Characterizing DNAPL Contamination and Vapor Intrusion in Dayton, Ohio

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ABSTRACT

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Vapor intrusion originating from volatilized organic compounds (VOCs) represents a growing concern for toxic chemical exposure to the public. Volatile nature of VOCs poses a threat for potential upward migration of toxic chemical fumes to intrude into buildings above this contamination. In southwestern Ohio, there exists a former manufacturing facility which housed underground storage tanks containing VOCs such as trichloroethylene (TCE), perchloroethylene (PCE), and chloroform. Some of these underground storage tanks leaked before they were removed in 1989, and this contaminated the soil and groundwater endangering the residences in the area of contamination. This study aimed to investigate the extent of DNAPL contamination in the sub-surface and vapor intrusion in residential homes by using geological, hydrogeological, and geochemical data collected by the Ohio EPA and US EPA .

Geologic cross-sections of the aquifer were created using 4 geologic well logs available in the area. Hydraulic head measurements from 13 monitoring wells, VOC sampling data from 13 monitoring wells, and 29 soil vapor sample sites were analyzed to create potentiometric surface maps and contaminant groundwater and soil vapor plume maps for PCE, TCE, and chloroform. Probable source areas for each of the contaminants were determined to be in the eastern portion of the facility based on these contour maps. Vapor intrusion sampling data from residences near the study site was analyzed to assess

the effectiveness of mitigation systems in residences, and the attenuation factors for each of the contaminants were determined by comparing baseline sub-slab concentrations to their relative indoor air baseline concentrations. PCE was found to have experienced the least attenuation with 0.028 of its sub-slab concentration moving indoors. Chloroform had an attenuation rate of 0.007, and TCE indoor air concentrations were decreased to 0.003 of their sub-slab concentrations. Bulk mass flux of TCE was estimated to have been between 2.15×10^{-8} mol/m²/s and 5.65×10^{-7} mol/m²/s in 4 residences near the facility. High attenuation rates for VOC migration into these residences coupled with effective mitigation systems showed a relatively low risk for harmful vapor intrusion exposure to residents overall.

The lack of groundwater contamination in the area that experienced the most severe VI contamination suggested that vapor intrusion risk cannot be directly attributed to groundwater contamination. In contrast, soil vapor contamination was suggested to more directly responsible for VI risk in homes. While it is suggested that sub-surface contamination east of the facility was due to migration of dissolved DNAPL plume, sufficient historic groundwater sampling data was not available to make a conclusive determination. It is suggested that DNAPL contamination still exists east of the UST facility given the detection of 4,300 ppbv of PCE and 1,200 ppbv of TCE in soil vapor sampling done in 2016.

DEDICATION

To my dearest family and friends. I could not have done this without your love and support.

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1. INTRODUCTION

1.1 Statement of Problem

Contaminants in groundwater are classified based upon some distinguishing physical or chemical characteristics. The term dense nonaqueous phase liquids, or DNAPLs, describe a group of chlorinated hydrocarbon liquids that have a specific gravity greater than water (Huling and Weaver, 1991). Certain DNAPLs, such as trichlorethylene (TCE) or tetrachloroethylene (PCE), are also considered to be volatile organic compounds (VOCs) due to their high vapor pressures (Costelloe-Kuehn, 2016). Because of their high vapor pressures, VOCs can evaporate faster than other types of liquid contaminants. Fast evaporation rates thus lead to a potential pathway for vaporization of these contaminants to intrude into the overlaying soil and structures above.

Vapor intrusion (VI) describes this upward migration of VOC vapors from contaminated soils or groundwater (Beckley, Mchugh, and Philp, 2016). Concern about VI into residential homes overlaying VOC contaminated groundwater has become an increasingly important issue. Before the early 1990s, VI research specifically focused on radon emissions (Bozkurt, Pennell, and Suuberg, 2009). Since then, VI was recognized as a significant source of toxic substance exposure from a wider variety of contaminants, and the EPA has released multiple guidelines for evaluating the potential for VI from contaminated groundwater and soils (Dawson and Kapuscinski, 2012).

Effective characterization of VI pathways has proven to be a difficult task due to many factors affecting VI intrusion rates and attenuation. For example, VOC concentrations tend to attenuate, or decrease, as they move from their source through the

overlaying soil and air (Abreu and Schuver, 2012). This would lead to different VOC concentration reading as the contaminant progresses through different media. In regards to indoor air concentrations, the attenuation in VOC concentration can be attributed to the mixing of VOC emissions in a building with its natural airflow (Abreu and Schuver, 2012).

The extent of attenuation may depend on a number of factors such as: (i) subsurface features that hinder the diffusion or advection of VOCs, (ii) biodegradation of contaminants which lead to a decrease in emissions along the pathway, (iii) the integrity of the foundation and walls, (iv) changes in groundwater properties with time, (v) pressurization of the building, or (vi) air exchange in the building (Abreu and Schuver, 2012). Given the large number of influences on VOC emission concentrations in a building, it can be difficult to gain an accurate assessment for VI risk. The US EPA has suggested to use a combination of field data, modeling, and general site information to assess the potential for VI risk (Yao, Pennell, and Suuberg, 2011). Therefore, many investigations of VI are site-specific in combining known pathways of VI with relevant site information.

1.2 Objective of Study

The DNAPL plume originated from a Delphi Automotive Plant that manufactured vehicle engine mounts and brake parts, and it was caused by leaks in underground storage tanks containing PCE, TCE, and chloroform, (Renninger, 2009). Multiple investigations have taken place in this area from both governmental agencies such as the US EPA in addition to private environmental consulting firms hired by the Delphi Corporation.

Objectives of this study were to: (i) identify sources of DNAPL contamination at the site, (ii) characterize the geological and hydrogeological settings of the surrounding area, (iii) delineate the groundwater plume migration, (iv) characterize organic vapor distribution and migration in the soil, (v), investigate VI intrusion pathways and attenuation, and (vi) assess the impact of vapor abatement mitigation systems installed in the residences affected by the Delphi VOC plume through analyses of available field and analytical data obtained from the Ohio EPA. It is hypothesized that through completion of this study, there will be evidence that residual DNAPL contamination still exists in the subsurface despite source removal and mitigation action.

2. BACKGROUND

2.1 Dense Nonaqueous Phase Liquids (DNAPLs)

Contamination of groundwater and soils by dense non-aqueous phase liquids (DNAPLs) has long been a topic of concern in the environmental realm. Certain chemical properties in DNAPLs, such as low solubility and a high specific gravity, make locating them in the subsurface difficult at times (Steimle, 2004). Remediation of DNAPL contamination in groundwater or soils can thus be challenging in just locating the extent of the problem which may in turn lead to longer contamination periods.

DNAPL contamination pathways can be difficult to follow due to the different ways it can react in the environment. As shown in figure 1, DNAPLs in the unsaturated zone can be present in four different phases: water, air, soil, and immiscible (Huling and Weaver, 1991). Accounting for all the possible media the contaminant may be present in would be a meticulous task before any remediation could occur.

Figure 1. Illustration of the four phases of DNAPL contamination in the unsaturated zone (Huling and Weaver, 1991).

There are multiple approaches in remediating DNAPL contaminated groundwater and soil sites. The US EPA has identified multiple techniques to treat DNAPL sources such as in situ thermal treatment, in situ chemical oxidation, surfactant/co-solvent flushing, groundwater recirculation, and in situ bioremediation (Steimle, 2004). Each of these techniques use different methods in treating DNAPL contamination. For instance, contaminants treated with in situ thermal technologies are subjected to intense heat in the source zone to volatilize or mobilize the DNAPL (Steimle, 2004). Application of a specific technique would depend upon the environmental factors of the site as well as how the chemical may react to the treatment.

Most DNAPLs are VOCs which can further complicate their remediation. VOCs evaporate more easily compared to water due to their high vapor pressure (Chen et al., 2014). When these chemicals leak into the environment due to improper disposal or storage, they can be dispersed along multiple pathways in soil and groundwater (Figure 2).

Figure 2. Possible contaminant pathways of a DNAPL contaminants in soil and groundwater as dissolved and vapor-phase plume (Kueper and Davies, 2009).

In regards to this study, three different VOCs are present in the Delphi VOC plume: trichloroethylene (TCE), tetrachloroethylene (PCE,) and chloroform (trichloromethane). Trichloroethylene and PCE are used in various industrial processes as solvents, and chloroform exists in the environment as a byproduct of adding chlorine to drinking water as well as in factories that use the chemical (Kollman and Frey, 2008). Leaking storage tanks of these chemicals can contaminate groundwater, soils, and the air due to their soluble and volatile nature.

Vapor intrusion (VI) of these chemicals can pose a serious health risk depending upon the level of exposure. While the low levels of TCE, PCE, and chloroform at the study site do not appear to be a danger for short-term health, some of the residences do have indoor concentrations that can pose a long-term health danger or cause cancer from chronic exposure (Kollman and Frey, 2008). Residents living above VOC plume thus had reason for concern of contamination. Other studies of VOCs around the country have

further shown that exposure to these chemicals can be hazardous to the skin, central nervous system, liver, and kidney (Chen et al., 2014). Future study of the pathways for this exposure should increase in time as more people become aware of the potential danger of VI.

2.2. Vapor Intrusion

Vapor intrusion describes the upward movement of organic vapors from contaminated groundwater or soils into the structures above (Beckley et al., 2016). Characterization of VI contamination is often challenging at times. Therefore, the US EPA has recommended using a multiple lines of evidence approach of analyzing field data, modeling, and geological information of a site (Pennell et al., 2016). Figure 3 shows an illustration of some pathways VI might follow into residential homes.

As depicted in figure 3 below, VOC gas emissions from contaminated soil and groundwater can intrude into building through a variety of pathways. Contaminant sources leaking from commercial or industrial buildings can leak into the sub-surface and contaminant soil and groundwater. Once a VOC contaminant reaches the sub-surface, volatilization can occur causing vapors to move upward through the soil. VI can then occur in the buildings above through cracks in their foundations, crawl spaces, or utility openings.

