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PREFERENTIAL PATHWAYS FOR VAPOR INTRUSION: SITE SCREENING AND FIELD SAMPLING OF SEWERS TO ASSESS INHALATION EXPOSURE RISKS

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PREFERENTIAL PATHWAYS FOR VAPOR INTRUSION:
SITE SCREENING AND FIELD SAMPLING OF SEWERS
TO ASSESS INHALATION EXPOSURE RISKS

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THESIS

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A thesis submitted in partial fulfillment of the requirements for the degree of
Master of Science in Civil Engineering
in the College of Engineering at the
University of Kentucky

By

Evan James Willett

Lexington, Kentucky

Director: Dr. Kelly Pennell, Associate Professor of Civil Engineering

Lexington, Kentucky

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ABSTRACT OF THESIS

PREFERENTIAL PATHWAYS FOR VAPOR INTRUSION:
SITE SCREENING AND FIELD SAMPLING OF SEWERS
TO ASSESS INHALATION EXPOSURE RISKS

Hazardous waste sites and aging wastewater infrastructure are common in the United States. There are hundreds of thousands of contaminated sites and more than a million miles of sewer pipes. Populations living close to hazardous waste sites often suffer from increased risk of adverse health effects due to exposure to contaminated environmental media. Vapor intrusion is one process by which nearby populations can be exposed to volatile organic compounds (VOCs). Aging wastewater infrastructure is important for vapor intrusion site assessments because sewer pipes can serve as preferential vapor transport pathways. Near contaminated sites, pipe deterioration allows migration of contaminants into sewers and potential accumulation of chemical vapors in sewer gas and nearby buildings. The objectives of this study are to develop a screening-level method to identify contaminated sites where additional evaluation of vapor intrusion is necessary, and then conduct field sampling at these sites to investigate sewers as potential vapor intrusion pathways. Sampling was conducted at four study sites, which consist of former and current dry cleaning facilities located in Lexington, Kentucky. The results of this study demonstrate that preferential vapor intrusion pathways such as sewers can facilitate the spread of vapor intrusion exposure risks beyond source areas of contamination.

KEYWORDS: vapor intrusion, preferential pathway, sewer systems, hazardous waste, sewer gas, volatile organic compounds

Evan James Willett

April 27, 2018

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SITE SCREENING AND FIELD SAMPLING OF SEWERS
TO ASSESS INHALATION EXPOSURE RISKS

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1 Introduction and Background

Recognition of soil gas intrusion as a national environmental health problem occurred in the 1980s due to concerns about radon intrusion [1]. Radon occurs naturally from the radioactive decay of uranium in soils and is the 2nd leading cause of lung cancer in the United States (US) [2]. As health concerns grew about radon intrusion into buildings, increasing awareness that volatile organic compounds (VOCs) of anthropogenic origin could pose a threat to indoor air quality also grew among regulators and hazardous waste professionals.

Vapor intrusion refers to the migration of VOCs from subsurface sources into overlying buildings and other enclosed spaces. Classically, the conceptual site model for this process has considered contaminated groundwater and soil to be sources of the volatile compounds that migrate into overlying structures. It was not until the 1990s that risk assessors and regulators began to formally consider the potential for vapor intrusion pathways near hazardous waste sites.

1.1 Hazardous Waste Sites

Sites listed on the National Priorities List (also referred to as "Superfund sites") are generally regarded as the Nation's worst hazardous waste sites that pose the greatest environmental health risks. Superfund sites are located in every state and are managed by the federal government. There are currently 1,341 sites on the NPL and 55 proposed for addition to the list [3]. However, these sites represent less than one percent of approximately 300,000 total contaminated sites estimated to exist nationwide [4]. For humans living and/or working close to these locations, exposure to contaminated environmental media, including groundwater, soil, and air, can lead to increased risk of

adverse health effects. Vapor intrusion is a public health concern for human exposure to toxic chemicals through the inhalation pathway [5]. As part of hazardous waste site exposure risk assessment activities, vapor intrusion pathways must be evaluated at nearly all sites contaminated with VOCs. Figure 1-1 shows a conceptual diagram of vapor intrusion into overlying structures.
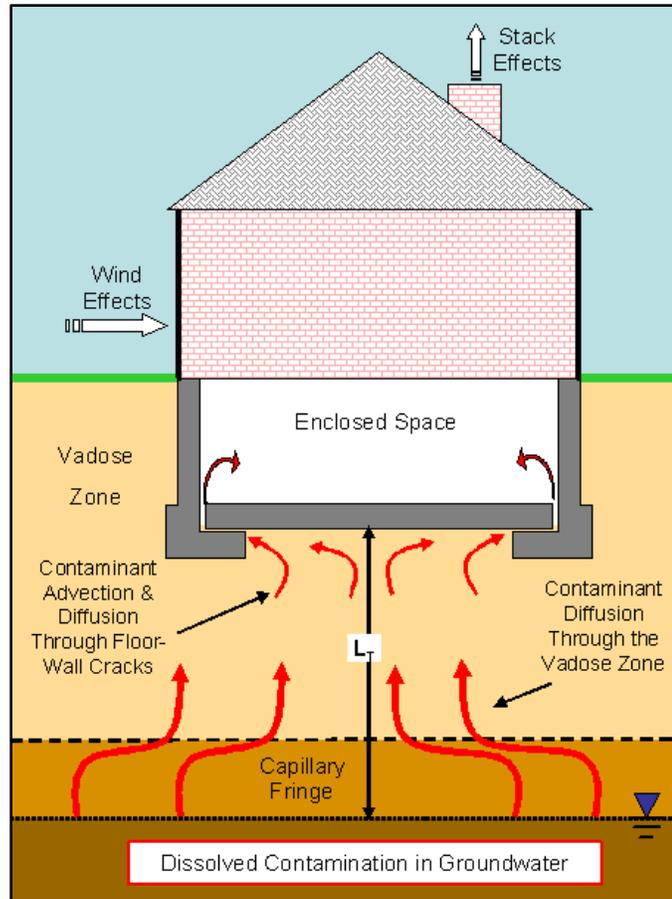
Figure 1-1: Conceptual diagram of vapor intrusion into overlying structures [6]

In the capillary fringe and vadose (i.e., unsaturated) zone, diffusion is the dominant chemical transport mechanism as chemicals volatilize and migrate upwards from an area of high concentration (e.g., groundwater source) to areas of lower concentration. Near the building foundation, both advection and diffusion work to allow migration of chemical vapors into the enclosed space, but advection is the dominant pathway. Advective transport

is caused by pressure differentials between the building and surrounding soil. These pressure differentials can be influenced by building characteristics, occupant behavior, and weather conditions such as wind speed and outside temperature [7].

1.2   Sewer Gas to Indoor Air Pathway

Recent studies have confirmed vapor entry through preferential pathways, especially sewers, suggesting that aging piping infrastructure systems may increase vapor intrusion exposure risks [8, 9]. In 2015, the United States Environmental Protection Agency (EPA) released its highly anticipated, finalized vapor intrusion guidance. This document stated, "EPA also recommends subsurface investigations of vapor intrusion consider whether sewers and other man-made conduits have the potential to transport [non-aqueous phase liquids], contaminated groundwater, and/or vapors (through soil) towards and/or directly into buildings" [10].

Within buildings, plumbing systems are designed to carry away wastewater and properly vent sewer gases, thereby preventing their entry into inhabited indoor air spaces. Sewer gas infiltration to indoor air is unlikely in "perfectly" maintained plumbing systems. Over time, however, vapor seals designed to protect against sewer air intrusion into structures may deteriorate (e.g., pipes crack, fittings and connections loosen, seals become dry). When this occurs, sewer gas vapors have been shown to enter indoor air spaces and accumulate at concentrations exceeding protective, risk-based screening levels in indoor air [8, 9, 11].

In areas where compromised sewer systems intersect VOC plumes in groundwater and soil, contaminated groundwater and soil vapors can easily enter the sewer via infiltration at pipe and manhole failure locations. In addition to infiltration, water and

vapors containing VOCs can enter wastewater pipes through direct discharges to the sanitary sewer system. As a result, indoor air becomes directly connected to sewer air that can contain elevated VOC concentrations. Field studies have provided evidence of sewer systems conveying contaminated groundwater and vapors considerable distances away from delineated groundwater plumes [12]. This creates a need to identify sewer systems that have a high potential to serve as transport pathways of VOC liquids and vapors. Figure 1-2 depicts a conceptual model of how VOCs within a sewer system could enter a building via the sewer gas to indoor air pathway. Typical locations of vapor leaks in a building's plumbing system include cracked pipes, dry vapor traps, loose fittings, faulty seals, and leaking joints [13].

The sewer gas to indoor air pathway is an unexpected and overlooked problem related to aging infrastructure which has been gaining considerable attention and is being included in state and federal guidance [10]. In addition, the Department of Defense (DOD) [14, 15] and EPA [11, 12] have been engaged in research efforts to better understand this exposure risk pathway.

The sewer gas to indoor air pathway is just one example of a preferential migration route. For vapor intrusion assessments, a preferential migration route is a naturally occurring subsurface feature or anthropogenic subsurface conduit expected to exhibit little resistance to groundwater flow (i.e., exhibits a relatively high hydraulic conductivity) or vapor flow in the vadose zone (i.e., exhibits a relatively high gas permeability). In addition to sewer lines and manholes, other anthropogenic migration routes include utility vaults and corridors, subsurface land drains, permeable fill, and underground mine workings that intersect subsurface vapor sources or vapor migration routes [16].
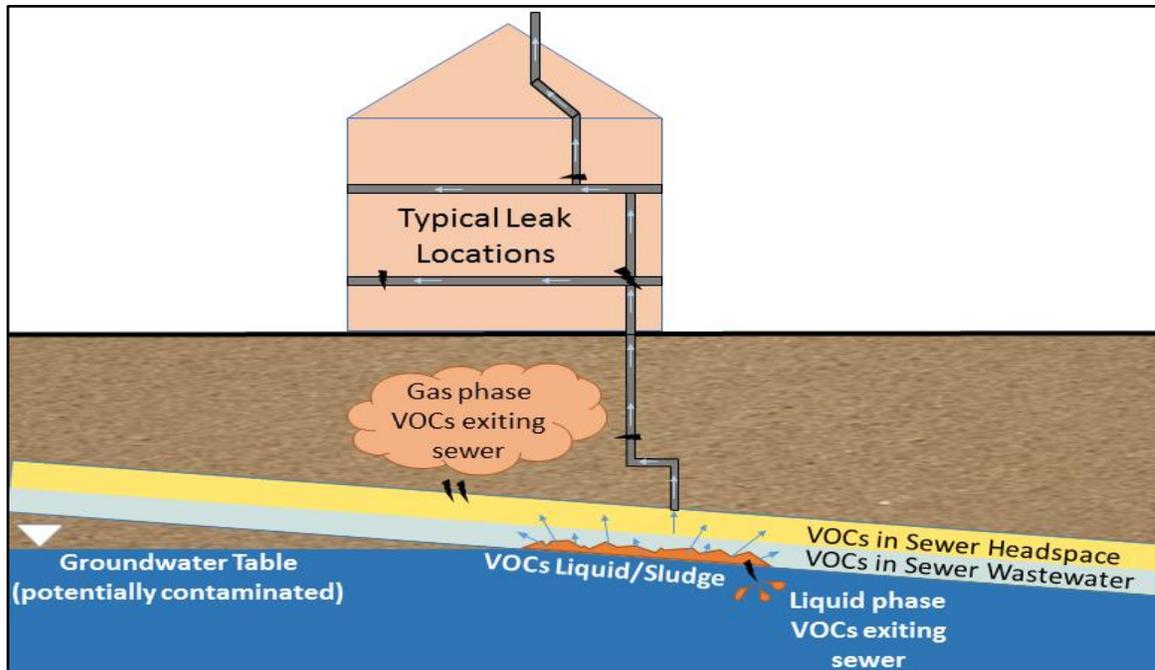
Figure 1-2: Conceptual model of sewer gas to indoor air pathway [17]

In urban areas, extensive networks of subsurface utility corridors and sanitary sewer and storm pipelines are likely to exist, and their presence can significantly influence the migration of contaminants. A preferential migration route can significantly influence vapor intrusion when it is close enough to the VOC source and a building such that it may reasonably be expected to influence vapor migration towards or into the building. Sewer lines flowing through or underneath VOC sources become derivative sources of contamination. Depths of sewer lines and other conduits relative to groundwater are important considerations, as deteriorated pipes located below the groundwater table allow infiltration of contaminated groundwater. Characteristics of preferential pathways such as sewers should thus be considered during standard vapor intrusion investigations. Identification of preferential pathways is especially useful when conducting site screening around hazardous waste sites to determine what buildings have the potential for vapor intrusion impacts through these alternative VOC migration pathways.

The sewer gas pathway is difficult to characterize. It moves the assessment process away from the building and into nearby subsurface conduits. Furthermore, there is uncertainty about which sewers or buildings might have exposure risks. In turn, this uncertainty makes it difficult for regulators to make reliable decisions. Site assessments are complicated by the presence of these pathways, especially considering the aging infrastructure problem—and millions of sewer lines and laterals—in the US.

Dry cleaner sites, often contaminated with chlorinated VOCs (CVOCs), commonly have vapor intrusion issues. In one region of Denmark, more than 20% of dry cleaner sites have sewer gas as a major component of vapor intrusion [18]. Researchers conducting studies funded by DOD suggest that preferential sewer pathways may be important at 10% to 20% of vapor intrusion sites [19]. There is thus a need to screen sites to identify those with sewer gas intrusion issues.

