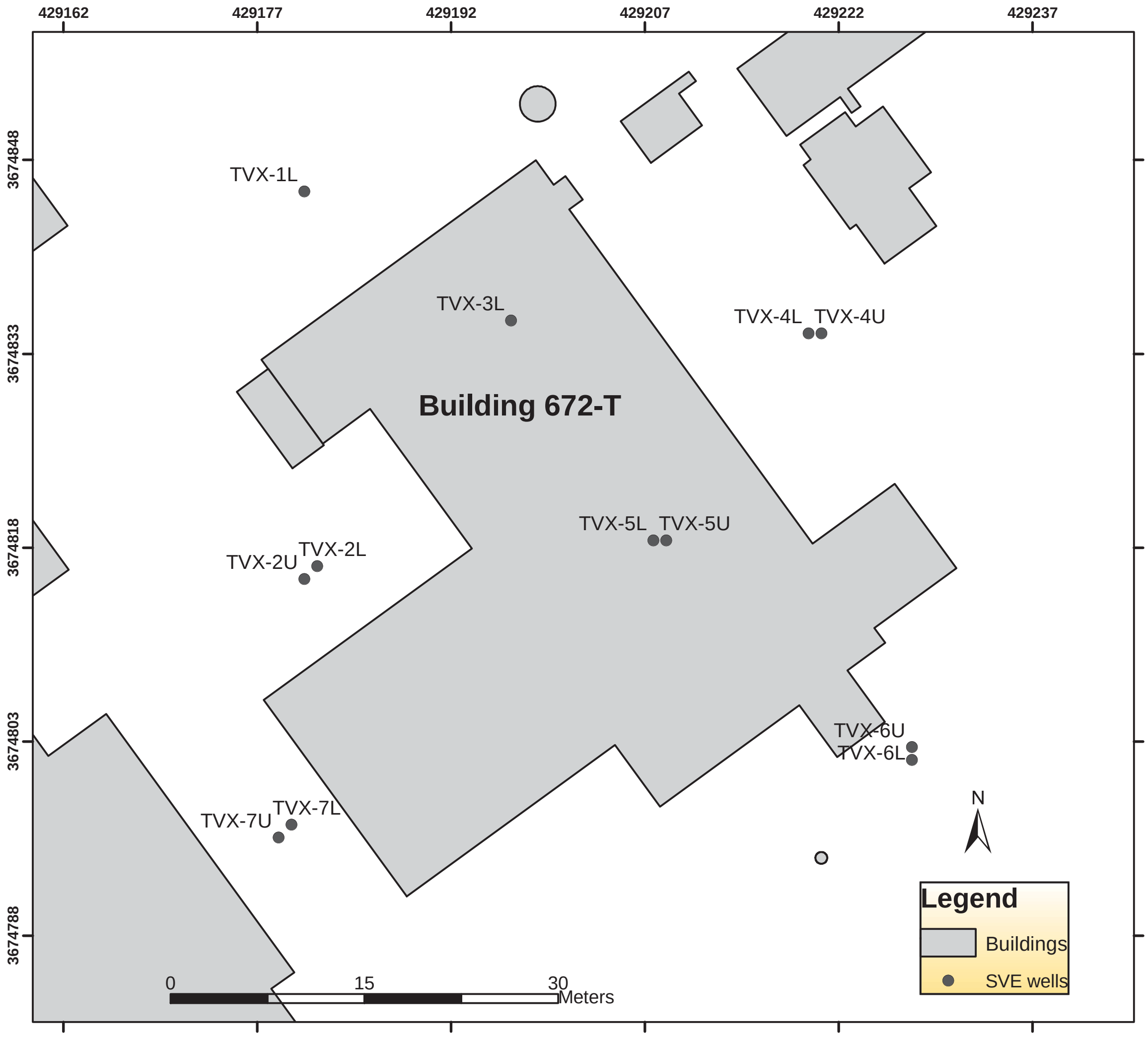

429162
429177
429192
429207
429222
429237
3674848
3674833
3674818
3674803
3674788
TVX-1L
TVX-3L
TVX-4L
TVX-4U
Building 672-T
TVX-5L
TVX-5U
TVX-2U
TVX-2L
TVX-6U
TVX-6L
TVX-7U
TVX-7L
N
Legend
Buildings
SVE wells
0
15
30
Meters