Figure 3. Illustration of multiple VI pathways into residential homes from a contaminant source (US EPA, 2015).

Quantifying VI levels can be difficult at times. For instance, many household items or chemicals contain organic compounds similar to contaminants in soil or groundwater which can distort indoor VI concentrations (Erdogan and Hsieh, 2014). If investigating multiple residences for VI, it may prove difficult or time-consuming in determining the household cleaners or products affecting indoor vapor readings in each home. It would be more prudent to complement direct measurements of indoor air concentrations with other information such as meteorological measurements and background sampling (Brenner, 2010). This multi-step approach may help better model

VI pathways into buildings since it can account for any distortion due to background contaminants or air fluctuations

Although testing indoor air may not give definitive results, it could still help identify whether or not there are VOCs present in a building (Beckley et al., 2016). Comparison of these indoor air samples with the allowable EPA indoor concentrations would also show whether there exists a health risk for building occupants. If an accurate model of VI pathways were to be developed, risk of VI in building could be more easily predicted. Equation 1 was used in a computer model to determine indoor air concentration (Bozkurt et al., 2009).

$$C_{\text{indoor}} = \frac{A_{\text{ck}}J_{\text{t}}}{A_{\text{e}}V_{\text{b}}+Q_{\text{ck}}} \quad (1)$$

Where: A_{ck} = Area of a foundation crack; J_{t} = bulk mass flux of a contaminant “i”; A_{e} = air exchange rate in the building; V_{b} = volume of the basement; Q_{ck} = soil-gas flow rate through the crack

2.2.1 Characterizing VI Risk

There are several factors that can reveal the risk of VI occurring in a building. For example, groundwater contamination directly below or within 100 feet of a building may be a trigger to initiate a VI investigation (Boyer et al., 2016). If the groundwater is contaminated with a VOC, there could also be contaminated soil from the volatilization of this VOC. Additionally, methane generating conditions that cause an oxygen deficient

environment may also lead to VI in a building's basement (Boyer et al., 2016). A wet basement or sump containing detectable levels of a contaminant may also trigger a VI investigation if the contaminant has the potential to vaporize (Boyer et al., 2016).

Therefore, multiple groundwater, soil, and indoor air measurements should be taken to properly determine if there is a risk of VI.

2.2.2. Determining VI Rates and Attenuation

Vapor intrusion is largely driven by differences in concentrations and pressure between contaminated areas in the subsurface and affected buildings above (Abreu and Schuver, 2012). When VOCs intrude into a structure, they may become attenuated due to a wide variety of reasons. For example, indoor air exchange rates can have a significant impact on the attenuation of chemical concentrations in a structure (Dawson and Kapuscinski, 2012). Indoor air exchange rates can vary from building to building, so it is important to note that site-specific investigations are required to quantify the air exchange rate of each building being investigated. Seasonal variations of heating and cooling in building operations can also have an effect on the attenuation of toxic chemical concentrations since this would affect the air circulation within a building (Dawson and Kapuscinski, 2012).

Subsurface conditions, building design and condition, and differentials in air pressure in the foundation of a building can all have impacts on the rate of VI (Dawson and Kapuscinski, 2012). With regards to subsurface conditions, higher concentrations of VOCs in the soil or groundwater would provide more opportunities for the volatilization of contaminants. Difference in the permeability of various layers of soil in the subsurface

may also restrict vapor migration from groundwater contamination sources (Boyer et al., 2016). Changes in groundwater level, source concentration, and infiltration rates can also affect VI within a building, and biodegradation of the contaminants along the VI pathway would also aid in the attenuation of the contaminant (Abreu and Schuver, 2012).

Background VOC levels can also play a significant role in the rate or attenuation of VI. When assessing VI, it is important to be aware of any indoor contamination sources such as consumer products, home furnishings, or building materials that may be contributing to indoor air concentration readings (Dawson and Kapuscinski, 2012). Any indoor sources emitting VOC vapors can distort readings into showing false positives for VI. Outdoor sources such as combustion processes may also infiltrate buildings which would also affect indoor air concentration readings for VI. Overall, there are many factors to account for when investigating VI rates or attenuation.

2.2.3. Existing VI Mitigation Methods

There are several existing VI mitigation techniques that are used to help reduce or prevent VI in buildings. For instance, removing the contaminated soil and groundwater can serve as a solution for VI (Mosley, Cody, Lutes, Doorn, and Frizzell, 2008). This method would directly solve the VI problem since it directly eliminates the source of the VI process. Another method of mitigating VI would be to eliminate the entry routes for VI into buildings (Mosley et al., 2008). Repairing damaged basements or foundations below a structure would help lessen the likelihood of VI occurring.

Another method in mitigating vapor intrusion in homes would be to install an active subsurface depressurization system. Specific types of active subsurface

depressurization systems include: Sub-slab Depressurization Systems (SSDS), Sub-Membrane Depressurization Systems, Block Wall Depressurization Systems, and Drain Tile Depressurization Systems (Boyer et al., 2016). These systems all work to apply a negative pressure field to vulnerable areas of a building in order to prevent VI into the building (Boyer et al., 2016). The technology in these systems is similar to the soil vapor extraction systems used in the Delphi VOC plume case.

2.3. VOC Plume Site in Dayton, Ohio

The Delphi VOC plume site resides in the city of Dayton, Ohio. Contaminants in the Delphi VOC plume originated from the Delphi facility located at 2701 Home Avenue in Dayton, and the plant specialized in the manufacturing of vehicle engine mounts and brake products (Renninger, 2009). General Motors was the original owner of the plant until the Delphi Corporation separated from GM to take ownership of the facility in 1999 (US EPA, 2007). With this transfer of ownership, Delphi assumed responsibility for the plant. However, in October 2005, the Delphi Corporation filed for bankruptcy (US EPA, 2007).

General Motors had originally kept volatile organic contaminants such as PCE, TCE, and chloroform in underground storage tanks until 1989 (US EPA, 2007). Leaks from these tanks or their pipelines in the past may be the primary reason for the existence of a VOC plume containing these contaminants in the soil and groundwater today. From 2005-2006, the Delphi Corporation conducted its own private investigation for the potential of VI from the VOC plume originating from their facility, and they found

elevated VOC soil gas concentrations (Renninger, 2009). These findings led to the subsequent involvement of the Ohio EPA and US EPA.

Figure 4. Map of Delphi facility in Dayton, Ohio outlined in blue with examples of homes affected by VI shown in green (Hull and Associates Inc., 2014a).

Beginning in 2007, the Ohio EPA and US EPA District 5 began working together to investigate the potential VI resulting from the leaked VOCs used at the Delphi facility (Renninger, 2009). Action levels developed from this investigation for residential indoor air screen levels found in the investigation are detailed in Table 1. As a result of this investigation, the Delphi Corporation was made to develop an action plan to mitigate VI in homes affected by the VOC plume (Renninger, 2009). Based on the results of this investigation, the Delphi Corporation had to pay for sub-slab depressurization systems in homes with high concentrations of VOCs while maintaining quarterly monitoring programs with other homes that are at risk for future VI (US EPA, 2007).

Table 1. Residential indoor air and sub-slab screening action levels developed by the Ohio Department of Health. Units are labeled in parts per billion per volume of air (US EPA, 2007).

Volatile Organic Compound	Long-term Screening Level for Residential Sub-Slab Air	Long-term Screening Level for Residential Indoor Air	Short-term Screening Level for Residential Sub-Slab Air	Short-term Screening Level for Residential Indoor Air
Chloroform	22 ppbv	2.2 ppbv	500 ppbv	50 ppbv
TCE	4.0 ppbv	0.4 ppbv	1,000 ppbv	100 ppbv
PCE	120 ppbv	12 ppbv	2,000 ppbv	200 ppbv

The Ohio EPA continues to monitor the Delphi VOC plume presently while the US EPA has ceased its involvement. This study intends to work cooperatively with the Ohio EPA in characterizing the extent of the Delphi VOC plume as well as in

characterizing nature and any future hazard for VI in residences. Considering that people can spend an average of 64-94% of their time indoors, the growing risk for exposure to VOCs should become an increasing area of research in the future (Provoost et al., 2009).

3. METHODS

3.1 Site Characterization

The first step for this project involved identifying the main causes of DNAPL contamination at the Delphi facility. Sampling data from the former Delphi corporation's investigation of the site was provided by the Ohio EPA for analysis in this study. A total of 222 soil samples, 13 monitoring wells, and 35 soil vapor samples were reviewed along with scanned maps showing the approximate locations of these sample sites from the original Ohio EPA and US EPA investigation (Ohio EPA, 2018). This data provided important information for the site such as hydraulic head values, well log stratigraphy, and VOC contaminant concentrations. Spatial coordinates for these sites were then estimated using Google Earth in comparison to the maps. The sample points that tested for positive traces of PCE, TCE, or chloroform were then entered into Microsoft Excel, and they were organized by whether they were groundwater, soil, or soil vapor samples.

Determining the geological and hydrogeological settings of the Delphi site was crucial in determining how the contaminants may behave in the area. Well log data from monitoring wells at the Delphi site was obtained from the Ohio Department of Natural Resources (Ohio Department of Natural Resources, n.d.). Each well log contained stratigraphy information at the point where each well was dug, and multiple stratigraphy columns were created to help show any correlating layers across the site. A geologic cross-section was then created using Microsoft Excel and Paint 3D using the stratigraphy data from the well logs. Other hydrogeological parameters such as hydraulic conductivity and permeability were obtained from files provided by the Ohio EPA.

3.2 Contaminant Plume Analysis

There were two zones of the Delphi facility that were contaminated: the soil and groundwater. Plume maps showing contamination in these two zones were hand-drawn to help illustrate contaminant migration. Extent of both the groundwater and soil vapor contamination areas was determined to help show the residences that were affected by VI from this plume. Future VI contamination risk in residences within the plume's transport path was also estimated with this data. Characterization of the organic vapor distribution was necessary since areas where groundwater is contaminated may not necessarily have organic vapor migration through the soil.