1.3   Aging Infrastructure

Aging infrastructure in the US is a national challenge. In its 2017 Infrastructure Report Card, the American Society of Civil Engineers (ASCE) assigned US wastewater infrastructure a grade of D+. This grade indicates poor performance based on capacity, condition, funding, future need, operation and maintenance, public safety, resilience, and innovation. The grade does constitute, however, a small improvement over the grades of D- and D assigned for US wastewater infrastructure in 2009 and 2013, respectively [20]. Nearly one million miles of public sanitary sewer mains and half a million miles of private sanitary sewer laterals are currently buried in the subsurface across the US. Many of the public sewer mains were installed roughly 70 years ago after World War II as a quickly increasing population necessitated construction of new wastewater systems [21].

Sanitary sewer systems are designed to transport residential, commercial, and industrial liquid wastes to wastewater treatment plants with minimal loss of wastes in transit. Although, as these systems approach or continue to exceed their design life expectancy, poor performance and increased losses are anticipated consequences. Fracturing, separation, and settlement of pipes are to be expected. A combination of physical and chemical factors contributes to sewer degradation, including earth subsidence, biological intrusion, pipe settling, and pipe material corrosion.

Over the next two decades, an estimated $271 billion of capital investments in US wastewater infrastructure will be necessary to meet current and future demands and water quality regulations. With failing pipe networks expected to account for three quarters of total funding, aging sewer lines thus pose a major challenge for modern cities [22]. At $6.24 billion, Kentucky ranks 15th out of 50 states for investment needed in wastewater infrastructure over the next 20 years. Conveyance system repair ($1.80 billion) and construction of new conveyance systems ($2.12 billion) comprise the majority (62.8%) of funding needs [23].

1.4 Project Objectives

The objectives of this project are two-fold:

1. Develop a screening-level method to identify contaminated sites where additional evaluation of vapor intrusion may (and may not) be necessary.
2. Conduct field sampling at selected study sites to investigate sewers as potential vapor intrusion pathways.

Geographic information system (GIS) data and metadata about contaminated groundwater sites and surrounding sewer systems, in addition to information obtained through communication with wastewater authorities and hazardous waste site regulators, were used

to select field study sites where surrounding sewers would be investigated as potential vapor intrusion pathways. These field study sites consist of former or current dry cleaning facilities in Lexington, Kentucky that have known groundwater contamination issues associated with CVOCs.

2   Literature Review

The following sections contain a review of literature pertinent to this study.

2.1   Vapor Intrusion Regulations

In 2002, EPA's Office of Solid Waste and Emergency Response (OSWER), now the Office of Land and Emergency Management (OLEM), issued draft guidance for evaluating subsurface vapor intrusion [24]. This document provided general guidance for evaluating the potential for vapor intrusion pathways at cleanup sites, but did not provide any information on the role of sewer lines and other alternative pathways on vapor intrusion. At the time, EPA noted that the guidance did not include measures to delineate and mitigate potential vapor intrusion risks. To fill this void, a number of state agencies, academic researchers, and public and private sector technical working groups began establishing additional guidance for assessing and managing vapor intrusion. In 2010, EPA was charged with finalizing its vapor intrusion guidance. In 2015, EPA released the finalized guidance [10].

Key updates to this guidance that were not discussed in the draft guidance include the use of multiple lines of evidence in evaluating and making decisions about risks from vapor intrusion, and the ability of sewer lines and subsurface conduits to serve as subsurface vapor sources and preferential vapor migration routes (e.g., the sewer gas to indoor air pathway). EPA recommended that the vapor intrusion conceptual site model identify known or suspected preferential migration routes that could facilitate vapor migration long distances from the source area and at higher concentrations than otherwise expected. Identification of these routes is important from both an assessment and policy

standpoint in order to better understand the overall vapor intrusion issue, improve air quality at vapor intrusion-impacted buildings, and limit human inhalation exposure risks.

2.2 Historical Use of Chlorinated Solvents by Dry Cleaners

In general, hazardous waste sites with groundwater contamination issues associated with VOCs, such as petroleum hydrocarbons (PHCs) and chlorinated solvents, are a major issue. These sites are likely to have vapor intrusion issues. Nearly 80% of Superfund sites are contaminated with VOCs [25]. It should be noted that PHCs attenuate in the subsurface due to aerobic biodegradation in the vadose zone and are often much less persistent, posing lower vapor intrusion exposure risks than CVOCs. CVOCs do not degrade in the vadose zone. PHCs and CVOCs are only slightly soluble in water and form separate-phase liquids, commonly referred to as non-aqueous phase liquids (NAPLs), in the environment. PHC liquids are light NAPLs (LNAPLs), meaning that they are less dense than water and float on the groundwater surface. CVOC liquids, meanwhile, are dense NAPLS (DNAPLs), meaning that they are more dense than water and sink in groundwater to the bottom of aquifers [26]. Due to these important differences, EPA issued separate vapor intrusion guidance documents for CVOCs and petroleum-based VOCs [10, 27].

For CVOCs, dry cleaning facilities are of particular concern because chlorinated solvents have been used historically for dry cleaning operations, and these facilities are often located within or near residential areas. In addition, many dry cleaning facilities do not have environmental remediation budgets to address the extensive contamination resulting from legacy operations. In Denmark, regulators estimate that sewer systems are important alternative exposure pathways for vapor intrusion at more than 20% of contaminated dry cleaning sites in the Central Denmark Region [18].

Carbon tetrachloride was one of the first chlorinated solvents used for dry cleaning purposes in the US when it began to be imported from Germany in 1898. Trichloroethylene (TCE) was introduced as a dry cleaning solvent in the US a few decades later, in 1930. In 1934, tetrachloroethylene (PCE) was introduced. By 1940, the US dry cleaning industry was using an estimated 45 million pounds of carbon tetrachloride, five million pounds of TCE, and 12 million pounds of PCE annually. Chlorinated solvent shortages during World War II led dry cleaning facilities to predominantly use petroleum-based solvents. By the 1960s, the popularity of carbon tetrachloride had waned. PCE became the preferred dry cleaning solvent in the US, with the dry cleaning industry accounting for about 90% of all PCE consumption. TCE, meanwhile, gained footing in another industry, becoming the most used degreasing solvent in the US [28].

As public awareness of the adverse environmental effects was recognized and regulations were passed to protect environmental and human health, production and utilization of PCE began to decline. Major US regulations for drinking water, water pollution control, air quality management, and hazardous waste include the following:

- Drinking water:
  - Safe Drinking Water Act (1974)
- Water pollution control:
  - Federal Water Pollution Control Act (1972)
  - Clean Water Act (1977)
- Air quality management:
  - Clean Air Act (1963; amended in 1970, 1977, and 1990)
- Hazardous waste:
  - Resource Conservation and Recovery Act (1976)
  - Comprehensive Environmental Response, Compensation, and Liability Act (1980)
  - Toxic Substances Control Act (1976)
  - Hazardous Materials Transportation Act (1975)
  - Hazardous and Solid Waste Amendments (1984)
  - Superfund Amendments and Reauthorization Act (1986)

Usage of PCE peaked in the US in 1980 [29]. In 1986, the US Department of Commerce determined there to be about 21,800 dry cleaning facilities in the US. Of these facilities, about 18,900 (86.7%) used PCE. A couple years later, the International Fabricare Institute conducted a survey of dry cleaning equipment and plant operations in the US, concluding that 70.7% of survey respondents discharged separator water (i.e., spent solvent dissolved in water) either to sanitary sewer or septic systems [28].

Several important events for PCE dry cleaning occurred in 2006. First, the California Air Resources Board voted to phase out usage of PCE in dry cleaning by 2023 [30]. A few months later, dry cleaning chemical manufacturers and dry cleaning companies were identified as responsible parties and were required to pay more than $178 million in damages for PCE contamination of water wells and other properties in Modesto, California [31]. EPA also promulgated a final rule for National Perchloroethylene Air Emissions Standards for Dry Cleaning Facilities. This immediately disallowed the use of PCE in new dry cleaning machines installed in residential buildings and also prohibited use of all existing PCE dry cleaning equipment in co-residential dry cleaning facilities beginning in December 2020 [32]. Inhalation exposure risks for nearby populations were important driving factors in this decision.

Today, investigations of vapor intrusion pathways are included as part of nearly all hazardous waste site human health risk assessments, with the sewer system being one of the more recent pathways of concern for chemical transport. Developing a comprehensive strategy for assessing the contribution of the sewer line as a possible source for vapor intrusion ultimately allows for better site characterization and optimized, site-specific remediation plans. Several important field studies investigating vapor intrusion and

preferential transport pathways have been conducted and are discussed in the subsequent section.

2.3   Previous Sewer Vapor Intrusion Investigations

In 1992, Izzo et al. conducted a study in California's Central Valley Region and identified sanitary sewer lines as the main discharge point for dry cleaners of wastewater containing dissolved PCE, free-phase solvent, and solids containing PCE. This was one of the first studies to highlight the presence of PCE contamination near dry cleaners and to find evidence of a sewer system acting as a preferential transport pathway for liquid VOC migration. Most of the dry cleaners included in the study discharged PCE-containing wastewater directly to the sanitary sewer system, at which point the PCE exfiltrated from leaky sewer lines into surrounding groundwater and soil. The discharges of PCE from dry cleaners to sewer laterals were approved and standard methods of waste disposal. This presented complex political and legal issues since most dry cleaners are small businesses that lack adequate financial resources to conduct environmental investigations and cleanup. To prevent further contamination, the study noted that discharges of solvent-containing wastewater to sewer lines should be limited or prohibited [33].

Almost two decades later, regulatory action led to several separate field investigations at various sites across the US and in Denmark that confirmed that sewers could transport vapors into indoor air. These disconnected regulatory actions were later catalyzed by more recent peer-reviewed publications that confirmed the sewer gas to indoor air pathway as part of several higher-profile research studies.

With the oversight of the New York State Department of Environmental Conservation, Distler and Mazierski (2010) completed a consultant-led vapor intrusion

assessment in a residential area adjacent to an industrial area in Niagara Falls, New York. They measured elevated soil gas VOC concentrations at multiple sampling locations. The results were confounding, as shallow groundwater VOC concentrations were limited and there was considerable distance between the elevated soil gas sampling locations and the nearby industrial area. Additional soil gas and sewer vapor sampling provided evidence of VOC transport through subsurface utility tunnels and sewer lines [34].

Regulatory action in Denmark led to a consultant-led study by Riis et al. (2010). This study, conducted in a former industrial area in Skuldelev, Denmark, found indoor air PCE concentrations greater than sub-slab PCE concentrations for some houses within the area. Upon further investigation, it was found that contaminated groundwater infiltrating into fractures and shear failure offsets in sewer lines was serving as the primary migration pathway and source of contamination. Gas-phase transport of contaminants into the sewer was determined to be insignificant. Once in the sewer system, the groundwater contaminants volatilized to sewer air and migrated through the sewer network and into connected homes by advection and diffusion. Tracer gas testing confirmed the infiltration of sewer gases into homes through plumbing fixtures. This confirmed that leaky sewer lines can act as preferential transport pathways for vapor intrusion into buildings near hazardous waste sites [9].

Vroblesky et al. (2010) investigated infiltration and subsequent transport of dissolved groundwater contamination stemming from a former dry cleaning facility at Marine Corps Recruit Depot in Parris Island, South Carolina. An above-ground storage tank used for PCE storage was overfilled on at least one occasion, resulting in transport to a catch basin and ultimately to soil and groundwater after heavy rains caused drainage of

the catch basin. This was the cause of one of two groundwater PCE plumes at the site. The other plume was determined to result from exfiltration of PCE contamination from sanitary sewer lines constructed of vitrified clay pipes. The sanitary sewers, located above the groundwater table, served as sources of contamination originating from direct discharges of solvent-containing wastewater from the former dry cleaning facility. The storm sewers, located below the groundwater, served as receptors of contaminated groundwater that was subject to volatilization as it migrated through the sewer. No indoor air concentrations of nearby buildings were collected during this study, but the subsurface investigations highlight the importance of considering the possible influence of sewer systems during vapor intrusion site assessments. Also of note is the researchers' use of GIS maps of the site and surrounding sewer systems, as well as their use of in-line sewer cameras to examine sewer integrity [35].

One of the first peer-reviewed publications to confirm and develop the conceptual model for the sewer gas to indoor air pathway described a study conducted by Pennell et al. (2013) in the greater Boston, Massachusetts area. The study site was a residential area adjacent to a former dry cleaning chemical handling facility. A pattern of high first floor PCE concentrations and low basement PCE concentrations was observed in several rounds of sampling in one of the homes. These counterintuitive results conflicted with the vapor intrusion site conceptual model, which assumes that vapor-forming chemicals migrate upwards into buildings through cracks, holes, and gaps in building foundations. If vapors migrate upwards, then the highest concentrations are expected in a building's basement, or the first floor if the building does not have a basement. The anomalous results led the researchers to investigate other possible sources contributing VOCs to indoor air.

Interestingly, the homeowner also reported sewer-like odors on the first floor of the home. During follow-up sampling events, the researchers found elevated PCE concentrations at the toilet plumbing connection on the first floor. Sewer gas laden with PCE was therefore the source of first floor PCE concentrations, which were high enough to pose unacceptable human health risks [8].

McHugh et al. (2011) reported an analytical method to distinguish indoor and vapor intrusion sources of VOCs. The researchers applied the compound-specific stable isotope analysis method. This method works by evaluating indoor air samples for carbon and chlorine isotope ratios, which differ depending on the source of contamination. The results of this investigation identified sewer gas as the primary source of TCE in one of five sampled homes [36].