Fig. 11

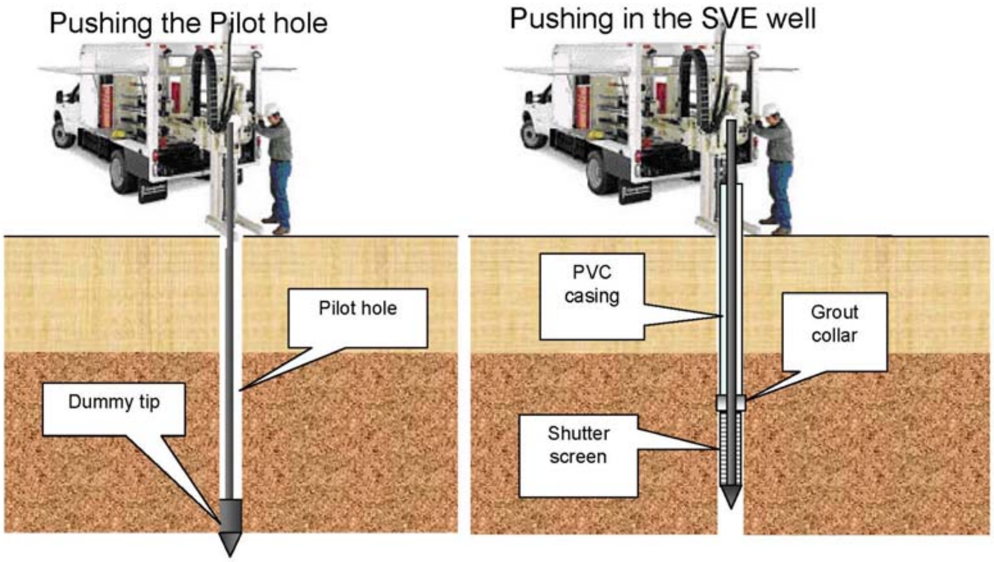

Pushing the Pilot hole
Pilot hole
Dummy tip
Pushing in the SVE well
PVC casing
Grout collar
Shutter screen