3.2.1 Characterization of the Dissolved Groundwater Plume

Patterns of groundwater flow, such as flow direction and velocity, were characterized using available hydraulic conductivity and hydraulic head data. Potentiometric surface maps were constructed to show contours of hydraulic head which illustrate the flow of groundwater from areas of high hydraulic head to those with low hydraulic head, and these flowlines run perpendicular to the hydraulic head contours. Head data from 7 monitoring wells in the area were used in determining groundwater flow direction. A potentiometric surface map of the study site was hand-drawn to illustrate the flow of groundwater in the area. This aided in understanding the advective transport of contaminants from the source zone. Upon generation of a potentiometric surface map, plume maps were then drawn showing the distribution of TCE, PCE, and chloroform in the groundwater based on the available groundwater sampling data.

Contaminant retardation was estimated using equations 2-5 below derived from Schwartz and Zhang (2003, p.422-424).

$$\log k_{oc} = 0.088 + 0.909 \log k_{ow} \quad (2)$$

$$K_d = f_{oc} K_{oc} \quad (3)$$

$$R_f = 1 + (1 - n/n) p_s k_d \quad (4)$$

$$V_c = V_w / R_f \quad (5)$$

The value for $\log K_{ow}$ of chloroform, 1.97, was obtained from Hansch, Leo, and Hoekman (1995). TCE used a $\log K_{ow}$ value of 2.51 (Chiao, Currie, & McKone, 1994b). The $\log K_{ow}$ value for PCE used was 2.58 (Chiao, Currie, & McKone, 1994a). Fraction of organic carbon (f_{oc}) was estimated to be 0.0005 (IRTC, 2015). Since the perched aquifer was comprised of sand and gravel, the density of the media (p_s) was estimated to be 2.65 (Appelo and Postma, 2004, p.84). Once contaminant retardation factors (R_f) were calculated for each of the chemicals, estimated contaminant velocities (V_c) were then determined.

In order to further characterize the dissolved DNAPL plume migration in the groundwater and soil, plume maps were created digitally using Surfer. Soil vapor and groundwater data was organized into Microsoft Excel spreadsheets with their sampling coordinates, and then the data was input into Surfer using the coordinates and sample readings. For contour maps of the contaminants to be created, a gridding method needed to be chosen for the data set. The kriging method of gridding data was chosen for this

study given the limited number of samples for some of the data sets. Equation 6 shows the equation used by Surfer to compute Z values at each node in the grid (Golden Software, 2017).

$$Z_A = \sum_{i=1}^n W_i Z_i \quad (6)$$

Where Z_A is the estimated value of grid node A, n is the number of neighboring data points, Z_i is the value at location I with a weight, W_i .

Once the input data was converted to a grid, a contour map layer was created using this data. An image of the study site was then added as a basemap layer from Google Maps (2018) to show approximately where the contaminants were present at the time of sampling. These plume maps created using Surfer allowed for a better understanding of the spread of contamination of each of the chemicals. This helped illustrate where each contaminant may have originated from the former Delphi site. Two sets of contour maps were created using data from June of 2011 and September of 2011. A digitalized version of the potentiometric surface map of the area was also modeled using Surfer. By modeling plume migration, useful information was obtained for predicting the future risk of groundwater contamination and VI in the study area.

3.2.2 Analysis of the Organic Vapor Distribution and Migration in Soil

Since the groundwater DNAPL plume made up only one part of the conceptual VI model, it was also important to characterize the organic vapor distribution and migration in the soil. Soil data from 33 sampling points was used for generating vapor plume map using Surfer for 4 different time periods of sampling. The same kriging method of gridding data used in the groundwater contour maps was once again applied to create contour maps of the plume migration in the soil. Data sets for soil vapor samples were categorized into the following 4 time periods: 2006 Pre-SVE (Soil Vapor Extractor) Samples, 2006 Post-SVE, 2011, and 2016. The 2016 soil vapor data was obtained from a more recent study done by the Ohio EPA (2016). Each time period had samples of chloroform, PCE, and TCE concentrations at sites on and around the facility.

3.3 Characterizing Vapor Intrusion

Characterization of the VI occurring in residences affected by the Delphi VOC plume site involved the comparison of soil vapor and groundwater dissolved plume maps with sampling data from the residences affected by VI. Data showing indoor air contamination at residences near the facility was investigated to delineate relationship among concentrations in the sub-surface as compared to indoor and sub-slab readings and understand the overall characteristics of VOC VI pathways.

3.3.1 Investigating VI Pathways and Attenuation in Residences

The conceptual VI pathways model developed by the US EPA (Eq. 1) was used to quantify the bulk mass flux of VI and attenuation in residences. Maps provided by the Ohio EPA showed residences having exceeded safe indoor air contamination levels.

Their proximity to the plume site may have played a role in their VI contaminations, or older buildings proved to be more vulnerable since they may have more deterioration in their foundation. Knowledge of these VI pathways may help mitigate risk of future VI from occurring in other homes or buildings threatened by the Delphi VOC plume.

Sub-slab and indoor air sampling data from 4 residences were chosen for analysis of VI attenuation and effectiveness of mitigation systems installed. These residences were chosen since they had multiple samples taken over several years as compared to some residences which only had a one or two sampling dates, and the 4 residences chosen also all had mitigation systems installed to lower VOC sub-slab and indoor concentrations. Sub-slab and indoor air sample readings were extracted into an Excel spreadsheet for further analysis.

3.3.2 Assessing Efficiencies of Mitigation Systems

The 4 residences that were chosen for analysis each had an in-home mitigation system installed because of the threat of vapor intrusion in the sub-surface. In order to visually assess the effectiveness of these mitigation systems, the sub-surface and indoor air sampling data for each of the residences was illustrated using line graphs created in Microsoft Excel. Each home had a line graph created for the sub-surface and indoor air sample data for the three contaminants (TCE, PCE, chloroform) as well as one master line graph containing the data from all the contaminants. Tables for this data were also created to help show actual sample readings at each date which allowed for calculating the efficiency of the mitigation systems in each of the homes.

3.3.3 Modeling of TCE Bulk Mass Flux in Residences

Using the data provided for the four residences affected by VI, bulk mass flux of TCE for each residence was estimated using Equation 1. This was done to help quantify the amount of contaminant entering each residence to better understand the attenuation factor when the contaminant moves from the sub-surface into a building. Indoor air concentrations of TCE were taken from the actual sampling data provided by the Ohio EPA while parameters such as the indoor air exchange rate and soil-gas flow rate were taken from the model done by Bozkurt et al. (2009). The volume of each home with a full basement was estimated by multiplying the living area of the ground floor multiplied by an assumed height of 7 feet. For the homes that had only a partial basement, the living area of the ground floor was halved and then multiplied by 7 feet. All volumes were then converted to cubic meters.

4. RESULTS

4.1 Geological Setting of Delphi Site

Multiple stratigraphy columns were created using well log data available from the Ohio Department of Natural Resources (ODNR) online well log database. Well logs at four areas of the eastern part of the facility were selected to help understand the geological setting underneath the facility. A map of the locations of each of the well logs can be found in Figure 5 below.

Figure 5. Facility map obtained from ODNR showing well log locations. Facility is outlined in gray.

Four stratigraphy columns were created at each of these locations using well log data obtained from ODNR. These columns were created using the software program

Sedlog 3.1 (Zervas, Nichols, Hall, Smyth, Lüthje, and Murtagh, 2009). Figures 6.1-6.4 show the stratigraphy columns of three well logs located on the facility's property along with another well on South Ardmore Ave near houses affected by VI.

Figure 6. Extrapolated Geologic Cross-Section A-A' of the Study Area

The westernmost well log available, 2038629 (Fig. 6.1), illustrated an upper permeable layer of coarse sand, gravel, and boulders that was approximately 2 m thick near the surface. Below this layer there existed a 1.2-m impermeable layer of brown silty clay. Below the first impermeable layer was a permeable layer of coarse sand and gravel approximately 1.8 m thick underlain by another brown silty clay layer 1.8 m in thickness. After the second impermeable layer of clay, there was a deep primary aquifer comprised of sand and gravel that extended the rest of the depth of the well (7 m).

Well log 2038626 (Fig. 6.2) was located about 100 mm east of well 2038629. This well was drilled to a depth of 3.5 mm, and it was comprised of an upper permeable layer of sand and gravel approximately 1.8 mm thick followed by a less permeable layer of silt and clay also 1.8 mm in thickness. This correlates with the second permeable layer found in the first well log along with the second clay layer both of the same thickness and composition.

Another well log, 2038632 (Fig 6.3), was available near the easternmost end of the facility approximately 400 mm east of well 2038626. This stratigraphic column showed an upper permeable layer of coarse gravel and sand 1.2 mm in thickness followed by a gray clay layer 0.6 mm thick located approximately 3 mm below the surface at a similar depth to the previous well logs. Followed by this impermeable clay layer was an aquifer comprised of 1.8 mm of brown sand and gravel. Another layer of clay was present 4.5 m below the surface approximately 1.3 m in thickness followed by the primary aquifer comprised of sand.

The final well log available from the ODNR was well 2000868 located on South Ardmore Avenue 150 m east of the previous well log. Below the surface there was 2 m of light brown sand and gravel which would be a permeable layer for groundwater. This upper aquifer was separated by a much thicker lower aquifer by 0.6 m of brown sandy clay which would serve as an aquitard between the two aquifers. The lower aquifer was comprised of sand and gravel and found to be 5 m in thickness.

Moving eastward from the westernmost well to the easternmost involved a total elevation change of approximately 4 m. This causes the uppermost gravel and sand layers

in the west to have been eroded away along with an upper clay aquitard layer that existed in the western set of well logs available. There still exists a pattern though of alternating permeable sand and gravel layers that can vary from one to three m in thickness with less permeable clay aquitard layers approximately 1 m.