Guo et al. (2015) completed a long-term vapor intrusion study using continuous monitoring techniques. The study site was a house located near Hill Air Force Base, Utah that overlies a groundwater plume containing TCE, 1,1-dichloroethylene, and 1,1,1-trichloroethane. By implementing controlled-pressure-method testing, soil gas sampling, and screening-level emissions calculations, the researchers found that subsurface pipe networks (i.e., sewer mains and land drains), could be significant alternative pathways for vapor intrusion. An important aspect of this study is the presence of an open pipe below the building foundation, believed to be a foundation drain. The pipe was connected to a sewer line containing elevated VOC concentrations. After installing a valve and closing the pipe to prohibit the release of vapors, VOC concentrations in the house decreased. This provided evidence that the land drain was acting as a preferential vapor intrusion pathway at the site [37].

McHugh et al. (2017) conducted a field study at the EPA vapor intrusion research duplex located in Indianapolis, Indiana. This residence is the subject of many investigations to better understand vapor intrusion processes. The purpose of this particular research study was to evaluate the role of a combined sewer line in VOC migration at the house. Tracer gas, sewer vapor, soil gas, and indoor air testing took place at the site. At least two former dry cleaning sites with known PCE groundwater plumes are located north of the duplex and upstream in the sewer system. An elevated PCE concentration (353 µg/m^3) was detected in a sewer manhole adjacent to one of the dry cleaning sites, and PCE concentrations in excess of 100 µg/m^3 were detected in several manholes upstream of the two dry cleaning sites. Some of the manhole depths were shallower than underlying groundwater, suggesting that infiltration of contaminated groundwater into the sewer was not responsible for detections of PCE at these manholes. Tracer gas studies demonstrated gas transport from the sewer main into the duplex. Sewer vapor samples collected in the sewer main in front of the duplex confirmed the presence of PCE and chloroform. The study concluded that sewer lines help facilitate VOC transport from the subsurface contamination source to the vicinity of the duplex building [11].

2.4   Sampling Methods

There is no standard method for detecting the potential contribution of sewer gas pathways in vapor intrusion investigations. Tracer gas tests can be used to identify leakages in sewer pipes, joints, land drains, home plumbing systems, and other components. Various methods to numerically assess contaminant concentrations have been developed and suggested for use in previous vapor intrusion investigations. EPA has developed a series

of analytical methods for measuring VOC concentrations in indoor and ambient air samples. These include EPA Method TO-15 and EPA Method TO-17 [38-40].

Method TO-15 (grab sampling) utilizes evacuated stainless-steel canisters and analysis by GC/MS (SIM). With this method, the concentration at a given point in time can be determined. This method is commonly used to collect soil gas and indoor air samples. Method TO-17 (passive sampling) utilizes tubes packed with adsorbent materials that are thermally desorbed in a laboratory and analyzed by GC/MS. Passive sorbent samplers are much smaller than evacuated stainless-steel canisters and can be used for sample collection times greater than 24 hours. This method provides a time-integrated concentration over the sampling duration. This is especially useful for measuring contaminant concentrations that exhibit short-term temporal fluctuations over orders of magnitude [41]. Performance of passive sorbent samplers depends on sampler design, the type of sorbent, and the target VOCs. Underestimation of contaminant concentrations can occur if there is back diffusion of VOCs from the sorbent during the sampling duration, or if there is irreversible sorption of VOCs onto the sorbent [42]. Additionally, it is important to try to ensure that detection limits for whichever method is used are at least low enough to detect concentrations at risk-based screening levels.

In recent years, real-time and continuous monitoring has been gaining attention as a viable sampling method because it allows for high-frequency collection of data points. On-site analysis improves the speed and quality of site investigations and allows investigators to quickly decide where next to sample. Multiple analyses using Methods TO-15 and TO-17 are sometimes not possible due to cost and access limitations. Real-time, continuous analyzers can be used to collect multiple samples at a sampling location in one

hour, or even multiple samples at different sampling locations at the same time. This allows near-instantaneous collection and analysis of data to locate sampling locations of concern, vapor transport pathways, and indoor sources of VOCs. Data from these analyzers can also be used to analyze long-term trends and can even be correlated with building operation data (i.e., air exchange rates and indoor/outdoor pressure differentials) [43].

2.5   Preliminary Studies

Our research group utilized grab samplers (TO-15), passive samplers (TO-17 and Radiello®), and a novel continuous gas monitoring technology (Autonomous Rugged Optical Multigas Analyzer (AROMA)) to assess sanitary sewers as a vapor intrusion alternative pathway near a hazardous waste site over the years of 2014 to 2017. The results of this research are published [12] and included collaboration with consultants, a sensor company, and EPA.

A large, 1.5-mile-long chlorinated solvent groundwater plume containing elevated levels of TCE (>5 µg/L) exists near the study area located in Mountain View, California. Vapor intrusion issues have been well-documented in buildings overlying the groundwater plume. The sanitary sewer system investigated in the study is constructed of vitrified clay that is known to leak over time. The system was installed in the 1950s—with updates in the 1960s—and historically received wastewater discharges containing concentrated hazardous chemicals from the semiconductor and electronics manufacturing industry. The sewer system intersects the contaminated groundwater plume and continues outside the plume and known vapor intrusion area to a residential community. In the mid-2000s, subsurface contamination was found outside the well-delineated TCE groundwater plume in this residential community. EPA identified historic discharges of TCE to the degraded

sewer system as the source of TCE "hot spots" throughout this neighborhood. Figure 2-1 shows the research study area and locations of TCE hot spots in relation to the groundwater plume.
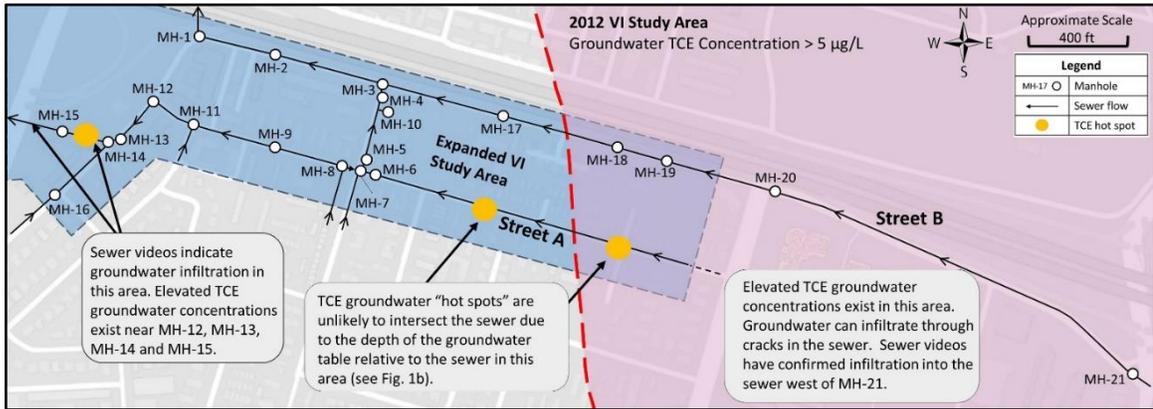
Figure 2-1: Preliminary research study area [12]

Sanitary sewer manholes and cleanouts served as sampling locations, and samples were collected at various depths within the manholes. Manholes and cleanouts are typically easily accessible sampling locations for investigating sewers as vapor transport pathways. Manholes provide information about sewer mains, while cleanouts provide information closer to the point of potential exposure (e.g., indoor air).

Concentrations of TCE and other VOCs were detected above EPA inhalation exposure screening levels at several manholes in the study area using multiple sampling techniques, but concentrations varied both spatially and temporally. Temporal variations in TCE concentrations in the sewer system were found to exist over short-term (hourly) and longer-term (monthly) periods. Passive sampling, grab sampling, and continuous monitoring provided insight about these variations that may not have been seen if only one sampling method had been utilized. Figure 2-2 shows sewer gas TCE concentrations detected in a single manhole from August 2015 to June 2017 using four different sampling methods.
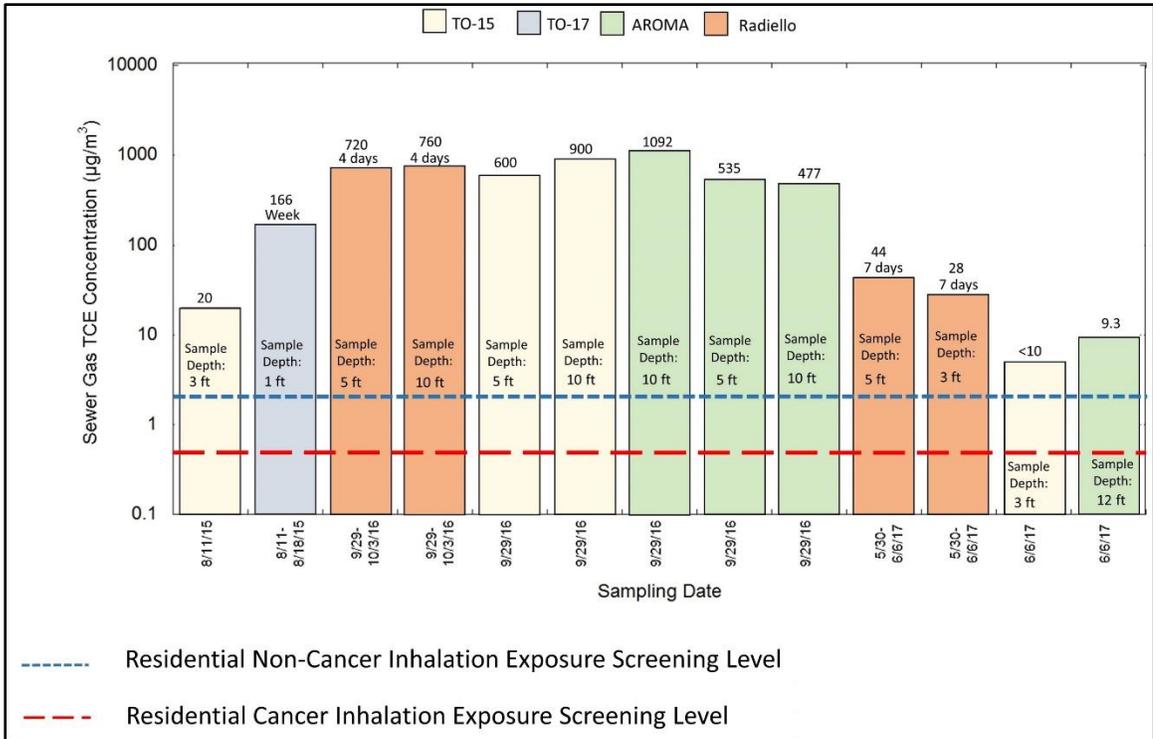
Figure 2-2: Sewer gas TCE concentrations at a single manhole, 2015 to 2017 [12]

Figure 2-2 illustrates that regardless of depth or sampling method, TCE concentrations detected in this manhole during 2016 sampling events were one to two orders of magnitude greater than in 2015 and 2017. This manhole is located a considerable distance from the delineated groundwater TCE plume shown on Figure 2-1. The exact reason for the observed temporal variations in TCE sewer gas concentrations at this manhole could not be determined. Groundwater elevations relative to the bottom of the sewer elevation may have resulted in intermittent groundwater infiltration into the sewer system. The contribution of sewer ventilation as compared to mass transfer of TCE from sewer liquid to the gas phase during sampling events could have also played a role in the observed temporal variability. It is plausible that the temporal variability of VOC concentrations in sewer gas observed in this study may also exist in sanitary sewer systems at (and near) other sites with shallow, VOC-contaminated groundwater.

3   Research Approach

The following sections contain details about the site screening approach, site descriptions, and field sampling approach for this study. In general, the approach begins with geospatial screening using data for sewers that may be easily accessible, yet potentially limited in terms of overall accuracy and quality for some geographic locations. Next, superimposition of hazardous waste site information atop geospatial sewer data helps determine what areas may have VOC contamination and be prone to sewer gas intrusion. After reviewing geospatial information, procurement of sewer records and hazardous waste site records helps determine which locations are appropriate for further investigations. Finally, field sampling can be conducted to assess sewer gas at selected sites.

This approach is limited because Kentucky does not have a publicly searchable database of hazardous waste sites. The Kentucky Department of Environmental Protection (KYDEP) provided information about geographic locations of key sites in 2014, and later a formal records request was submitted to obtain site-specific information. Another limitation of the research described herein was the ability to access locations for sampling because the researchers did not have approval to access all hazardous waste sites of interest. Additionally, sewer manholes and groundwater monitoring wells at some approved sites could not be accessed as part of this research study.

This research approach is still valuable as a site screening method because it is meant to serve as a jumping-off point to identify areas where additional characterization is warranted and where sewer gas intrusion may not have been previously investigated. The approach combines knowledge of both sewers and hazardous waste sites, without beginning with sewer gas concentrations as the only metric by which sewer gas intrusion

is assessed. Furthermore, in other states, such as California, where databases such as GeoTracker [44] exist and are publicly searchable for information about hazardous waste sites and groundwater contamination, this screening approach may prove to be beneficial.

3.1 Site Screening Approach

There are many confirmed reports of sewer gas intrusion into indoor air spaces near hazardous waste sites, but there are no established screening protocols to assess the potential for sewer gas to indoor air pathways to be present at a site. Three key considerations can be reviewed to screen sites of potential concern for vapor intrusion through preferential sewer pathways:

1. What are the conditions and characteristics of subsurface sewer systems near the site?
2. What is the nature of contamination at the site?
3. What are the conditions and characteristics of plumbing systems in buildings near the site?

Consideration 1 is important for assessing the overall condition and likelihood for pipe deterioration of sewer lines near the site and thus the potential for intrusion of groundwater and vapors. Consideration 2 is important for evaluating whether deteriorated sewer lines intersect plumes of contaminated groundwater and vapors, thus allowing infiltration of contaminants into the sewer system. Consideration 3 is important for examining whether plumbing systems of buildings near hazardous waste sites are non-vapor-tight, thus allowing intrusion of contaminants in sewer gas into indoor air spaces. Consideration 3 is the most difficult to evaluate because it often involves invasive investigations that need approval from building owners.