Fig. 12

Fig. 13

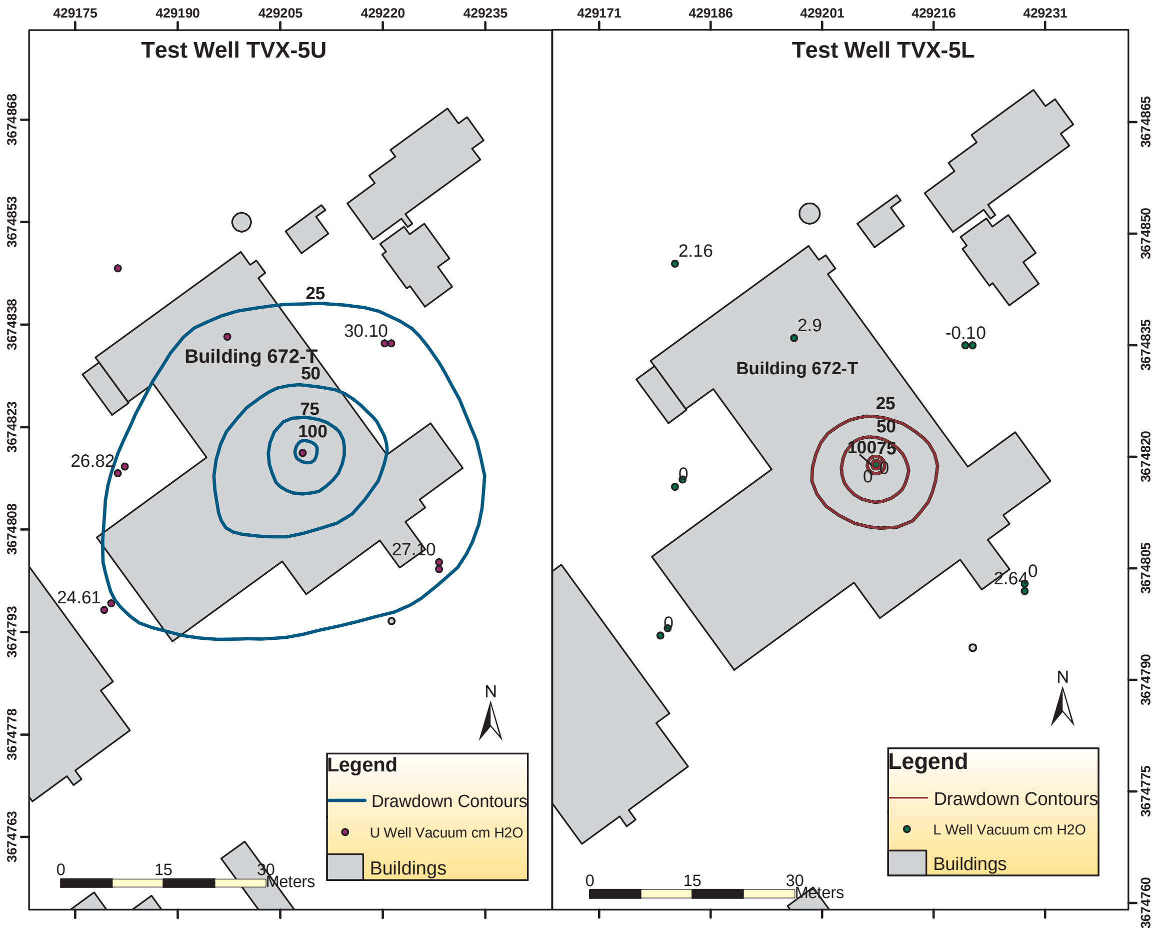

Test Well TVX-5U
Test Well TVX-5L
Building 672-T
Building 672-T
25
50
75
100
30.10
26.82
27.10
24.61
2.16
2.9
-0.10
2.64
0
10075
Legend
Drawdown Contours
U Well Vacuum cm H2O
L Well Vacuum cm H2O
Buildings
0
15
30
Meters
N
429175
429190
429205
429220
429235
429171
429186
429201
429216
429231
3674868
3674853
3674838
3674823
3674808
3674793
3674778
3674763
3674865
3674850
3674835
3674820
3674805
3674790
3674775
3674760

Table 1

SVE well	flow rate (slpm)	vacuum (mm Hg)	specific capacity (slpm/ mm Hg)	TCE (ppmv)	CCl_4 (ppmv)	PCE (ppmv)	$CHCl_3$ (ppmv)	C-DCE (ppmv)
TVX-1L	620.1	276.1	2.2	0.8	<0.1	<0.1	<0.1	<0.1
TVX-2L	1500.8	213.4	7.0	1.4	0.1	0.4	<0.1	<0.1
TVX-2U	1424.3	123.0	11.6	0.5	0.1	0.1	<0.1	<0.1
TVX-3L	147.2	288.7	0.5	6.9	<0.1	<0.1	<0.1	<0.1
TVX-4L	407.8	293.7	1.4	10.8	<0.1	<0.1	<0.1	<0.1
TVX-4U	1925.5	208.3	9.2	2.3	<0.1	0.0	<0.1	<0.1
TVX-5L	192.6	281.1	0.7	8.4	<0.1	0.7	<0.1	2.0
TVX-5U	3284.8	90.4	36.4	1.8	0.1	<0.1	<0.1	<0.1
TVX-6L	218.0	326.3	0.7	6.2	<0.1	<0.1	<0.1	<0.1
TVX-6U	2373.0	125.5	18.9	0.2	<0.1	<0.1	<0.1	<0.1
TVX-7L	8.5	288.7	<0.1	62.5	27.7	0.6	1.6	19.1
TVX-7U	3502.8	110.4	31.7	1.9	0.2	0.2	<0.1	<0.1

Table 2

Well Name	Test well TVX-7U	Test well TVX-7L	Test well TVX-5U	Test well TVX-5L	Test well TVX-3L	Test well TVX-1L	Test well TVX-2U	Test well TVX-2L	Test well TVX-6U	Test well TVX-6L	Test well TVX-4U	Test well TVX-4L
TVX-1L	16.99	*	19.86	2.16	3.25	test well	7.01	10.69	8.89	0.97	11.63	2.16
TVX-2L	29.85	*	27.13	2.64	3.18	5.59	12.93	test well	11.76	1.35	12.73	2.39
TVX-2U	31.60	*	26.82	2.62	3.15	5.59	test well	17.73	11.79	1.35	12.78	2.36
TVX-3L	19.48	*	28.17	2.90	test well	7.59	8.59	14.86	12.14	1.37	16.71	3.15
TVX-4L	-0.03	*	-0.18	-0.20	-0.03	-0.18	-0.10	-0.05	1.14	-0.91	0.15	test well
TVX-4U	16.84	*	30.10	2.95	3.15	4.75	6.17	8.92	15.19	1.68	test well	5.84
TVX-5L	23.80	*	41.00	test well	3.30	5.16	8.48	13.06	15.57	1.80	19.76	3.89
TVX-5U	24.18	*	test well	3.53	3.23	5.00	8.36	12.47	16.46	1.83	19.61	3.40
TVX-6L	19.38	*	28.12	2.64	2.92	4.11	5.97	9.83	19.71	test well	14.91	2.95
TVX-6U	19.91	*	27.10	2.46	2.82	3.84	5.51	8.99	test well	2.06	15.04	2.90
TVX-7L	-0.58	*	14.99	1.37	2.01	3.84	7.26	15.60	6.65	0.81	5.79	1.09
TVX-7U	test well	*	24.61	2.16	2.74	4.34	10.21	13.79	11.86	1.37	11.18	2.06

*** no vacuum measures were recorded**