From analysis of the well log data available, the subsurface of the area where most of the contamination existed can be summarized as an upper perched aquifer of sand and gravel, an impermeable clay aquitard layer, and a lower primary aquifer also composed of sand and gravel. The upper perched aquifer tended to be near the surface averaging about 2 m in thickness followed by a clay with a thickness of 0.6 m to 1 m. A lower primary aquifer exists beneath this impermeable clay layer, but this aquifer did not exhibit much VOC contamination as compared to the upper perched aquifer.

4.2 Hydrogeological Data and Groundwater Contaminant Migration

Groundwater flow was modeled using Surfer to create a potentiometric surface map using the well data detailing hydraulic head values for in the area. Since most of the contaminants were detected in upper aquifer, this study focused upon it rather than the lower primary aquifer. Figure 7 shows the primary flow of groundwater of the shallow aquifer in the area is directed eastward. As the primary mechanism of contaminant transport in the area was due to advection, it is suggested that contaminants should be present east of the locations of the former underground storage tanks. Locations of these former underground storage tanks are shown in Figure 8.

Hydraulic conductivity was estimated to be an average of 27.36 m/d or 0.0019 m/sec in the upper sand and gravel aquifer, and the effective porosity for sand and gravel

was estimated to be 0.3. The hydraulic gradient for the study area was estimated to be 0.02343 using Figure 7 as a reference. Linear groundwater velocity was then estimated to be 0.129 m/day dividing the product of the hydraulic gradient and conductivity by the effective porosity. Based on contaminant retardation, actual contaminant velocities for chloroform, TCE, and PCE were estimated to be 0.097 m/day, 0.064 m/day, and 0.059 m/day respectively.

Figure 7. Groundwater Potentiometric Surface Map

Figure 8. Locations of former underground storage tanks at the facility (Ohio EPA, 2010).

4.2.1. June 2011 Groundwater Data

Once groundwater flow was confirmed to be moving to the east, the next step was to determine the extent of contamination in the upper aquifer for TCE, PCE, and chloroform. Groundwater sampling data was limited to June and September of 2011 since the groundwater in the area is not used for drinking water. Sample values for 7 monitoring wells during these 2 months were obtained for study. Contour maps of the contaminants sampled in June of 2011 are found in Figures 10.1-10.3 while the maps for September 2011 are found in Figures 11.1-11.3.

Figure 10.1. June 2011 Groundwater Contour Map of Chloroform Contamination. Contours are in ug/L.

Figure 10.2. June 2011 Groundwater Contour Map of PCE Contamination. Contours are in ug/L.

Figure 10.3. June 2011 Groundwater Contour Map of TCE Contamination. Contours are in ug/L.

From analysis of the June 2011 groundwater data (Fig. 10.1-10.3), chloroform had the highest contamination levels in the groundwater at 370 ug/L at DBW 118, and it was also the contaminant that was detected most frequently at the monitoring wells. Most of the contaminants in the groundwater also appeared to be coming from the historic location of underground storage tank area K. Monitoring well DAW-116 had the highest concentration of PCE contamination at 150 ug/L as seen in Fig. 10.2 while TCE was greatest at DBW-120 at 30 ug/L (Fig. 10.3). All contaminants had at least one reading higher than recommended MCL standards for drinking water (see Table 2); however, the

water in this area is not used for drinking which is why it was not the subject of greater investigation.

Table 2. Ohio EPA and US EPA Drinking Water MCL Standards

Pollutant	Ohio EPA (ug/L)	US EPA (ug/L)
Chloroform	80	5
TCE	5	5
PCE	5	5

4.2.2. September 2011 Groundwater Data

The September 2011 groundwater samples (Fig. 11.1-11.3) did not show much of a change from the June 2011 data. Chloroform sample detection appear to have decreased over the course of three months. For example, the chloroform contamination at DBW-118 decreased from 370 ug/L to 170, and other chloroform samples seemed to have decreased as well. In contrast, TCE was detected in an additional monitoring well (DAW-116) as compared to June which may indicate advection transport eastward since DAW-116 is located east of other contaminated wells.

Figure 11.1. September 2011 Groundwater Contour Map of Chloroform Contamination. Contours are in ug/L.

Figure 11.2. September 2011 Groundwater Contour Map of PCE Contamination. Contours are in ug/L.

4.3 Contaminant Migration in Soil

Soil vapor data for the area was much more abundant in contrast to groundwater. A total of 28 soil vapor sampling sites were extracted from the investigation paperwork. Sample data was separated into four distinct periods of time: 2006 Pre-SVE (before a soil vapor extractor placed on-site), 2006 Post-SVE, 2011, and 2016. Within each time period, contaminant data for TCE, PCE, and chloroform was given in parts per billion per volume of air (ppbv), and the detection limit for the sampling equipment was 0.01 ppbv. All sampling for soil vapor contaminants was completed at depths between 2.5 m to 3 m depending upon the thickness of the upper aquifer which increases eastward as evidenced

in the previous stratigraphy columns. Figure 12 shows the soil vapor sampling sites that were able to be extracted from the reports provided.

Figure 12. Locations of soil vapor sampling sites as indicated by black triangles on the map. Samples were taken from 2006 through 2016.

4.3.1. 2006 Pre-SVE Installation Soil Vapor Data

The earliest data set available involved contaminant readings taken in 2005 and 2006 before a soil vapor extractor (SVE) was installed on the facility grounds. These

samples represented the highest concentrations of contaminants before SVE mitigation of the soil vapor took place. It is believed that some of the contaminated soil at the facility was removed; however, no conclusive data on this source removal was found in the documents provided. Chloroform appeared to originate at two sources as seen in Figure 13.1 with the contaminant reaching Bish Avenue and South Ardmore Avenue. PCE (Fig. 13.2) and TCE (Fig. 13.3) were more concentrated in the easternmost part of the facility with PCE having the highest concentration of all the contaminants peaking at 56,000 ppbv. Appendix B contains the specific soil vapor sampling values for the dataset.

Figure 13.1. 2006 Pre-SVE Installation Soil Vapor Chloroform Readings. Contours are in ppbv at 200 ppbv intervals.

Figure 13.2. 2006 Pre-SVE Installation Soil Vapor PCE Readings. Contours are in ppbv at 4000 ppbv intervals.

Figure 13.3. 2006 Pre-SVE Installation Soil Vapor TCE Readings. Contours are in ppbv at 1000 ppbv intervals.

4.3.2. 2006 Post-SVE Installation Soil Vapor Data

Four SVE remediation systems were installed on the study grounds in April of 2006 where it ran 8 hours a day, but it began running continuously in July of 2006. Additional soil vapor samples were taken in September of 2006 which are illustrated in Figures 14.1-14.3. Figure 14.1 illustrates the chloroform soil vapor concentrations which still existed near Bish and South Ardmore Avenues, but the source appears to have centered on one area after mitigation installation. PCE (Fig. 14.2) and TCE (14.3) do not illustrate significant changes in concentration as well. Overall, there did not appear to be a significant difference in contaminant concentrations between the Pre-SVE and Post-SVE datasets. In some sample sites, contaminant concentrations appeared to increase

Figure 14.2. 2006 Post-SVE Installation Soil Vapor PCE Readings. Contours are in ppbv at 4000 ppbv intervals.

Figure 14.3. 2006 Post-SVE Installation Soil Vapor TCE Readings. Contours are in ppbv at 1000 ppbv intervals.

4.3.3. 2011 Soil Vapor Data

The next set of soil vapor sampling data found occurred 5 years later during August of 2011. Although data for less sample sites were available, the values available showed a distinct drop in concentrations of all contaminants. For example, sample 13D (Table 7) showed concentrations of all three contaminants to be less than 1% of their Post-2006 SVE values. This represents the effectiveness of the soil vapor extraction system in removing contaminants in the soil vapor on-site after running 24/7 for 5 years. Chloroform levels dropped significantly over time as illustrated in Figure 15.1. PCE concentrations showed as significant decrease as well (Fig. 15.2). For example, Sample 01D (Appendix B) decreased to 590 ppbv from being 45,000 ppbv in 2006. TCE soil

vapor concentrations showed a similar pattern of decrease as the other contaminants (Fig. 15.3). After 5 years of mitigation, the soil vapor contamination seemed to be limited to within the facility grounds.

Figure 15.1. 2011 Soil Vapor Chloroform Readings. Contours are in ppbv at 20 ppbv intervals.

Figure 15.2. 2011 Soil Vapor PCE Readings. Contours are in ppbv at 200 ppbv intervals.

Figure 15.3. 2011 Soil Vapor TCE Readings. Contours are in ppbv at 50 ppbv intervals.

4.3.4. 2016 Soil Vapor Data

June of 2016 provided the most recent data samples available from the study area when the Ohio EPA performed a field report taking soil gas samples off-site in the residential area bordering the facility. These sample sites are shown in Figure 16. Although most readings taken in the area came back negative, a few sampling sites did still register positive contaminant readings. For example, sample site SG-16 (Appendix B) just southeast of the facility recorded concentrations of 4300 ppbv and 1200 ppbv for PCE (Fig. 17.2) and TCE (Fig. 17.3) respectively. Chloroform had the lowest concentrations found between the 3 VOCs investigated in 2016, but trace amounts were

still detected on Bish Avenue near where the suspected source was located (see Fig. 17.1).

Figure 16. 2016 sampling sites from Ohio EPA field assessment study. Yellow indicates new soil gas sampling sites while the red indicates previously sampled soil vapor sites.

Figure 17.1. 2016 Soil Vapor Chloroform Readings. Contours are in ppbv at 20 ppbv intervals.

Figure 17.2. 2016 Soil Vapor PCE Readings. Contours are in ppbv at 200 ppbv intervals.

Figure 17.3. 2016 Soil Vapor TCE Readings. Contours are in ppbv at 100 ppbv intervals.