The non-invasive screening approach developed and used in this study focuses on Considerations 1 and 2, which can be evaluated through data collection from and

collaboration with wastewater authorities and hazardous waste site regulators. Important information for evaluating these two considerations include extents of contamination plumes, VOC concentrations in plumes, known sewer pipe failure locations, and plume and pipe intersection locations. Considerations 1 and 2 provide a more informed idea of which areas (i.e., near hazardous waste sites) have the potential for increased exposure risks in indoor air and may require additional sampling to evaluate Consideration 3.

A step-wise screening approach was followed to identify hazardous waste sites of concern for the sewer gas to indoor air pathway that could be further evaluated by field sampling:

1. Download geospatial data for sewer systems and hazardous waste sites from online resources.
2. Submit open records request(s) for reports and geospatial data about hazardous waste sites and sewer sites to local, state, and/or federal government agencies.
3. Analyze data about hazardous waste sites and nearby sewer systems and select sites of concern.
4. Conduct interviews and meetings with stakeholders (e.g., government personnel) that have important knowledge about the selected sites of concern.
5. Develop a conceptual site model for each site to identify sources, receptors, and pathways associated with the site.
6. Collect field data for sewer gas to investigate the suitability of the screening approach.
7. Refine the conceptual site model for each site using field data and communicate findings with stakeholders and decision-makers to support remedial decision-making.

The following sections elaborate on how this approach was carried out in the context of this study.

3.1.1 Data Collection and Site Selection

Physical addresses of hazardous waste sites in Kentucky with known groundwater contamination issues were obtained electronically from the Division of Waste Management

(DWM) of KYDEP in 2014. An open records request submitted to the Kentucky Energy and Environment Cabinet (EEC) facilitated this data collection. KYDEP-DWM oversees the cleanup of contaminated sites within Kentucky to reduce risks to human health and the environment. The obtained dataset was filtered to evaluate only contaminated groundwater sites located in Lexington-Fayette County, Kentucky for future ease of accessibility for site sampling. Table 3-1 provides a summary of this filtered dataset.

Table 3-1: Contaminated groundwater sites in Fayette County, Kentucky

KYDEP Site Status	Number of Sites
Active	10*
Managed	4
Closed	15
Note: *6 of 10 are dry cleaning facilities	

Geospatial shapefile data of sanitary sewer systems in Kentucky were initially downloaded from the Kentucky Infrastructure Authority (KIA) Water Resources Information (WRIS) online portal in 2015. After narrowing the focus of the study to Lexington-Fayette County, Kentucky for future ease of site accessibility, updated geospatial data—specifically for the sanitary sewer system in Lexington—was obtained from the Lexington-Fayette Urban County Government (LFUCG) Division of Water Quality (DWQ). An open records request submitted to the LFUCG Council Clerk's Office facilitated this data collection. LFUCG-DWQ manages the city's storm sewer system and sanitary sewer system. The sanitary sewer system comprises more than 1,400 miles of sewer pipe, 81 pump stations, and two large wastewater treatment plants (i.e., Town Branch and West Hickman) [45].

The updated geospatial data set retrieved from LFUCG-DWQ was used to conduct this study. This data includes spatial and metadata for the sanitary sewer pipes and

manholes in the city. Data downloads are no longer available through the KIA WRIS website. Instead, wastewater infrastructure maps for sanitary sewer systems across Kentucky are now available through an Internet-based mapping application [46].

Hazardous waste site locations in Fayette County were then superimposed onto geospatial sewer system data. The combined data set was then evaluated to determine attributes of the sites and surrounding sewer systems:

- Site regulatory status
    - Active, managed, or closed
    - Previous site usage
- Contamination characteristics of the site
    - Type (e.g., CVOCs, PHCs)
    - Groundwater concentrations
    - Geographic extents of plumes
- Sanitary sewer characteristics
    - Pipe age (i.e., construction date)
    - Pipe material
    - Intersection of pipes and contamination plumes

As mentioned previously, sites with groundwater contamination issues stemming from VOCs, such as PHCs and chlorinated solvents, are likely to have vapor intrusion issues. Dry cleaning facilities are of particular concern because chlorinated solvents have been used historically for dry cleaning operations, and these facilities are often located within or near residential areas. Legacy contamination within sewer systems surrounding dry cleaning facilities is also a concern due to suspected historical discharge of free-phase solvents and wastewater containing dissolved solvents to sanitary sewer lines. Only active dry cleaning facilities (i.e., six sites) were considered as potential field sampling locations. Active sites are defined as sites with ongoing cleanup and/or monitoring activities.

Materials and construction date of sanitary sewer pipes surrounding the hazardous waste sites are important for assessing the potential for pipe degradation and infiltration of

contamination. Sewer pipe deterioration is affected by a multitude of parameters. Pipe characteristics that can be considered include pipe diameter, length, age, slope, depth, and material. Pipe material is an especially important variable impacting deterioration. For example, vitrified clay pipes are prone to leakage at pipe joint locations and cast iron pipes are prone to corrosion in certain soil environments. For this study, "aging" sewer lines were defined as pipes constructed 30 or more years ago.

Evaluating the consequences of failure of sewer pipes alongside the likelihood of failure of sewer pipes allows for assessment of the overall risk of failure of the pipes. Consequences of pipe failure that can be considered for sewer gas intrusion include sewer pipe depth, number of building lateral connections, intersection between sewer pipes and subsurface contaminant plumes, proximity to nearest building, type of building that the sewer pipe serves, toxicity of contaminants in plumes, concentration of contaminants in plumes, etc. Some of these factors, such as sewer pipe depth, contaminant toxicity, and contaminant plume concentrations, were considered when selecting sites of concern for additional evaluation by field sampling.

Four sites have been selected for further evaluation by field sampling based on the geospatial evaluation. While additional contaminated dry cleaning sites were identified as potential field sampling locations, it was not practical to sample all the sites.

3.2   Site Descriptions

Site documents were obtained electronically via open records requests to the Kentucky EEC. Documents included site characterization reports, corrective action plans, and groundwater and soil monitoring reports. Locations and characteristics of sanitary sewer pipes and manholes around the sites were determined through site reconnaissance as

well as review of sewer GIS data and pipe and manhole inspection reports (when available) obtained from LFUCG-DWQ. Personal interviews and meetings with personnel at KYDEP and LFUCG-DWQ were also integral for obtaining important details about the hazardous waste sites and surrounding sewer systems. Summaries of each site's location, history, groundwater, soils, surrounding sanitary sewer system, and remedial activities are provided below.

Site descriptions are limited by the information presented in obtained reports, as subsurface investigations have not been conducted to the same extent for all sites. Supplementary soil data was retrieved from the Web Soil Survey (WSS), an online soil mapping application maintained by the US Department of Agriculture Natural Resource Conservation Service [47]. WSS provides soil information produced by the National Cooperative Soil Survey. Identifiable geographic characteristics and site names have been redacted from all site descriptions, maps, and data.

3.2.1 Site A

Site A consists of a formerly operational dry cleaning facility and its surroundings. The site is no longer under the regulatory jurisdiction of KYDEP-DWM. Although Site A is listed as an "active" site in the hazardous waste site dataset obtained from KYDEP-DWM in 2014, no historic or ongoing groundwater monitoring activities have occurred at the site.

3.2.1.1 Location and History

Site A is located in a commercial area east of downtown Lexington, Kentucky. The former dry cleaning facility at the site is situated at the southwest corner of an L-shaped building. The site is bounded to the north, east, and west by commercial property, and to

the south by a major collector roadway. Properties in the general site vicinity are zoned for commercial and residential purposes. An elementary school is located less than 0.2 miles from the site to the north. Properties to the south and west are used for commercial purposes, while properties to the north and west are used for both commercial and residential purposes [48]. The dry cleaning business leased space and operated at the site from 1986 to 1995 [49-51], but the dates and duration of on-site chlorinated solvent usage could not be determined from site documents. Site A is of interest for this study due to the dry cleaning operations that took place for nearly a decade, which suggest possible impacts to local groundwater and surrounding sewers.

3.2.1.2 Local Groundwater and Soils

Documents obtained for this site do not include any information on local groundwater and soils. According to the WSS, Site A is underlain by soils consisting of urban land, made land, and Bluegrass-Maury silt loams. Urban land and made land soils have high runoff potential, but there is no information about the drainage, permeability, and parent material characteristics of these soils at the site. Bluegrass and Maury series soils at the site are well-drained with moderate permeability and low runoff potential. These soils form from silty material over clayey residuum weathered from phosphatic limestone [47]. Surface elevation of the site as interpreted from a topographic map of the area is approximately 995 to 1005 ft above mean sea level (msl) [52].

3.2.1.3 Groundwater Monitoring

No groundwater monitoring data are available and no groundwater monitoring wells are present at Site A.

3.2.1.4 Remedial Activities

Site documents obtained for this site do not include any information on remedial activities. It is assumed that remedial activities have not occurred at the site.

3.2.1.5 Sanitary Sewers

Sewer GIS data, site reconnaissance, and correspondence with LFUCG-DWQ revealed the locations of several sanitary sewer pipes and manholes near Site A. LFUCG-DWQ verified that several of these manholes were accessible for sampling. Accessible manholes are defined as manholes owned by LFUCG and located in a LFUCG easement. Manhole sampling locations were selected in an attempt to assess sewer gas concentrations of chemicals in sewer mains directly adjacent to the site as well as sewer mains downstream of the site in the direction of sewer liquid flow.

Five manholes were selected for potential sampling at Site A. These manholes are hereafter referred to as MH-A1, MH-A2, MH-A3, MH-A4, and MH-A5. Figure 3-1 shows the locations of manhole sampling locations and sanitary sewer pipes around the former dry cleaning facility at Site A. MH-A3 was originally selected as a potential sampling location but was ultimately deemed unsuitable on the day of sampling due to heavy surface water infiltration into the manhole. Four manholes were ultimately sampled at Site A.

The surrounding sanitary sewer system is composed of 8 in. diameter vitrified clay pipes installed in approximately 1970 (exact installation date unknown, but estimated by LFUCG-DWQ to be between 1965 and 1983). Sanitary sewer mains are located in close proximity (i.e., <100 ft) to the site. Nearby manholes have depths (grade to invert) ranging from 4.1 ft to 6.5 ft. The depth of local groundwater is unknown, since no groundwater monitoring has taken place at the site.
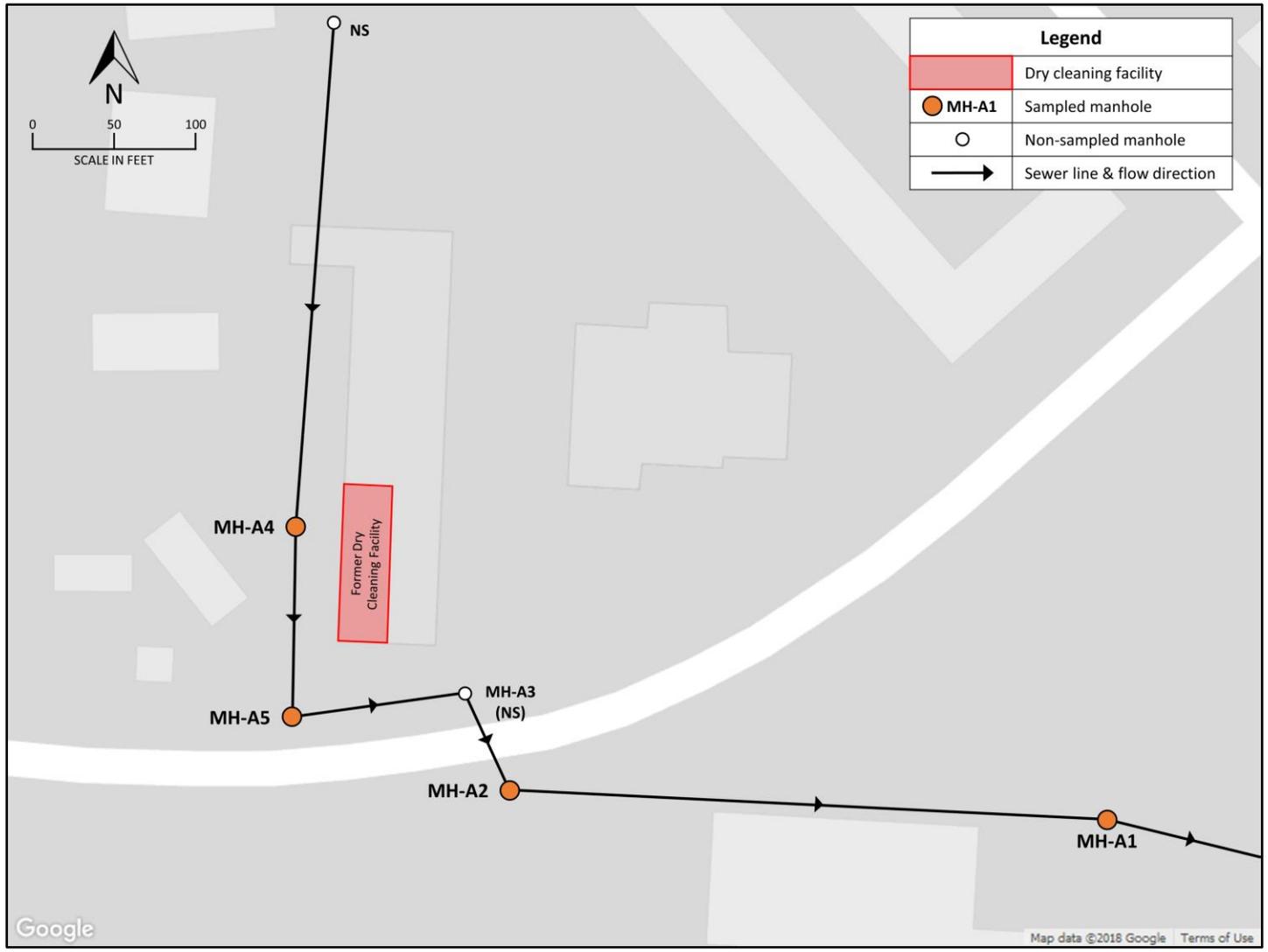
Figure 3-1: Site A sanitary sewer system

3.2.2   Site B

Site B consists of a formerly operational dry cleaning facility and its surroundings. The dry cleaning facility is under the regulatory jurisdiction of KYDEP-DWM. The majority of information provided for Site B has been summarized from site documents obtained through an open records request: Subsurface Investigation [53], Corrective Action Plan [54], and Groundwater Monitoring Report [55].