4.4 Analysis of Vapor Intrusion in Residences

Once the contaminant plumes in the groundwater and soil were characterized, residential sub-slab and indoor air sampling data was analyzed to determine any patterns. Sub-slab and indoor air sampling data from 4 residences near the facility was used to graph trends for contaminant concentration over time in each of the homes. Each of the residences chosen for this study had sub-slab depressurization mitigation systems (SSD) installed to combat elevated VOC concentrations in the sub-surface. The four residences were all located on South Ardmore Ave near the facility grounds. Table 3 below contains the recommended screening and action levels for VOCs detected in residential structures.

Locations of the four residences can be observed in Figure 18. Appendix C at the end of the paper contains the measured VOC levels for each of the residences.

Table 3. Ohio Department of Health recommended screening levels for VOCs in residences

Contaminant Name	Sub-Slab Long Term Screening Level (ppbv)	Sub-Slab Short-Term Action Level (ppbv)	Indoor Air Long-Term Screening Level (ppbv)	Indoor Air Short-Term Action Level (ppbv)
Chloroform	22	500	2.2	50
TCE	4	1,000	0.4	100
PCE	120	2,000	12	200

Figure 18. Locations of four residences with mitigation systems

4.4.1. Analysis of 55 South Ardmore Avenue

Beginning with 55 South Ardmore Ave, the baseline sub-slab TCE concentration at the home was 360 ppbv which was above the sub-slab screening level outlined by the Ohio Department of Health (ODH). The indoor air concentration of TCE (2.4 ppbv) was above the indoor air long-term screening level of 0.4 ppbv set by ODH as well. Although the short-term action level for indoor air TCE was not exceeded, an SSD system was still installed in the home. Once the SSD system was installed, VOC levels dropped below ODH standards for all contaminants in indoor and sub-slab areas. Figures 19.1 through 19.4 below illustrate the decrease in contaminant concentration over time. Sub-slab and indoor air concentrations of TCE and PCE both decreased over time resulting in harmless detection values. Indoor and sub-slab chloroform values at 55 South Ardmore Ave did experience an unexpected increase around 400 days after the mitigation system was installed (see Fig. 19.2) which may have been the result of background indoor sources. Sampling at the residence ceased after 700 days.

Figure 19.1. Sub-Slab and Indoor Air VOC Concentrations in 55 South Ardmore Ave

Figure 19.2. Sub-Slab and Indoor Air Chloroform Readings in 55 South Ardmore Ave

Figure 19.3. Sub-Slab and Indoor Air TCE Readings in 55 South Ardmore Ave

Figure 19.4. Sub-Slab and Indoor Air PCE Readings in 55 South Ardmore Ave

The bulk mass flux of TCE at a residential home was estimated using Equation 1.

Data from 55 South Ardmore Ave was used for the indoor air concentration (C_{indoor}) of

TCE, and the volume of the basement (V_b) was estimated using the available square footage of the home (per floor) multiplied by an assumed height of 7 ft in the basement. Values for the area of cracks in the foundation (A_{ck}) and the indoor air exchange rate (A_e) were taken from the modeling parameters used by Bozkurt et al. (2009). A value of 0.64 m^3 from Scenario C (Bozkurt et al., 2009) was chosen for use since it most closely resembled the stratigraphy of the study area by having a continuous clay layer approximately four meters from the surface. Table 4 below shows the specific values for the model used to estimate the resulting bulk mass flux of TCE.

Table 4. TCE Bulk Mass Flux for 55 South Ardmore Ave

55 South Ardmore Ave TCE Bulk Mass Flux		
C_{indoor}	2.5	ppbv
C_{indoor}	13	$\mu\text{g}/\text{m}^3$
C_{indoor}	0.000013	g/m^3
C_{indoor}	0.00000010	mol/m^3
A_{ck}	0.199	m^2
A_e	0.000138889	1/s
V_b	67	m^3
Q_{ck}	0.64	m^3/s
J_t	3.33624E-07	$\text{mol}/\text{m}^2/\text{s}$

Where C_{indoor} = TCE indoor air concentration, A_{ck} = the estimated area of cracks in the foundation, A_e = the indoor air exchange rate, V_b = the estimated volume of the basement of 55 S Ardmore Ave, Q_{ck} = the soil-gas flow rate through the crack into the building, and J_t = the bulk mass flux of TCE.

4.4.2 Analysis of 59 South Ardmore Avenue

Sub-slab VOC concentrations of chloroform and TCE at 59 South Ardmore Avenue greatly exceeded short-term action levels set by ODH, so an SSD system was installed at the residence. Despite the sub-slab TCE concentration being over 10,000 ppbv, the baseline indoor air TCE concentration only recorded at 4.2 ppbv. The chloroform indoor air concentration only registered as 0.67 ppbv as compared to the 2200 ppbv in the baseline sub-slab sample. Installation of the mitigation system decreased indoor air and sub-slab VOC concentrations significantly in as little as 30 days. The last set of data samples occurred in 2016 where only sub-slab samples were obtained since the property was vacated by the owner.

Figures 20.1 through 20.4 show line graphs comparing contaminant concentrations at the residence over time. As evidenced by Fig. 20.1, sub-slab and indoor air concentrations for all VOCs decreased significantly once the mitigation system was installed. Indoor air and sub-slab VOC levels remained below MCLs during the monitoring process, but the property was vacated in 2012 which marked the end of the sampling data.

Figure 20.1. Sub-Slab and Indoor Air VOC Concentrations in 59 South Ardmore Ave

Figure 20.2. Sub-Slab and Indoor Air Chloroform Readings in 59 South Ardmore Ave

Figure 20.3. Sub-Slab and Indoor Air TCE Readings in 59 South Ardmore Ave

Figure 20.4. Sub-Slab and Indoor Air PCE Readings in 59 South Ardmore Ave

Bulk mass flux of TCE at 59 South Ardmore Avenue was estimated using the model below in Table 5. Since 59 South Ardmore Avenue only possessed a partial basement, the volume was calculated by taking one-half of the area of the ground floor multiplied by an assumed height of 7 ft. All other values remained constant as used in the previous model for 55 South Ardmore Ave (see Table 4).

Table 5. TCE Bulk Mass Flux for 59 South Ardmore Ave

59 South Ardmore Ave TCE Bulk Mass Flux Model		
C_{indoor}	4.2	ppbv
C_{indoor}	23	$\mu\text{g}/\text{m}^3$
C_{indoor}	0.000023	g/m^3
C_{indoor}	0.00000017	mol/m^3
A_{ck}	0.199	m^2
A_e	0.000138889	1/s
V_b	105	m^3
Q_{ck}	0.64	m^3/s
J_t	5.65044E-07	$\text{mol}/\text{m}^2/\text{s}$

Where C_{indoor} = TCE indoor air concentration, A_{ck} = the estimated area of cracks in the foundation, A_e = the indoor air exchange rate, V_b = the estimated volume of the basement of 59 S Ardmore Ave, Q_{ck} = the soil-gas flow rate through the crack into the building, and J_t = the bulk mass flux of TCE.

4.4.3 Analysis of 75 South Ardmore Avenue

While sub-slab and indoor air VOC levels at 75 South Ardmore Avenue did not exceed any short-term action levels, they did exceed the long-term screening levels developed by the Ohio Department of Health. A sub-slab depressurization mitigation

system was installed in the home to ensure the VOC levels did not increase in the home. VOC levels dropped in as little as 30 days at the residence for both the sub-slab and indoor air sampling areas. Figure 21.1 shows the decreases in VOC concentration in the home over time. As similar to 55 South Ardmore Ave, indoor air readings for chloroform showed some fluctuations over time in contrast to the consistent low readings of TCE and PCE. This could again possibly be contributed to background contaminants in the home.

Figure 21.1. Sub-Slab and Indoor Air VOC Concentrations in 75 South Ardmore Ave

Figure 21.2. Sub-Slab and Indoor Air Chloroform Readings in 75 South Ardmore Ave

Figure 21.3. Sub-Slab and Indoor Air TCE Readings in 75 South Ardmore Ave

Figure 21.4. Sub-Slab and Indoor Air PCE Readings in 75 South Ardmore Ave

The bulk mass flux of TCE at 75 South Ardmore Avenue was estimated using the model from Bozkurt et al. (2009). This home contained a full basement, so the full square area of ground floor was multiplied by an assumed 7 ft height to estimate the volume. All other parameters were kept constant.

Table 6. TCE Bulk Mass Flux for 75 South Ardmore Ave

75 South Ardmore Ave TCE Bulk Mass Flux		
C_{indoor}	0.2	ppbv
C_{indoor}	1	$\mu\text{g}/\text{m}^3$
C_{indoor}	0.000001	g/m^3
C_{indoor}	0.00000001	mol/m^3
A_{ck}	0.199	m^2
A_e	0.000138889	1/s
V_b	119	m^3
Q_{ck}	0.64	m^3/s
J_t	2.15894E-08	$\text{mol}/\text{m}^2/\text{s}$

Where C_{indoor} = TCE indoor air concentration, A_{ck} = the estimated area of cracks in the foundation, A_e = the indoor air exchange rate, V_b = the estimated volume of the basement of 75 S Ardmore Ave, Q_{ck} = the soil-gas flow rate through the crack into the building, and J_t = the bulk mass flux of TCE.

4.4.5 Analysis of 110 South Ardmore Avenue

PCE contamination in the sub-slab area of 110 South Ardmore Avenue was measured at 3600 ppbv which exceeded the short-term action level set by ODH. As a result, a SSD system was installed in the residence to decrease VOC levels in the residence. After 30 days, PCE was decreased in the sub-slab region to 0.29 ppbv. The majority of TCE and chloroform samples registered as “n/d” (non-detect) at the residence during monitoring. Sub-slab PCE contamination did increase to 4 ppbv after remaining under one ppbv for the first year of mitigation, and it registered as 3.2 ppbv in year two of

mitigation. Continued operation of the SSD system ended in 2012 when the property was vacated by the owner.

Figure 22.1 illustrates the decreases in VOC concentrations in 110 South Ardmore Avenue once the mitigation system was installed. Breaks in the lines on the figure mark points where the contaminant registered as N/D (non-detect) in either the sub-slab or indoor air media. Sub-slab PCE concentrations did show an abrupt increase after one year of mitigation rising to 4 ppbv after reading under 1ppbv for the first year.

Figure 22.1. Sub-Slab and Indoor Air VOC Concentrations in 110 South Ardmore Ave

Figure 22.2. Sub-Slab and Indoor Air Chloroform Readings in 110 South Ardmore Ave

Figure 22.3. Sub-Slab and Indoor Air TCE Readings in 110 South Ardmore Ave

Figure 22.4. Sub-Slab and Indoor Air PCE Readings in 110 South Ardmore Ave

The bulk mass flux of TCE was estimated using the values provided below in Table 7. Since 110 South Ardmore Avenue only had a partial basement, the volume was estimated using the same technique as done for the 55 South Ardmore Avenue model. All other parameters were kept as constants as in the previous models.

Table 7.TCE Bulk Mass Flux for 110 South Ardmore Ave

110 South Ardmore Ave TCE Bulk Mass Flux		
C_{indoor}	0.58	ppbv
C_{indoor}	3	$\mu\text{g}/\text{m}^3$
C_{indoor}	0.00000311	g/m^3
C_{indoor}	0.000000024	mol/m^3
A_{ck}	0.199	m^2
A_e	0.000138889	1/s
V_b	66	m^3
Q_{ck}	0.64	m^3/s
J_t	7.73842E-08	$\text{mol}/\text{m}^2/\text{s}$

Where C_{indoor} = TCE indoor air concentration, A_{ck} = the estimated area of cracks in the foundation, A_e = the indoor air exchange rate, V_b = the estimated volume of the basement of 110 S Ardmore Ave, Q_{ck} = the soil-gas flow rate through the crack into the building, and J_t = the bulk mass flux of TCE.

5. DISCUSSION

5.1 General Area Overview

The upper perched aquifer under the former Delphi facility contained the highest contaminant concentrations in the area. DNAPL contaminants in the underground storage tanks were conceivably leaked into this layer which would explain the highest concentrations occurring in the upper aquifer. From analysis of soil vapor and groundwater VOC concentrations, it is suggested that contaminant leakage originated near former underground storage tank areas A, B, and K (see Figure 7). Despite source removal of the USTs in the 1980s, high soil vapor concentrations in 2006, such as 56,000 ppbv of PCE and 7,400 ppbv of TCE suggests the existence of residual DNAPL contaminants. Over time, these residual DNAPL contaminants could have evaporated to cause the high soil vapor concentrations detected at the beginning of the site investigation.

5.2 Groundwater VOC Transport Results

Given the limited groundwater data available, it is difficult to determine exact VOC contaminant transport pattern. Groundwater flows eastward in the upper aquifer, and this correlates with VOC contamination on South Ardmore Ave which is located east of the former Delphi facility. Groundwater concentrations in the available data sets tended to be much lower than their soil vapor counterparts which could be attributed to the low solubility and volatile nature of the contaminants. The solubility of PCE and TCE in groundwater at 25°C is 210 mg/L and 1,280 mg/L respectively which shows they are not very soluble in groundwater (Lawrence, 2006). In contrast, chloroform is much more

soluble in groundwater with a solubility between 7,200 and 9,300 mg/L (Watts, Long, & Meek, 2004). Chloroform readings were the highest of the 3 VOCs sampled for in groundwater which could be attributed to it being more soluble in groundwater than TCE and PCE.

Linear groundwater velocity was then estimated to be 0.129 m/day. Based on this velocity, the advective front of the contamination could have reached South Ardmore Avenue in as little as one year based on advective contaminant transport in the groundwater. Continued contaminant concentrations in the area since UST removal in the 1980s was attributed to residual DNAPLs in the upper aquifer above the impermeable clay layer.

5.3 Soil Vapor Contaminant Results

Residual contaminants in the upper aquifer could explain the lingering contaminant concentrations in the area despite source removal and mitigation action performed in the area. The 2016 soil gas sample, SG-16, showed concentrations of PCE and TCE at 4300 ppbv and 1200 ppbv respectively which indicates significant contamination may still present on South Ardmore Avenue. Limited groundwater sampling data of the area hinders any further conclusions on the matter. This continued soil vapor contamination may suggest contaminant transport in the past or existence of unidentified source of DNAPL in the area. Nevertheless, elevated readings of PCE and TCE soil vapor concentrations in the area as recent as 2016 suggest further contamination eastward of the facility possibly due to an unidentified source or contaminant plume development.

The vapor pressure of each contaminant may explain sampling detection over time. For example, the vapor pressures for TCE and PCE are around 7.6 kPa and 1.8 kPa at 20°C respectively (Most & Pope, 1989). Chloroform meanwhile has a much higher vapor pressure of 21.3 kPa at 20°C which causes it to volatilize more quickly than TCE and PCE (Watts et al., 2004). Since chloroform volatilizes the fastest, it would have volatilized earlier than the TCE and PCE after leaking from the USTs. Volatilizing quickly would expose the chloroform vapors in the soil to more biodegradation or emission into the atmosphere (or intrusion to houses) over time than the PCE and TCE which may explain why chloroform has the lowest soil vapor concentrations once the investigation began in 2006 while PCE had the highest from taking more time to volatilize.

Contamination in the soil vapor throughout the study site was evident before mitigation in 2006 despite low groundwater VOC concentrations. This would imply that the threat of vapor intrusion in buildings cannot simply be based on groundwater contamination alone. Pennell et al. (2016) also had similar conclusions in that relying on groundwater concentrations in assessing vapor intrusion risks is not a reliable method. Residual VOC contamination in the sub-surface as seen at this site shows a deviation from conceptual VI models that rely on significant VOC groundwater contamination. Multiple approaches for investigation are necessary to effectively characterize VI risks at contaminated sites.

5.4 Residential Area VOC Results

With respect to the 4 residential homes analyzed in the study, there appeared to be a correlation between high concentrations of sub-slab VOCs and elevated VOCs inside of

the homes. Chloroform indoor air concentrations were inclined to be about 1/100 of their sub-slab concentrations. PCE indoor air concentrations averaged to be 3/100 of their respective sub-slab readings, and TCE indoor air concentrations averaged to be 3/1000 of their sub-slab concentrations. These comparisons show that PCE had the least attenuation through the foundations of the homes. All 4 of these homes had similar concrete slabs as foundations in their basements, so their differences in attenuation could not be attributed to significant difference in foundation construction. Further research is needed to determine whether PCE does attenuate less than TCE and chloroform during VI.

5.5 Relationship Between Indoor Air and Sub-Slab VOCs

Comparison of indoor air VOC concentrations versus their respective sub-slab concentrations at 4 South Ardmore Avenue residences helped reveal a relationship in the attenuation of VOCs as they migrated upward into these homes. All 4 homes had basements with concrete slabs providing similar settings for comparison of the VOCs migration pathways. PCE appeared to experience the least attenuation between sub-slab and indoor air concentrations with a rate of 3/100 of the sub-slab concentration migrating into the home. This value held for sub-slab VOC concentrations ranging from 300-10,000 ppbv as found in the four residences analyzed. Equation 7 illustrates this relationship obtained by taking the ratio of sub-slab concentration versus its respective indoor air concentration.

$$y = 0.03x \text{ for } 2 \leq x \leq 3600 \text{ ppbv} \quad (7)$$

Where: y = indoor air concentration of PCE (ppbv), x = sub-slab concentration of PCE (ppbv)

TCE experienced the most attenuation as a vapor when migrating from sub-slab into the homes with a rate of 3/1000 of its sub-slab concentration), and chloroform had an attenuation rate of 1/100 of its sub-slab concentration migrating into the homes. Equations 8 and 9 below show these linear relationships for TCE and chloroform respectively. It is unknown as to why PCE had the least attenuation between the three contaminants.

$$y = 0.003x \text{ for } 250 \leq x \leq 10,0000 \text{ ppbv} \quad (8)$$

Where: y = indoor air concentration of TCE (ppbv), x =sub-slab concentration of TCE (ppbv)

$$y = 0.01x \text{ for } 12 \leq x \leq 2200 \text{ ppbv} \quad (9)$$

Where: y = indoor air concentration of chloroform (ppbv), x = sub-slab concentration of chloroform (ppbv)

5.6 TCE Bulk Mass Flux Modeling

Through the use of Equation 1, the bulk mass fluxes of TCE VI at residential homes were estimated. Results of this modeling showed that 59 South Ardmore Avenue had the greatest bulk mass flux of TCE as seen in Table 5. Volume of a basement did not

seem to affect bulk mass flux since the greatest 2 bulk mass fluxes of TCE did not occur in both full or partial basements. Estimates from this model for this scenario may have been overestimated since the assumed groundwater contamination used by Bozkurt et al. (2009) was greater than at South Ardmore Avenue.

6. CONCLUSIONS

6.1 Contaminant Origin and Transport

The 3 VOCs appear to have originated from former UST areas A, B, and K. It is likely that the USTs and pipelines containing the VOCs were buried at a shallow depth of 1-3 m placing them above the lower clay impermeable layer separating the upper perched aquifer from the deeper primary aquifer below. Support for this assertion can be drawn from the high concentrations of VOCs detected in the perched aquifer via groundwater and soil vapor sampling versus significantly lower concentrations below the clay layer in the primary aquifer.

Contaminant plume migration occurring solely based on advective transport remains inconclusive due to insufficient field data; however, the fact that VOCs did migrate to the northeast and southeast of the facility, which follows groundwater flow direction to the northeast and southeast, does help support this scenario. Vapor intrusion occurring in residences along South Ardmore Avenue despite insignificant VOC groundwater contamination indicated that assessing VI risk cannot be solely based on groundwater sampling. The lack of VOC contamination in groundwater also does not necessarily indicate the lack of VI risk in an area.