3.2.2.1 Location and History

Site B is located in a commercial area south of downtown Lexington, Kentucky. The former dry cleaning facility at the site is situated at the northeast corner of a generally rectangular-shaped building. The site is bounded to the north by commercial property and a major collector roadway, to the west and south by a grassy riparian zone that slopes downwards towards a creek, and to the east by a paved parking lot and principal arterial roadway. Properties in the general site vicinity are zoned for commercial and residential purposes. Properties to the northwest are used for commercial and professional purposes. Properties in all other directions are used for residential purposes [48]. The dry cleaning business leased space and operated at the site beginning in 1984. The closure date, as well as dates and duration of on-site dry cleaning (i.e., potential chlorinated solvent usage), could not be determined from site documents. Site B is of interest for this study due to the current and historical presence of chlorinated solvents in the subsurface.

3.2.2.2 Local Groundwater and Soils

Historical groundwater data suggest that groundwater flow in the immediate vicinity of the former dry cleaning facility is towards the north-northwest with an average gradient of approximately 0.087 ft per ft. A small, ephemeral stream runs behind the facility

to the west [55]. According to the WSS, Site B is underlain by soils consisting of Lowell silty clay loam (6% to 12% slopes, severely eroded), Lowell-Faywood silt loam (6% to 12% slopes), and Newark silt loam (0% to 2% slopes, occasionally flooded). Lowell series soils at the site are well-drained with low to moderate permeability and moderate runoff potential. These soils form from clayey residuum weathered from limestone and shale. Newark series soils at the site are somewhat poorly drained with moderate permeability and low runoff potential. These soils form from mixed fine-silty alluvium [47]. Surface elevation of the site as interpreted from a topographic map of the area is approximately 980 ft to 1000 ft above msl [56].

3.2.2.3 Groundwater Monitoring

Nine groundwater monitoring wells are placed at Site B (shown on Figure 3-2). The proposed monitoring schedule specified in the Corrective Action Plan specified groundwater sampling at a frequency of two times per year. Since 2009, groundwater sampling has been performed only once per year in April or May. The primary VOCs of concern for groundwater sampling include PCE, TCE, cis-1,2-dichloroethylene (cis-1,2-DCE), trans-1,2-dichloroethylene (trans-1,2-DCE), and vinyl chloride (VC). Groundwater analyses also include results for a suite of other VOCs, including chloroform and BTEX. Currently, groundwater sampling only occurs at monitoring wells MW-1, MW-2, MW-7, and MW-9. Recent groundwater analytical data for Site B are provided in Section 4.3 of this thesis.

3.2.2.4 Remedial Activities

Three groundwater remediation technologies were considered for potential use at Site B. These technologies included dual-phase extraction, monitored natural attenuation

(MNA), and enhanced bioremediation. Dual-phase extraction was not selected because its efficacy is significantly dependent on the availability of groundwater. Consultants encountered an absence of significant volumes of groundwater during preliminary site characterization. Furthermore, the costs associated with dual-phase extraction were deemed uneconomical considering the low expected effectiveness of this method. Enhanced bioremediation was not selected because it was considered overly aggressive in the absence of sensitive receptors (i.e., potential domestic drinking water use) near the site.

MNA was selected as the method for remediation based on several factors, including the presence of buried utilities, limited availability of groundwater, limited extent of groundwater impact, low levels of VOCs detected in groundwater samples, and presence of cis-1,2-DCE that indicated the occurrence of reductive dechlorination at the site. Furthermore, MNA prevents creation of wastes requiring characterization and disposal. MNA offers a cost-effective and minimally invasive option to allow chemical degradation to continue unassisted.

3.2.2.5 Sanitary Sewers

Sewer GIS data, site reconnaissance, and correspondence with LFUCG-DWQ revealed the locations of several sanitary sewer pipes and manholes near Site B. LFUCG-DWQ verified that several of these manholes were accessible for sampling. Manhole sampling locations were selected in an attempt to assess sewer gas concentrations of chemicals in sewer mains directly adjacent to the site as well as sewer mains downstream of the site in the direction of sewer liquid flow.

Seven manholes were selected for potential sampling at Site B. These manholes are hereafter referred to as MH-B1, MH-B2, MH-B3, MH-B4, MH-B5, MH-B6, and MH-B7.

Figure 3-2 shows the locations of manhole sampling locations and sanitary sewer pipes around the former dry cleaning facility at Site B. MH-B2 and MH-B6 were originally selected as potential sampling locations after review of sewer GIS data, but they could not be located in the field during site reconnaissance and therefore could not be sampled. Five manholes were ultimately sampled at the site.

The surrounding sanitary sewer system is composed of a mixture of 8 in., 10 in., and 15 in. diameter PVC and vitrified clay pipes installed in approximately 1978 (estimated due to unknown exact installation date). Sanitary sewer mains are located in close proximity (i.e., <100 ft) to the site. Nearby manholes have depths (grade to invert) ranging from 5.4 ft to 11.3 ft. The depth of local groundwater below ground surface (bgs) ranges from 4.7 ft to 13.9 ft.
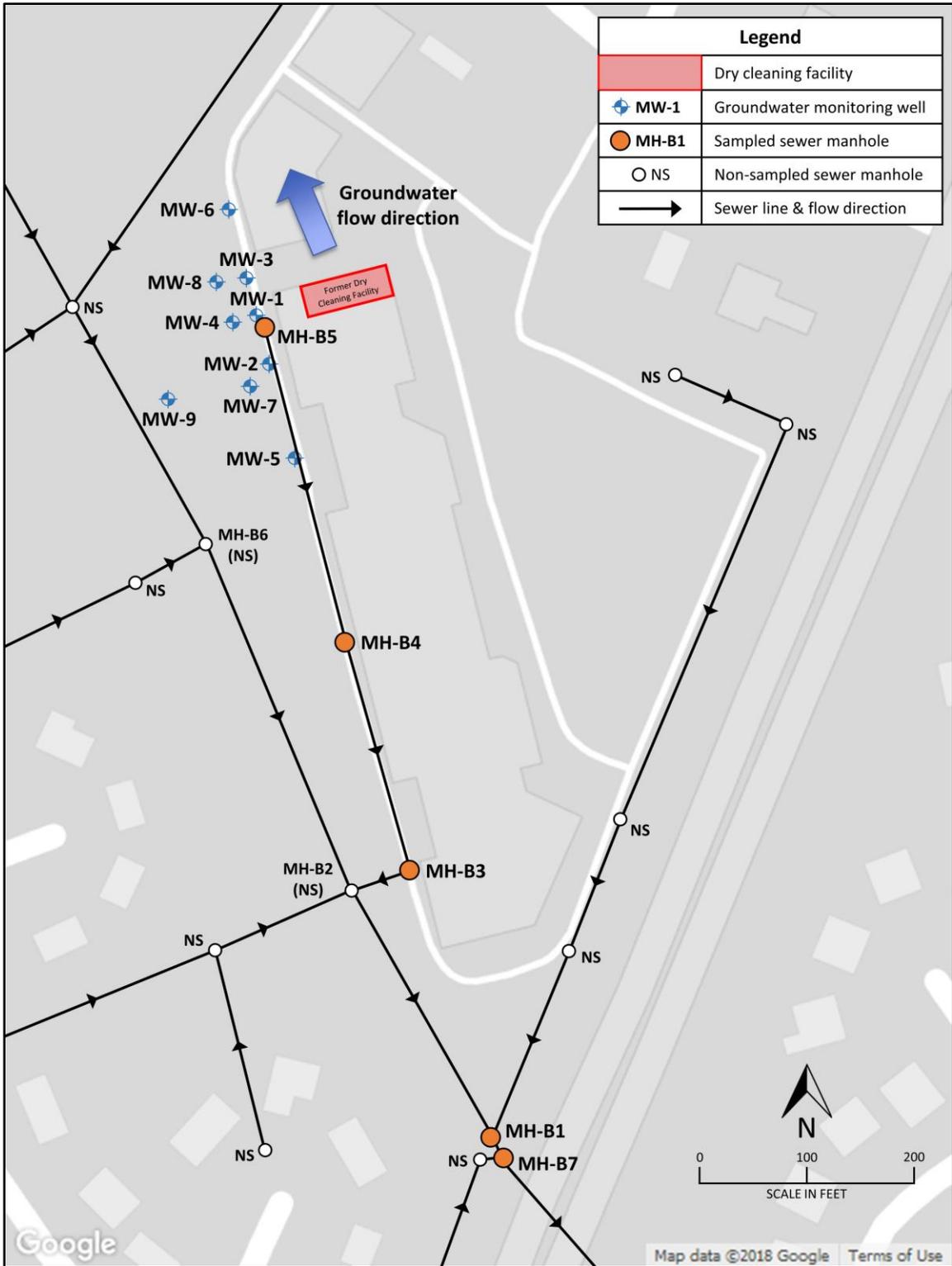
Figure 3-2: Site B groundwater monitoring wells and sanitary sewer system

3.2.3   Site C

Site C consists of a formerly operational dry cleaning facility and its surroundings. The dry cleaning facility is under the regulatory jurisdiction of KYDEP-DWM. The majority of information provided for Site C has been summarized from site documents obtained through an open records request: Interim Corrective Action Plan [57], Corrective Action Plan [58], Site Characterization Report [59], and Groundwater Sampling Results [60].

3.2.3.1 Location and History

Site C is located in a heavily commercial area south of downtown Lexington, Kentucky. The former dry cleaning facility at the site is situated at the corner of the southwest end of an L-shaped strip mall. The site is bounded to the north and east by commercial property, to the west by a paved asphalt parking lot, and to the south by a minor arterial roadway. Properties in the general site vicinity are zoned for residential, commercial, and professional office purposes. Properties to the south (beyond the roadway) are used for professional office and residential purposes, while properties to the north, east, and west are used for commercial purposes [48]. An active gasoline station abuts the property immediately to the east.

The dry cleaning business leased approximately 1,800 square ft in the commercial shopping center and operated from 1973 to 2001. The site was a vacant lot prior to the opening of the strip mall and dry cleaners, which were built using slab-on-grade construction. Dry cleaning operations, which involved the use of PCE, occurred on-site until 1993. From 1993 to the closing of the facility in 2001, dry cleaning operations were performed off-site and the facility was used only as a drop-off and pick-up location for dry

cleaned clothing; on-site handling of PCE and other CVOCs did not occur during this time. Site C is of interest for this study due to the current and historical presence of chlorinated solvents in the subsurface.

Following the departure of the dry cleaning business from the site, owners of the shopping center hired a consulting firm to conduct an environmental site inspection for property transfer purchases. VOCs were detected in the subsurface during initial inspections. The dry cleaning business subsequently retained the same consulting firm for additional subsurface investigations at the site. After the presence of VOCs in groundwater and soil samples was confirmed by additional investigations, the consulting firm developed and implemented interim corrective action for site remediation. The goal of corrective action was to reduce VOC concentrations in soil and groundwater to below maximum contaminant levels (MCLs), thus enabling future unrestricted use of the property.

3.2.3.2 Local Groundwater and Soils

Historical groundwater data suggest that groundwater flow in the immediate vicinity of the former dry cleaning facility is towards the south-southeast. West Hickman Creek and its tributaries provide surface drainage for surface drainage in the site vicinity. West Hickman Creek joins East Hickman Creek to create Hickman Creek, which eventually flows into the Kentucky River. Prior to construction of the site, drainage was previously directed toward a large pond located east-northeast of the shopping center, site drainage was directed to the east-northeast towards a large pond. Cut-and-fill grading activities during construction resulted in filling of the pond, thereby significantly altering the direction of surface runoff. Most surface runoff now flows into the storm sewer system

that runs along the minor arterial roadway to the south of the site and eventually discharges into a tributary of West Hickman Creek.

According to the WSS, Site C is underlain by soils consisting of Maury-Bluegrass silt loams (6% to 12% slopes) and Bluegrass-Maury silt loams (2% to 6% slopes). Maury series soils at the site are well-drained with moderate permeability and moderate runoff potential. Bluegrass series soils at the site are well-drained with moderate permeability and moderately high to high runoff potential [47]. Maury series soils mapped previously in the vicinity of the site exhibited hydraulic conductivities of 1.26 to 4 ft per day close to the surface and 0.4 to 1.26 ft per day at depths below five feet. Surface elevation of the site as interpreted from a topographic map of the area is approximately 1015 ft to 1040 ft above msl [61].

Soil borings collected in May 2003 reveal bedrock 19 ft to 21 ft below the surface of the site near the former dry cleaning facility, which is elevated above surrounding topography. At MW-5, MW-6, and MW-7 (shown on Figure 3-3), bedrock occurs at more shallow depths of 7.5 ft to 11.6 ft. Native material overlying bedrock is made of 6 ft to 10 ft of brown residual clay, which is generally stiff with low plasticity and relatively low permeability. A silty zone of 2 ft to 3 ft thickness occurs locally at the site, roughly 10 ft bgs. Overlying fill materials predominantly consist of reworked residual clay with gravel near ground surface.