6.2 Relationship Between Indoor Air and Sub-Slab VOCs

Analysis of indoor air and sub-slab VOC contaminants along South Ardmore Avenue showed that PCE experienced the least attenuation when migrating from the sub-surface into residences. In contrast, TCE had the highest attenuation factor which was a factor 10 higher than PCE. The cause for this was not evident. Additionally, in-home

mitigation systems installed at each of the 4 residences analyzed all were successful in decreasing indoor air VOC readings to below their MCLs. Fluctuations for indoor air chloroform readings were evident in multiple residences suggesting a common background contamination source may have been present.

6.3 Residual Contaminant Presence

Based on data from 2016, it is evident that there still exists some residual contamination from the VOCs despite continuous removal efforts at the facility. Soil gas samples, such as SG-16 and SG-17, showed concentrations of PCE and TCE as high as 4300 ppbv and 1200 ppbv. The pre-2006 SVE contour maps of VOC soil vapor concentrations showed a tendency for the contaminants to pool in an area, so it is plausible that there may exist previously unidentified contamination zones in the perched aquifer eastward of the facility in areas not affected by remediation action. The presence of contamination eastward of the facility may also be attributed to advective transport of contaminant from the UST leakage site in the west.

6.4 Suggestions for Future Study

There exist many potential avenues for further study of the former Delphi facility if circumstances permit. Detailed modeling of potential organic vapor contaminant migration in soil may show other areas of concern for VI further away from the facility that were not addressed by the Ohio EPA investigation. This could then lead to further analysis of contaminant migration from the sub-surface into buildings.

Additionally, the heightened soil VOC gas concentrations detected in 2016 suggest the possibility of continued contaminant presence in the sub-surface near

residential areas such as South Ardmore Avenue. Continued groundwater and soil sampling in the area is warranted; however, this would require the permission of residences in the area which may prove difficult given the socioeconomic conditions of the neighborhood. A mathematical equation could also be derived to calculate the indoor air concentration of VOCs as compared to sub-slab concentrations if baseline data from additional homes before mitigation could be acquired. The effects of other types of foundation as related to attenuation of VOCs could also be explored.

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APPENDIX A: GROUNDWATER VOC SAMPLING DATA

June 2011 Groundwater Readings			
Monitoring Well ID	Chloroform (ug/L)	PCE (ug/L)	TCE (ug/L)
MW 106	4.1	n/d	n/d
DBW 118	370	n/d	n/d
DBW 119	68	n/d	16
DBW 120	41	n/d	30
Handex MW-2	2.5	4.6	3.3
DCW 114	n/d	n/d	n/d
DAW 116	n/d	150	n/d

September 2011 Groundwater Readings			
Monitoring Well ID	Chloroform (ug/L)	PCE (ug/L)	TCE (ug/L)
MW 106	4.6	n/d	n/d
DBW 118	170	n/d	n/d
DBW 119	24	n/d	21
DBW 120	2.6	n/d	24
Handex MW-2	4.8	0.5	3.9
DCW 114	1.5	n/d	n/d
DAW 116	2.4	170	5.6

APPENDIX B: SOIL VAPOR VOC SAMPLING DATA

2006 Pre-SVE Soil Vapor Data							
ID	Date	Depth (ft)	Latitude	Longitude	Chloroform (ppbv)	PCE (ppbv)	TCE (ppbv)
01 D	4/4/2005	6.5-7	39.749785	-84.235513	810	38000	1000
02 D	4/4/2005	6.5-7	39.749834	-84.235265	8.4	14000	1100
03 D	5/5/2005	6.5-7	39.749886	-84.235124	410	30000	4000
04 D	4/4/2005	6.5-7	39.749926	-84.234915	820	1000	200
06 D	1/5/2006	6.5-7	39.750107	-84.234865	4.4	610	180
07 D	1/5/2006	8-8.5	39.750003	-84.235034	330	500	400
08 D	1/6/2006	8-8.5	39.750349	-84.235847	1800	11	570
09 D	4/4/2005	6.5-7	39.750531	-84.236279	2300	0.097	0.18
10 D	1/6/2006	6.5-7	39.750689	-84.236747	0.27	14	1.2
13 D	1/5/2006	8.5-9	39.749612	-84.235501	1.8	83	1.4
14 D	1/6/2006	7.5-8	39.749126	-84.235527	0.094	220	8.2
15 D	1/6/2006	6.5-7	39.748498	-84.235547	0.024	74	10
17	1/6/2006	6.5-7	39.751052	-84.234009	0.86	800	65
18	1/6/2006	6.5-7	39.750397	-84.234072	1.6	0.2	3.9
19	1/6/2006	10.5-11	39.749677	-84.234051	0.011	6.3	3.2
20	1/6/2006	6.5-7	39.748757	-84.234045	0.013	4.3	0.52
21	1/6/2006	6.5-7	39.749988	-84.234988	n/d	40000	6300
22	1/6/2006	6.5-11	39.749984	-84.235052	n/d	22000	4000
23	1/6/2006	6.5-11	39.749993	-84.235011	68	570	260
24	1/6/2006	9.5-10	39.749932	-84.235066	n/d	56000	7400
25	1/13/2006	10.5-11	39.749941	-84.235178	4100	21000	3600
26	1/4/2006	6.5-7	39.750593	-84.236166	670	0.071	0.094
27	1/4/2006	6.5-7	39.750698	-84.235991	490	0.079	69
28	1/4/2006	6.5-7	39.750423	-84.235552	270	3.5	33
29	1/4/2006	6.5-7	39.750663	-84.235282	330	620	100
30	1/4/2006	6.5-7	39.750306	-84.234818	23	0.071	4
31	1/4/2006	6.5-7	39.749637	-84.235072	1.5	170	320
32	1/4/2006	6.5-7	39.749649	-84.234679	0.15	680	4.2
33	1/4/2006	6.5-7	39.749749	-84.234474	2.4	2900	490

2006 Post-SVE Soil Vapor Data							
ID	Date	Depth (ft)	Latitude	Longitude	Chloroform (ppbv)	PCE (ppbv)	TCE (ppbv)
01 D	9/5/2006	6.5-7	39.749785	-84.235513	380	45000	2000
02 D	9/5/2006	6.5-7	39.749834	-84.235265	180	18000	1000
03 D	9/5/2006	6.5-7	39.749886	-84.235124	480	35000	7700
04 D	9/5/2006	6.5-7	39.749926	-84.234915	230	1000	100
06 D	9/5/2006	6.5-7	39.750107	-84.234865	n/d	3700	120
07 D	9/5/2006	8-8.5	39.750003	-84.235034	27	850	76
08 D	9/5/2006	8-8.5	39.750349	-84.235847	1200	37	620
09 D	9/7/2006	6.5-7	39.750531	-84.236279	5600	4.8	4
10 D	9/5/2006	6.5-7	39.750689	-84.236747	n/d	1.1	n/d
13 D	9/5/2006	8.5-9	39.749612	-84.235501	31	460	100
14 D	9/5/2006	7.5-8	39.749126	-84.235527	n/d	220	14
15 D	9/5/2006	6.5-7	39.748498	-84.235547	n/d	11	66
17	9/5/2006	6.5-7	39.751052	-84.234009	40	42	170
18	9/5/2006	6.5-7	39.750397	-84.234072	4.6	18	20
19	9/5/2006	10.5-11	39.749677	-84.234051	n/d	6.3	4.5
20	9/5/2006	6.5-7	39.748757	-84.234045	n/d	0.48	n/d
21	9/5/2006	6.5-7	39.749988	-84.234988			
22	9/5/2006	6.5-11	39.749984	-84.235052			
23	9/5/2006	6.5-11	39.749993	-84.235011			
24	9/5/2006	9.5-10	39.749932	-84.235066			
25	9/5/2006	10.5-11	39.749941	-84.235178			
26	9/5/2006	6.5-7	39.750593	-84.236166	890	n/d	n/d
27	9/5/2006	6.5-7	39.750698	-84.235991	880	n/d	160
28	9/5/2006	6.5-7	39.750423	-84.235552	260	8.2	53
29	9/5/2006	6.5-7	39.750663	-84.235282	830	1800	250
30	9/5/2006	6.5-7	39.750306	-84.234818	200	n/d	120
31	9/5/2006	6.5-7	39.749637	-84.235072	n/d	520	580
32	9/5/2006	6.5-7	39.749649	-84.234679	n/d	2500	n/d
33	9/5/2006	6.5-7	39.749749	-84.234474	n/d	10000	920

2011 Soil Vapor Data							
ID	Date	Depth (ft)	Latitude	Longitude	Chloroform (ppbv)	PCE (ppbv)	TCE (ppbv)
01 D	8/9/2011	6.5-7	39.749785	-84.235513	n/d	590	10
02 D	8/9/2011	6.5-7	39.749834	-84.235265	11	33	48
03 D	8/9/2011	6.5-7	39.749886	-84.235124	n/d	950	19
04 D	8/9/2011	6.5-7	39.749926	-84.234915	25	14	5.6
06 D	8/9/2011	6.5-7	39.750107	-84.234865	n/d	3.6	0.34
07 D	8/9/2011	8-8.5	39.750003	-84.235034	0.25	1.7	0.098
08 D	8/9/2011	8-8.5	39.750349	-84.235847	4.4	0.11	3.5
09 D	8/9/2011	6.5-7	39.750531	-84.236279	160	16	0.12
10 D	8/9/2011	6.5-7	39.750689	-84.236747	n/d	0.53	n/d
13 D	8/9/2011	8.5-9	39.749612	-84.235501	0.32	0.76	0.48
14 D	8/9/2011	7.5-8	39.749126	-84.235527	n/d	120	10
15 D	8/9/2011	6.5-7	39.748498	-84.235547	n/d	4.5	n/d
17	8/9/2011	6.5-7	39.751052	-84.234009			
18	8/9/2011	6.5-7	39.750397	-84.234072			
19	8/9/2011	10.5-11	39.749677	-84.234051			
20	8/9/2011	6.5-7	39.748757	-84.234045			
21	8/9/2011	6.5-7	39.749988	-84.234988			
22	8/9/2011	6.5-11	39.749984	-84.235052			
23	8/9/2011	6.5-11	39.749993	-84.235011			
24	8/9/2011	9.5-10	39.749932	-84.235066	50	930	55
25	8/9/2011	10.5-11	39.749941	-84.235178	350	2500	750
26	8/9/2011	6.5-7	39.750593	-84.236166			
27	8/9/2011	6.5-7	39.750698	-84.235991			
28	8/9/2011	6.5-7	39.750423	-84.235552			
29	8/9/2011	6.5-7	39.750663	-84.235282			
30	8/9/2011	6.5-7	39.750306	-84.234818			
31	8/9/2011	6.5-7	39.749637	-84.235072			
32	8/9/2011	6.5-7	39.749649	-84.234679			
33	8/9/2011	6.5-7	39.749749	-84.234474			