3.2.3.3 Groundwater Monitoring

Nine groundwater monitoring wells are placed at Site C (shown on Figure 3-3). The proposed monitoring schedule specified in the Corrective Action Plan specified groundwater sampling at a frequency of two times per year. Since 2013, groundwater

sampling has been performed only once per year in January. The primary VOCs of concern for groundwater sampling include PCE, TCE, cis-1,2-DCE, trans-1,2-DCE, and VC. Groundwater analyses also include results for a suite of other VOCs, including chloroform and BTEX. Currently, groundwater sampling occurs at all nine monitoring wells. Recent groundwater analytical data for Site C is provided in Section 4.3 of this thesis.

3.2.3.4 Remedial Activities

The objective of proposed corrective actions was to reduce contaminant concentrations in groundwater to below MCLs. Remediation alternatives were evaluated based on overall protection of human health and the environment, attainment of remediation goals, short- and long-term effectiveness, ability to be implemented, and estimated costs. Considering the time required to implement and assess performance of a corrective remedial action, in-situ remediation was strongly preferred over conventional vapor and groundwater extraction technologies (i.e., pump and treat, air sparging) for Site C. In-situ chemical oxidation (ISCO) using potassium permanganate ($KMnO_4$) was selected as the method for remediation based on several factors:

- Low residual concentrations of contaminants of concern (COCs) over most of the impacted area
- Small area of concentrated residual
- No identified source of concentrated residual in the soil

Potassium permanganate ISCO works excellently for transforming chlorinated ethenes into non-toxic products such as water (H_2O), carbon dioxide (CO_2), potassium (K^+), and manganese oxide (MnO_2), which is naturally present in soil. The oxidation reactions for destruction of chlorinated ethenes using potassium permanganate are as follows [62]:

PCE: $4KMnO_4 + 3C_2Cl_4 + 4H_2O \rightarrow 6CO_2 + 4MnO_2 + 4K^+ + 8H^+ + 12Cl^-$

TCE: $2KMnO_4 + C_2HCl_3 \rightarrow 2CO_2 + 2MnO_2 + 2K^+ + H^+ + 3Cl^-$

DCE: $8KMnO_4 + 3C_2H_2Cl_2 \rightarrow 6CO_2 + 8MnO_2 + 8K^+ + 2OH^- + 6Cl^- + 2H_2O$

VC: $10KMnO_4 + 3C_2H_3Cl \rightarrow 6CO_2 + 10MnO_2 + 10K^+ + 7OH^- + 3Cl^- + H_2O$
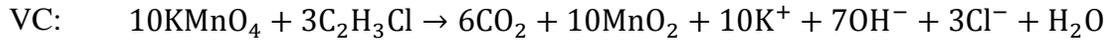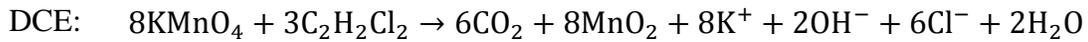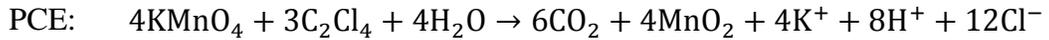
Another advantage of potassium permanganate ISCO is that potassium permanganate itself is non-toxic, thereby making it compatible with bioremediation that could be occurring naturally in the subsurface.

Anticipated injection rates of potassium permanganate into the saturated and unsaturated zones were 190 pounds (760 gallons) and 65 pounds (260 gallons), respectively; potassium permanganate was mixed with water for a 3% solution by weight. 69 injection borings were spaced at 9 ft center-to-center due to the presence of low permeability clays. Groundwater monitoring preceded and followed injection, which took place in January 2004. Subsequent monitoring results showed that COC concentrations greater than MCLs were still present in groundwater at some site locations. Additional remedial strategies were then considered.

In-situ remediation was again preferred to avoid obstructions to nearby businesses. Accelerated natural attenuation using biological technologies was considered the most favorable in-situ technology based on several factors:

- Low residual concentrations of COCs (i.e., favorable for biological treatment)
- Continued presence of biodegradation products in subsurface, indicating that natural attenuation is possible
- Low permeability soils limit the delivery, contact, and overall effectiveness of chemical oxidant injections
- Greater longevity of accelerated natural attenuation over chemical oxidation
  Hydrogen Release Compound (HRC™) and Hydrogen Release Compound

Extended Release Formula (HRC-X™) selected for injection. HRC™ and HRC-X™ have

estimated longevities of 18 months and three to five years, respectively. When introduced to the subsurface, these compounds slowly release electron donors that facilitate microbial degradation of the chlorinated COCs. The compounds can also migrate by diffusion or advection with groundwater flow.

Anticipated injection rates of HRC™ and HRC-X™ into the saturated zone were 3,450 pounds and 1,740 pounds, respectively; both compounds were heated prior to mixing and injection due to their high viscosities. 143 injection boring were spaced at 8 ft center-to-center due to the presence of low permeability clays. Groundwater monitoring preceded and followed injection, which took place in May 2008. Subsequent monitoring results showed that COC concentrations in most wells remained stable or decreased, with an overall decreasing trend. Continued formation of DCE and VC provided evidence of the continuing occurrence of reductive dechlorination in the subsurface.

3.2.3.5 Sanitary Sewers

Sewer GIS data, site reconnaissance, and correspondence with LFUCG-DWQ revealed the locations of several sanitary sewer pipes and manholes near Site C. LFUCG-DWQ verified that several of these manholes were accessible for sampling. Manhole sampling locations were selected in an attempt to assess sewer gas concentrations of chemicals in sewer mains directly adjacent to the site as well as sewer mains downstream of the site in the direction of sewer liquid flow.

Five manholes were selected for potential sampling at Site C. These manholes are hereafter referred to as MH-C1, MH-C2, MH-C3, MH-C4, and MH-C5. Figure 3-3 shows the locations of manhole sampling locations and sanitary sewer pipes around the former

dry cleaning facility at Site C. All manholes selected as potential sampling locations were ultimately sampled at the site.

The surrounding sanitary sewer system is composed of 8 in. diameter vitrified clay pipes installed in approximately 1970 (exact installation date unknown, but estimated to be between 1965 and 1983). Sanitary sewer mains are located in close proximity (i.e., <100 ft) to the site. Nearby manholes have depths (grade to invert) ranging from 4.1 ft to 12.0 ft. The depth of local groundwater bgs ranges from 9.74 ft to 19.96 ft. Site geology has predominately-low permeability, thus indicating that preferential transport of contaminants may occur along subsurface utility corridors that have higher permeability (e.g., sewers). Groundwater contamination has been detected at monitoring wells located along or a close lateral distance away from sanitary sewer lines.
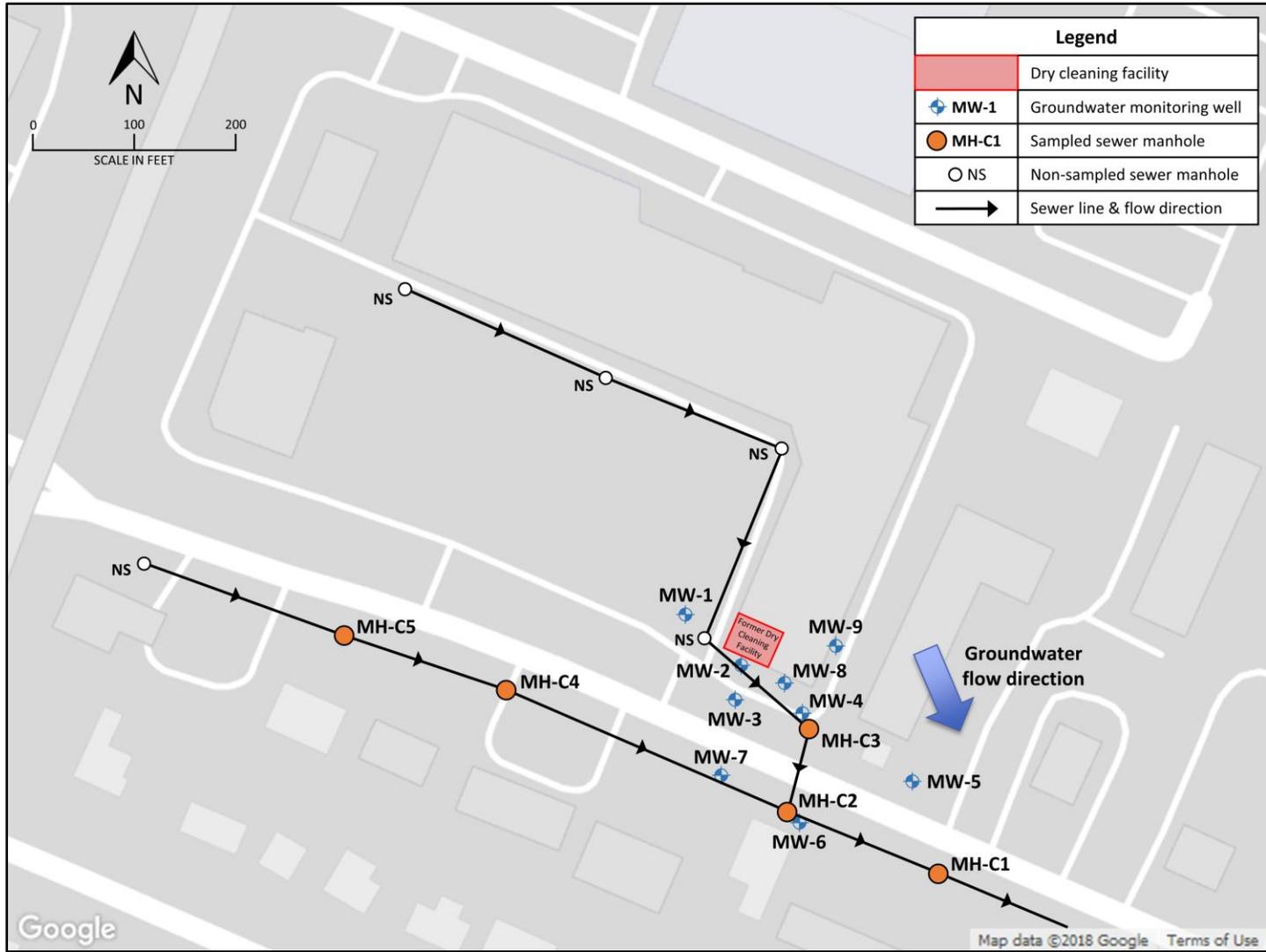
Figure 3-3: Site C groundwater monitoring wells and sanitary sewer system

3.2.4 Site D

Site D consists of a currently operational dry cleaning facility and its surroundings. The dry cleaning facility is under the regulatory jurisdiction of KYDEP-DWM. The majority of information provided for Site D has been summarized from the Corrective Action Plan [63], another Corrective Action Plan [64], and Status Report [65].

3.2.4.1 Location and History

Site D is located in a heavily commercial area south of downtown Lexington, Kentucky. The current dry cleaning facility at the site is situated in the southern portion of an L-shaped strip mall. The site is bounded to the north by a paved parking lot (minor collector roadway beyond), to the west by a paved parking lot (principal arterial roadway beyond), to the south by a paved/gravel alley (commercial property beyond), and to the east by a paved/gravel alley (residential property beyond). Properties in the general site vicinity are zoned for commercial and residential purposes. Properties to the north are used for professional office and residential purposes, properties to the south and west are used for commercial purposes, and properties to the east are used for residential purposes [48].

The dry cleaning business, which is still active, has leased space and operated in the main shopping center building at the site since 1960. The dates and duration of on-site chlorinated solvent usage could not be determined from site documents, but a conversation with an employee of the dry cleaner revealed that dry cleaning has not recently been performed on-site. Site D is of interest for this study due to the current and historical presence of chlorinated solvents in the subsurface.

3.2.4.2 Local Groundwater and Soils

Historical groundwater data suggest that groundwater flow in the immediate vicinity of the former dry cleaning facility is towards the north-northeast. Groundwater velocity and gradient have been estimated at approximately 5 to 6 ft per year and 0.018 ft per ft, respectively.

Soils at the site largely consist of reddish-brown clay to silty clay with numerous phosphate nodules. Soil borings drilled at the site have revealed a few silty/sandy layers. Little information has been documented about the specific lithology at the site; soil borings drilled at the site varied from approximately 11 ft to 18 ft bgs. Consultants hired to conduct an environmental inspection have assumed soil stratigraphy at the site. These assumptions are presented in Table 3-2.

Table 3-2: Site D soil stratigraphy

Depth Below Ground Surface	Soil Type
0 to 1 ft bgs	Gravel and fill from construction activities
1 to 3 ft bgs	Fill from construction activities
3 to 11.4 ft bgs	Clay and silty clay, or silt and clayey silt
11.4 to 15.8 ft bgs	Limestone bedrock

According to the WSS, Site D is underlain by soils consisting of urban land, made land (over silty materials), Bluegrass-Maury silt loams (2% to 6% slopes), and Maury-Bluegrass silt loams (6% to 12% slopes). Urban land and made land soils at the site have high runoff potential, but there is no information about the drainage, permeability, and parent material characteristics of these soils. Bluegrass series soils at the site are well-drained with moderately high to high permeability and low runoff potential. Maury series soils at the site are well-drained with moderate permeability and runoff potential [47]. Surface elevation of the site as interpreted from a topographic map of the area is

approximately 1000 ft to 1015 ft above msl [66]. Topography maps show that the surface slopes to the north, and potentiometric surface maps show that groundwater also flows to the north. A paved parking lot or buildings cover much of the site.

3.2.4.3 Groundwater Monitoring

Nine groundwater monitoring wells are placed at Site D (shown on Figure 3-4). The proposed monitoring schedule specified in the Corrective Action Plan specified groundwater sampling at a frequency of two times per year. Since 2013, groundwater sampling has been performed only once per year in January. The primary VOCs of concern for groundwater sampling include PCE, TCE, cis-1,2-DCE, trans-1,2-DCE, and VC. Groundwater analyses also include results for a suite of other VOCs, including chloroform and BTEX. Currently, groundwater sampling only occurs at monitoring wells MW-1, MW-2, MW-3, MW-6, and MW-9. Recent groundwater analytical data for Site D is provided in Section 4.3 of this thesis.

3.2.4.4 Remedial Activities

Remediation options at the site are limited by the abundance of buildings at the site as well as numerous utility lines buried in the subsurface behind (i.e., south of) the property. Pump and treat was deemed impractical due to poor recharge of most groundwater wells at the site. Additionally, clayey soils present at the site do not have adequate porosity and permeability for vapor extraction or other in-situ treatment methods.

Natural attenuation was determined to be occurring in the subsurface due to the presence of PCE degradation products. Original corrective actions at the site (i.e., in 2002) sought to augment natural attenuation with potassium permanganate ISCO. The benefits

and chemical reactions associated with the use of potassium permanganate for oxidation of chlorinated ethenes have been previously described for Site C.

Typical solutions of potassium permanganate in water for ISCO applications range from 4% to 6%. Injections were planned to take place at approximately 20-foot intervals primarily in the paved parking lot just north of the dry cleaning facility, depending on site utilities, subsurface obstructions, well locations, and other site features. Groundwater monitoring wells MW-1, MW-2, MW-3, and MW-4 were also planned for use as injection points. Specific details about the percent solution, injection rates, and number, spacing, and locations of injection borings are unknown because the post-injection report for the site could not be obtained. Groundwater monitoring preceded and followed injection, which took place in July and August, 2002. MNA was subsequently used for remediation to allow chemical degradation to continue unassisted until the COCs diminish to concentrations below MCLs.

3.2.4.5 Sanitary Sewers

Sewer GIS data, site reconnaissance, and correspondence with LFUCG-DWQ revealed the locations of several sanitary sewer pipes and manholes near the site. LFUCG-DWQ verified that several of these manholes were accessible for sampling. Manhole sampling locations were selected in an attempt to assess sewer gas concentrations of chemicals in sewer mains directly adjacent to the site as well as sewer mains downstream of the site in the direction of sewer liquid flow.

Five manholes were selected for potential sampling at Site D. These manholes are hereafter referred to as MH-D1, MH-D2, MH-D3, MH-D4, and MH-D5. Figure 3-4 shows the locations of manhole sampling locations and sanitary sewer pipes around the former

dry cleaning facility at Site D. All manholes selected as potential sampling locations were ultimately sampled at the site.

The surrounding sewer system is composed of 8 in. diameter PVC, vitrified clay, and ductile iron pipes installed in approximately 1930 (exact installation date unknown, so estimate is based on the oldest line in the center of town). Sanitary sewer mains are located in close proximity (i.e., <100 ft) to the site. Nearby manholes have depths (grade to invert) ranging from 3.0 ft to 8.2 ft. The depth of local groundwater bgs ranges from 6.4 ft to 10.4 ft. Three of the five groundwater monitoring wells that currently exist at the site (i.e., MW-2, MW-3, and MW-9) had detectable concentrations of PCE, TCE, cis-1,2-DCE, or VC during the most recent sampling event. Interestingly, these three monitoring wells are located along or a close lateral distance away from sanitary sewer lines, while the other two wells are not.
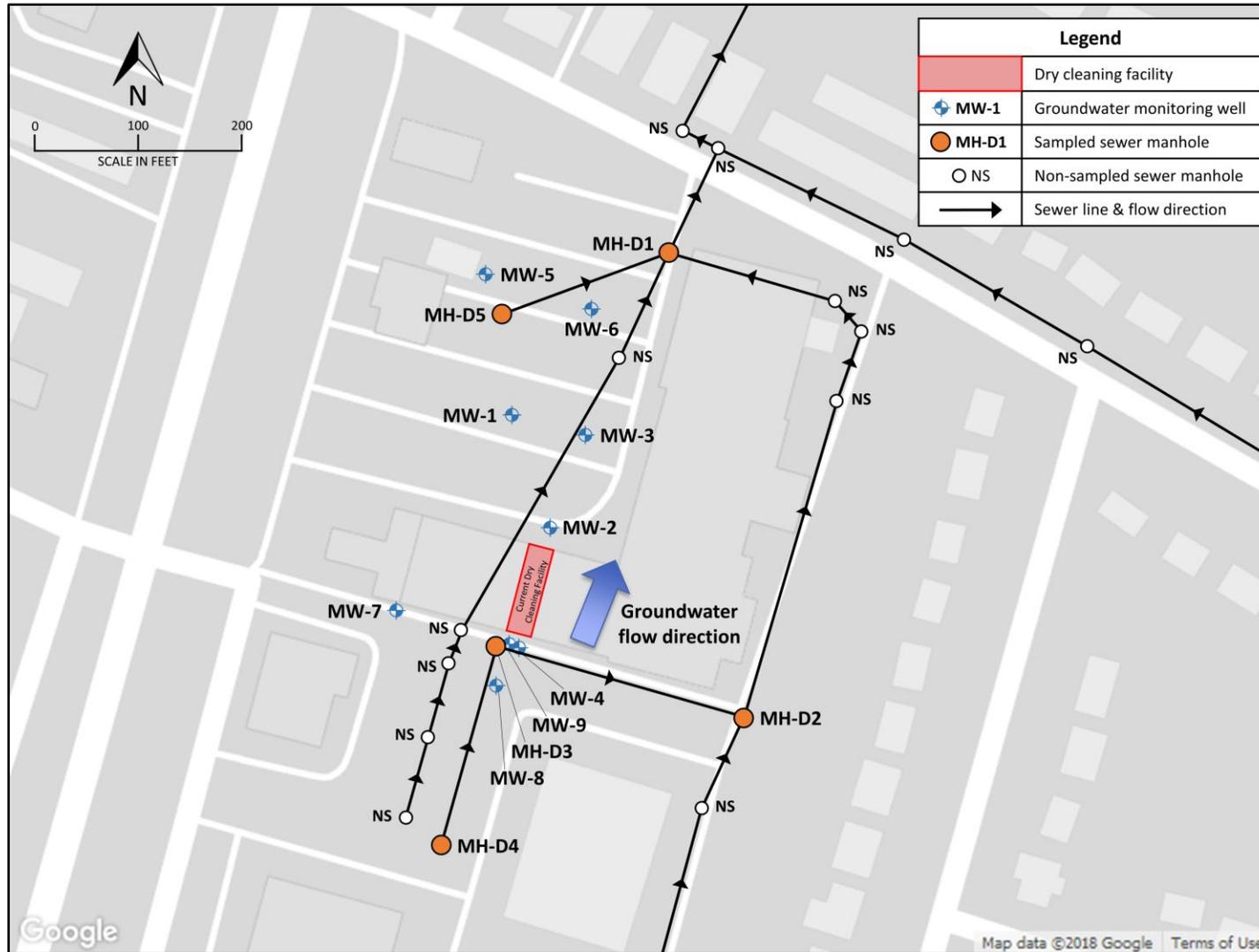
Figure 3-4: Site D groundwater monitoring wells and sanitary sewer system

3.3   Field Sampling Approach

Prior to field sampling, a health and safety plan was developed. The health and safety plan can be found in the Appendix. 19 sanitary sewer manholes were sampled during this study. Four manholes were sampled at Site A and five manholes were sampled at each of Sites B, C, and D. Manhole accessibility was verified with LFUCG-DWQ prior to field sampling; all sampled manholes are owned by LFUCG and located within an LFUCG easement. Manholes were located along sanitary sewer mains. Some sanitary sewer manholes identified as potential sampling locations during site screening activities could not ultimately be sampled, as they are not located within an LFUCG easement and therefore inaccessible. Sewer gas sampling could not be conducted concurrently with groundwater monitoring at any of the four sites.

At Site A, manholes were situated in a paved parking lot, along a street, and in a grassy area. Sanitary sewers at this site are within a sub-sewershed (NE2) of the North Elkhorn sewershed that conveys sewage to Town Branch Wastewater Treatment Plant (TB WWTP). At Site B, manholes were situated in a paved alley and in a grassy riparian zone, adjacent to a stream. Sanitary sewers at this site are within a sub-sewershed (EH3) of the East Hickman sewershed that conveys sewage to West Hickman Wastewater Treatment Plant (WH WWTP). At Site C, manholes were situated in paved parking lots, along a street, and in a grassy area. Sanitary sewers at this site are within a sub-sewershed (WH2) of the West Hickman sewershed that conveys sewage to WH WWTP. At Site D, manholes were situated in paved parking lots and a paved, gravel-covered alley. Sanitary sewers at this site are within a sub-sewershed (WR7) of the Wolf Run sewershed that conveys sewage to

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the TB WWTP. Figure 3-5 shows a map of the study site locations and their respective sewersheds in Fayette County, Kentucky.
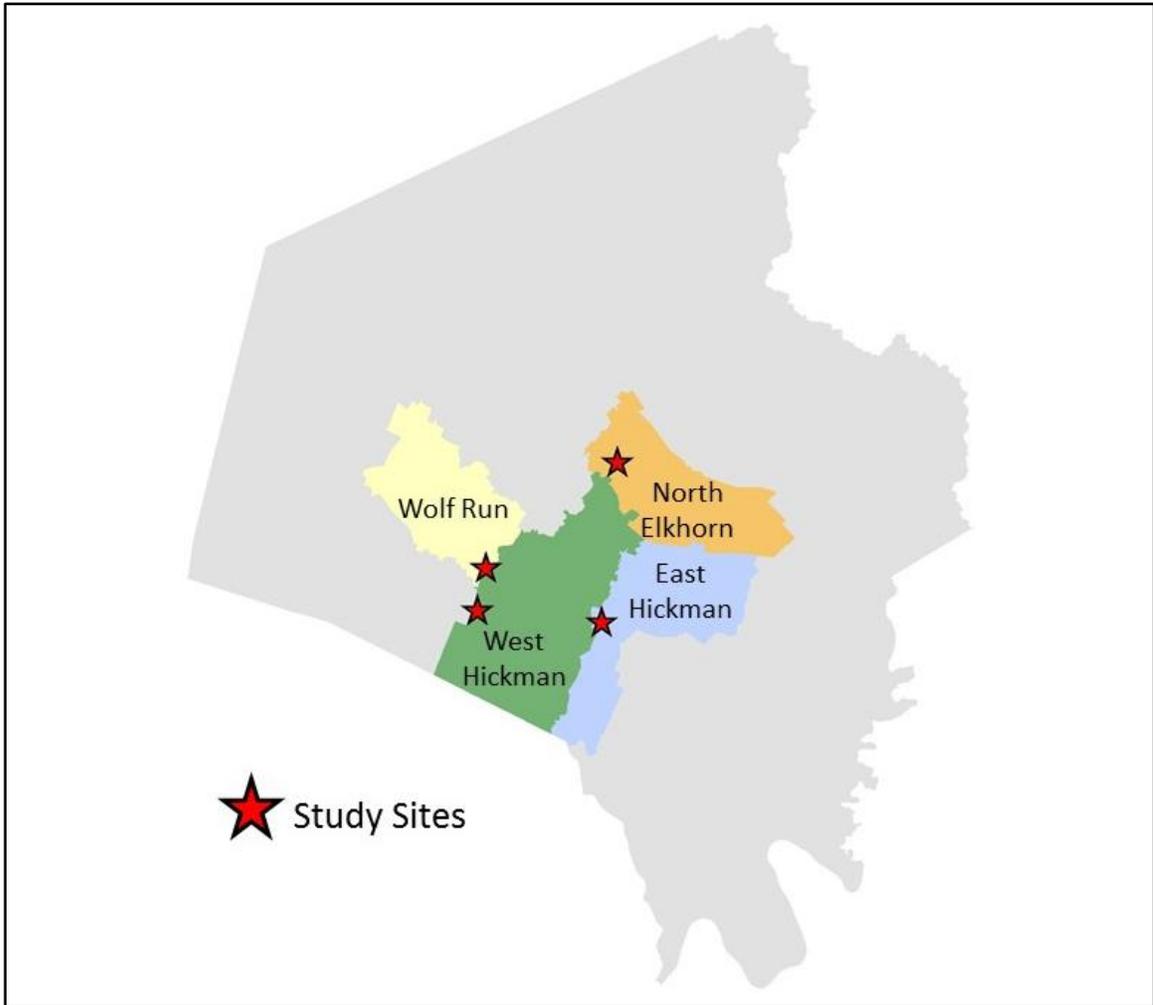
Figure 3-5: Study site locations and sewersheds in Fayette County, Kentucky

3.3.1   Sampler Deployment and Retrieval

Manhole covers were removed briefly during sampler deployment and retrieval to facilitate sampling activities, since there were no access points in the covers large enough for the samplers to pass through. LFUCG-DWQ provided assistance for manhole cover removal. Passive samples were collected at deep depths in manholes, approximately one foot above the top of the channel within the manhole. The manhole sampling train consisted

of an upper and lower portion. The upper portion was assembled in the laboratory prior to sampler deployment, and the lower portion was assembled in the field on the day of field sampling, immediately before sampler deployment. The upper and lower portions were connected in the field.