2016 Soil Vapor Data							
ID	Date	Depth (ft)	Latitude	Longitude	Chloroform (ppbv)	PCE (ppbv)	TCE (ppbv)
01 D		6.5-7	39.749785	-84.235513			
02 D		6.5-7	39.749834	-84.235265			
03 D		6.5-7	39.749886	-84.235124			
04 D		6.5-7	39.749926	-84.234915			
06 D		6.5-7	39.750107	-84.234865			
07 D		8-8.5	39.750003	-84.235034			
08 D		8-8.5	39.750349	-84.235847			
09 D		6.5-7	39.750531	-84.236279			
10 D		6.5-7	39.750689	-84.236747			
13 D		8.5-9	39.749612	-84.235501			
14 D		7.5-8	39.749126	-84.235527			
15 D		6.5-7	39.748498	-84.235547			
17		6.5-7	39.751052	-84.234009			
18		6.5-7	39.750397	-84.234072			
19		10.5-11	39.749677	-84.234051			
20	6/15/2016	6.5-7	39.748757	-84.234045	n/d	n/d	n/d
21		6.5-7	39.749988	-84.234988			
22		6.5-11	39.749984	-84.235052			
23		6.5-11	39.749993	-84.235011			
24		9.5-10	39.749932	-84.235066			
25		10.5-11	39.749941	-84.235178			
26	6/15/2016	6.5-7	39.750593	-84.236166	340	n/d	n/d
27	6/15/2016	6.5-7	39.750698	-84.235991	9.6	n/d	2.6
28		6.5-7	39.750423	-84.235552			
29		6.5-7	39.750663	-84.235282			
30	6/15/2016	6.5-7	39.750306	-84.234818	n/d	n/d	n/d
31		6.5-7	39.749637	-84.235072			
32	6/15/2016	6.5-7	39.749649	-84.234679		20	
33		6.5-7	39.749749	-84.234474			

Soil Gas Sampling 2016							
Soil Gas Sample	Latitude	Longitude	Date	Depth (ft)	Chloroform (ppbv)	PCE (ppbv)	TCE (ppbv)
SG-22	39.748840	-84.234133	6/15/2016	14	n/d	n/d	n/d
SG-08	39.750617	-84.236218	6/15/2016	10	370	n/d	n/d
SG-07	39.750674	-84.236035	6/15/2016	16	169	n/d	40
SG-15	39.750272	-84.234860	6/15/2016	16	22	n/d	13
SG-16	39.749597	-84.234726	6/15/2016	16	16	4300	1200
SG-17	39.749465	-84.234791	6/15/2016	16	n/d	1600	360

APPENDIX C: RESIDENTIAL SUB-SLAB AND VOC SAMPLING DATA

55 South Ardmore Ave VOC Data									
Sub-Slab VOC					Indoor Air VOC				
Days:	Date:	Chloroform (ppbv)	TCE (ppbv)	PCE (ppbv)	Date:	Chloroform (ppbv)	TCE (ppbv)	PCE (ppbv)	
0	Mar-08	12	360	2	Mar-08	0.21	2.5		0.12
30	Jun-08	1.1	12	0.7	Jun-08	0.29	0.41		0.19
60	Jul-08	0.43	2.5	0.13	Jul-08	0.25	0.33		0.11
180	Nov-08	0.15	2.7	0.14	Nov-08	0.17	0.29		0.12
420	May-09	0.49	1.8	0.12	May-09	2.8	0.25		0.09
450	Jun-09	0.21	2.4	0.12	Jun-09	0.21	0.2		0.12
690	Feb-10	0.14	0.73	0.098	Feb-10	0.16	0.18		0.12

59 South Ardmore Ave VOC Data											
Sub-Slab VOC						Indoor Air VOC					
Date:	Days:	Chloroform (ppbv)	TCE (ppbv)	PCE (ppbv)		Date:	Days:	Chloroform (ppbv)	TCE (ppbv)	PCE (ppbv)	
3/6/2008	0	2200	10000	40	baseline	0	3/6/2008	0.67	4.2	0.11	baseline
7/30/2008	30	0.86	10	0.2	60 days	30	7/30/2008	0.23	0.14	0.1	60 days
11/17/2008	60	0.16	1.6	0.096	180 days	60	11/17/2008	0.16	0.15	0.12	180 days
5/19/2009	180	0.23	0.69	0.11	360 days	180	5/19/2009	0.47	0.15	0.12	360 days
2/17/2010	360	0.16	0.26	0.1	3 years	360	2/17/2010	0.64	0.15	0.12	3 years
6/9/2011	1095	0.14	0.24	0.1	4 years	1095	6/9/2011	0.13	0.12	0.17	4 years
3/1/2012	1460	0.15	0.17	0.11	5 years	1460	3/1/2012	0.17	0.15	0.12	5 years

75 South Ardmore Ave VOC Data											
Sub-Slab VOC						Indoor Air VOC					
Days	Date:	Chloroform (ppbv)	TCE (ppbv)	PCE (ppbv)		Date:	Chloroform (ppbv)	TCE (ppbv)	PCE (ppbv)		
0	6/13/2007	295	316	4.3	baseline	7/19/2007	0.29	0.16	0.19	baseline	
30	1/9/2008	0.41	2.4	0.13	30 days	1/8/2008	0.32	0.14	0.41	30 days	
60	2/14/2008	0.26	1	0.097	60 days	2/14/2008	0.51	0.14	0.11	60 days	
180	6/24/2008	0.21	0.56	0.16	180 days	6/24/2008	0.53	0.14	0.11	180 days	
360	12/17/2008	0.14	0.24	0.1	360 days	12/17/2008	0.67	0.17	0.13	360 days	
1095	2/17/2010	0.15	0.14	0.11	3 years	2/17/2010	0.18	0.15	0.12	3 years	
1460	3/18/2011	0.31	0.14	0.11	4 years	3/18/2011	0.39	0.14	0.15	4 years	
1825	3/1/2012	0.61	0.14	0.11	5 years	3/1/2012	0.46	0.14	0.11	5 years	

110 South Ardmore Ave VOC Data									
Sub-Slab VOC					Indoor Air VOC				
Days	Date:	Chloroform (ppbv)	TCE (ppbv)	PCE (ppbv)		Date:	Chloroform (ppbv)	TCE (ppbv)	PCE (ppbv)
0	5/4/2007	58	270	3600	baseline	5/4/2007	0.5	0.58	19
30	1/8/2008	n/d	n/d	0.29	30 days	1/8/2008	n/d	n/d	0.69
60	2/14/2008	n/d	n/d	0.68	60 days	2/14/2008	n/d	n/d	0.12
180	6/24/2008	n/d	n/d	n/d	180 days	6/24/2008	n/d	n/d	0.49
360	12/17/2008	n/d	0.27	4.3	360 days	12/17/2008	n/d	n/d	n/d
1095	2/17/2010	0.25	0.3	3.2	year 2	2/17/2010	0.44	n/d	n/d
1460	Property vacant after year 2								
	*n/d signifies no detection								

APPENDIX D: WELL LOG STRATIGRAPHY DATA

ODNR Well Log 2038629		
SCALE (m)	LITHOLOGY	NOTES
14		Gray coarse gravel, 45.72cm
13		Black coarse gravel and sand; 76.2 cm
12		Light gray clay, gravel, boulders; 91.44 cm
11		Brown silty clay; 121.92 cm
10		Brown coarse sand and gravel; 106.68 cm
9		Brown fine-coarse sand; 76.2 cm
8		Brown silty clay, 162.88 cm
7		Brown coarse sand and gravel; 91.44 cm
6		Brown fine to coarse sand; 152.40 cm
5

ODNR Well Log 2038626		
SCALE (m)	LITHOLOGY	NOTES
	<p>Asphalt/concrete; 21.33 cm</p> <p>Light gray sandy clay; 54.86 cm</p> <p>Sand and gravel; 137.16 cm</p> <p>Sandy silt; 121.92 cm</p> <p>Gray clay; 60.96 cm</p>

ODNR Well Log 2038632		
SCALE (m)	LITHOLOGY	NOTES
6		Gray coarse gravel and sand; 121.92 cm
5		Brown sand; 60.96 cm
4		Gray clay; 60.96 cm
3		Brown sand and gravel; 91.44 cm
	Sandy clay; 60.96 cm
2		Brown fine to coarse sand; 30.48 cm
	Gray clay; 76.2 cm
1		Gray coarse sand; 15.24 cm
	Gray clay; 60.96 cm
	Brown-gray fine to coarse sand; 30.48 cm

ODNR Well Log 2000868		
SCALE (m)	LITHOLOGY	NOTES
7		Light brown fine to coarse sand and gravel; 198 cm
6
5		Brown sandy clay; 61 cm
4		Brown fine to coarse sand and gravel; 503 cm
3
2
1

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