The upper portion consisted of two neodymium magnets with eyebolts, two lengths of steel wire, and a stainless-steel O-ring. Neodymium magnets were small (1.26 in. diameter by 1.38 in. height) and capable of resisting 65 lbs of pulling force (normal to surface). A length of 20-gauge steel wire was connected to the eyebolt of each magnet, and both pieces of steel wire were then connected to the stainless steel O-ring. The extended length, from magnet to magnet, was at least 22.75 in.—and typically several inches longer—to ensure a proper fit inside the manhole. LFUCG standard specifications for sanitary sewer manhole covers require cast iron material, 22.75 in. diameter, and two pick holes about 1.25 in. wide and 0.5 in. deep with 3/8 in. undercut all around. The manhole cover sits atop a cast iron frame [67]. The magnetic properties of cast iron were exploited to connect the magnets on the sampling train to the manhole frame.

The lower portion consisted of a length of twisted mason line and the passive sampler. One end of the twisted mason line was securely tied to the top (i.e., non-sampling end) of the passive sampler and the other end was securely tied to the stainless-steel O-ring. The sampling train was then ready for passive sampling. A diagram of the manhole sampling train and passive sampler used in this field study is provided in Figure 3-6.
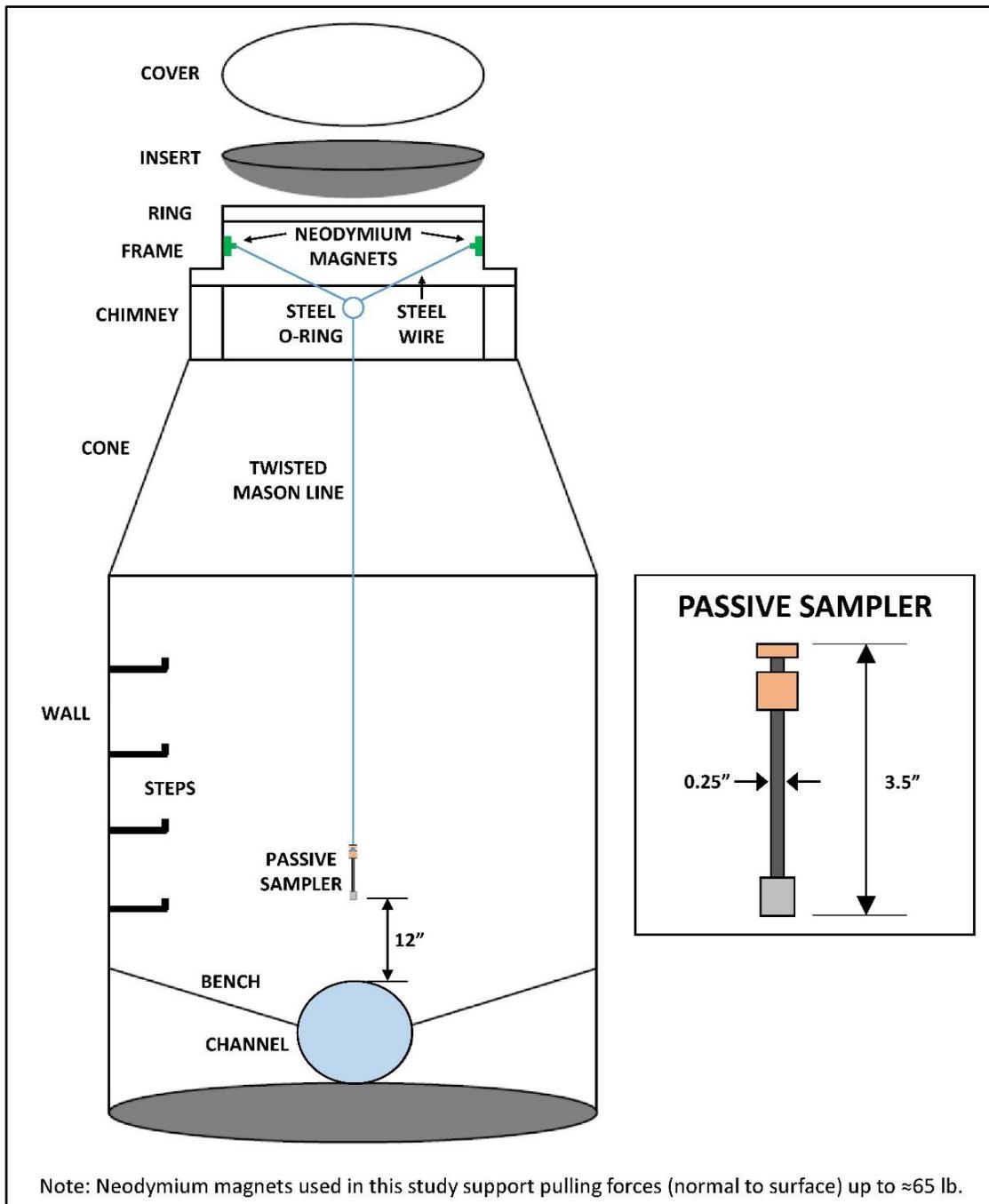
Figure 3-6: Diagram of manhole sampling train and passive sampler

3.3.2 Passive Sampling

Passive sewer gas sampling methods use adsorbent samplers to capture VOCs from air without forcing the flow rate of gas. Passive samplers used in this study, thermally-conditioned, stainless-steel tubes packed with Carbopack X (TO-17), were supplied and

analyzed by Beacon Environmental Services, Inc. (Beacon) of Forest Hill, Maryland. Carbopack X is graphitized carbon black (GCB) with a surface area of 240 m^2/g and mean pore volume of 100Å. It is one of the strongest GCBs available and retains a more broad range of VOCs than other adsorbent materials [68]. Passive sampling using these tubes works by the natural transport of contaminant vapors across a concentration gradient in an air gap present inside the inlet of the tubes, and subsequent adsorption of contaminants on the Carbopack X within the tube.

The primary advantage of Carbopack X for this field study is its hydrophobicity, making it suitable for sampling in high humidity settings such as sewer manholes [69]. Virtually no water is retained on the adsorbent material during sampling if the sampling tube and sampled air are the same temperature. If the sampling tube is colder than the sampled air, then condensation occurs [70]. Condensation was present on some of the samplers used in this study upon retrieval from manholes.

The adsorbent-packed tubes came equipped with brass endcaps on each end of the tube to form an impermeable seal for the Carbopack X before and after sampling. Once the remainder of the sampling train was prepared for the manhole and air sampling was ready to commence, the brass endcap on the inlet side of the tube was removed and replaced with a diffusive sampling cap; the other brass endcap on the outlet side of the tube remained fastened during the sampling event. The purposes of the diffusive sampling cap were to create a diffusive air gap between the sampling cap and Carbopack X adsorbent, and to prevent atypical air movement in the air gap that might occur in windy areas [71]. Figure 3-7 shows a passive sampling tube with a diffusion cap attached.

Figure 3-7: Passive sampler with diffusion cap attached

After a passive sampler was attached to the remainder of a sampling train and fitted with a diffusion sampling cap, it was ready to be suspended in a targeted manhole. After opening each manhole, the cast iron frame was inspected and steel wool was used to remove any flaky material or build-up of rust that might weaken the attraction between the frame and cause the magnets to detach during the sampling period. Magnets were then affixed to the manhole frame and the entire sampling train was slowly lowered down into the manhole. The manhole cover was then replaced.

Following a sewer air exposure period of six days, passive diffusion samples were sealed and shipped to Beacon's laboratory for analysis following Method TO-17. Thermal desorption-gas chromatography/mass spectrometry (TD-GC/MS) instrumentation targeted a custom set of chlorinated and hydrocarbon compounds. Targeted compounds included PCE, TCE, cis-1,2-DCE, trans-1,2-DCE, chloroform, benzene, toluene, ethylbenzene, p- & m-xylenes, and o-xylene. VC was not targeted due to prohibitive analytical cost, as it would have required a separate passive sampler containing a stronger adsorbent because of its high volatility. Toxicity information for human inhalation exposure to these compounds, as well as common sewer gas constituents (e.g., hydrogen sulfide), can be found in the Appendix.

ISO 16017-2 (*Indoor, ambient and workplace air-sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography-Part 2: Diffusive sampling*) procedure was used by Beacon to convert the adsorbed mass on each sampler to a gas concentration. The concept of passive sampling is based on Fick's first law of diffusion, which states that the molar flux of a gas due to diffusion is proportional to the concentration gradient (i.e., gas molecules will diffuse from an area of high concentration to an area of low concentration) [72]. Equation 3-1, defined by Fick's first law of diffusion, was used by Beacon to calculate concentrations of target compounds in sewer gas (C, in µg/m^3):

$$C = \frac{M \times d \times 1000}{U \times t} \tag{3-1}$$

where M = the mass of target compound adsorbed (ng), d = dilution factor (unitless), U = diffusive uptake rate (mL/min), and t = sampling time (min). Uptake rates vary for each VOC depending on the chemical's unique diffusivity properties and interaction with the adsorbent being used, as well as the configuration of the sorbent tube. Equation 3-2 defines the ideal uptake rate (U_{ideal}, in mL/min) for a given VOC:

$$U_{ideal} = D \times \frac{A}{L} \times 60 \tag{3-2}$$

where D = diffusion coefficient of the compound in air (cm^2/s), A = cross-sectional area of the sorbent tube (cm^2), L = length of the air gap between the diffusion sampling cap and surface of sorbent, and 60 = conversion factor from mL/s to mL/min. U_{ideal} is theoretical. The real, or effective diffusive uptake rate (U_{eff}, or simply U in Equation 3-1) can vary significantly from U_{ideal} due to a chemical's volatility, strength of the sorbent, back diffusion of the chemical from the sorbent, and sorbent saturation. These combined effects

are captured as a sampling efficiency (α) that relates U_{eff} and U_{ideal}, as shown in Equation 3-3:

$$U_{eff} = \alpha \times U_{ideal} \qquad (3\text{-}3)$$

Table 3-3 provides uptake rates reported by Beacon for the targeted compounds in this study. There are no uptake rates published for trans-1,2-dichloroethylene or chloroform; uptake rates for these compounds were estimated by Beacon using Graham's Law.

Table 3-3: Uptake rates of targeted compounds

Compound	Uptake Rate (mL/min)
PCE	0.47
TCE	0.49
trans-1,2-DCE	0.57
cis-1,2-DCE	0.57
Chloroform	0.50
Benzene	0.66
Toluene	0.51
Ethylbenzene	0.45
p- & m-Xylenes	0.45
o-Xylene	0.45

Figure 3-8 shows a cross section of a passive sorbent tube sampler that resembles the samplers used during this study.
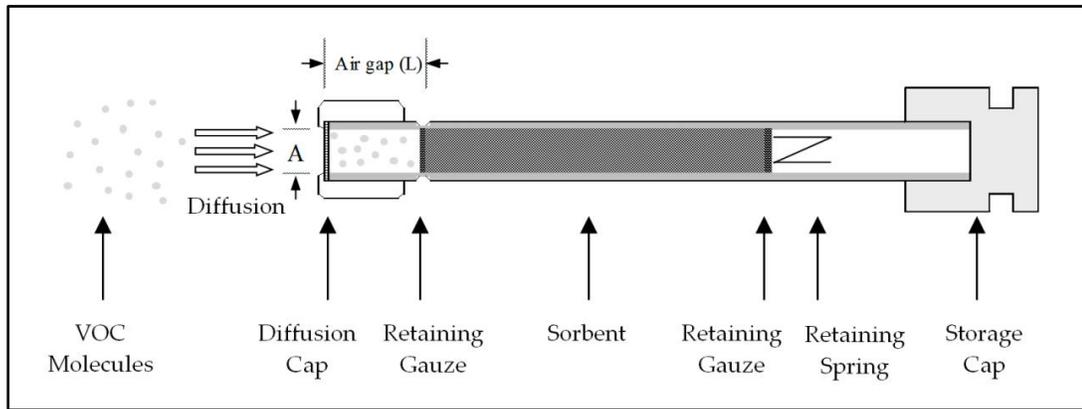
Figure 3-8: Passive sampler cross section [73]

For Beacon laboratory analysis by Method TO-17 using TD-GC/MS, the limit of detection (LoD) was 5 ng per analyte. The lowest point on the calibration curve, also known as the limit of quantitation (LoQ), was 10 ng per analyte. The highest point on the calibration curve was 200 ng per analyte. During TD-GC/MS analysis of sorbent tubes, the tubes are heated to promote thermal desorption of analytes from the sorbent into the tube headspace. Vapors are then entrained in carrier gas flow and transferred onto the capillary column via splitless injection or split injection. For a splitless injection, the entire sample is passed to the capillary column. Splitless injection is used when sample concentrations are low. For a split injection, the sample is divided so that a portion of the sample is passed to the capillary column and the remainder is passed to the split line (i.e., out of the instrument). Split injection is used to perform on-instrument dilution when sample concentrations are high. Dilution can be controlled by adjusting the split ratio, which is the ratio of split flow (i.e., the amount of sample transferred to the split line) to column flow (i.e., the amount of sample transferred to the capillary column) [74].

The laboratory performed dilutions for samples MH-B5 (cis-1,2-DCE and PCE), MH-C1 (PCE), MH-C2 (TCE and PCE), MH-D1 (PCE), and MH-D5 (toluene) in order to decrease the detected concentration of listed compounds into the calibration range of the TD-GC/MS. Samples MH-C1, MH-C2, MH-D1, and MH-D5 were diluted once (dilution factor = 5.97), and sample MH-B5 was diluted twice (total dilution factor = 31.83). LoDs and LoQs for each sample and analyte can be calculated using Equation 3-1 [75].

3.3.3   Additional Site Sampling

A photoionization detector (PID) (RAE Systems MiniRAE 3000) was utilized as a portable VOC monitor to screen locations with high total VOC concentrations for health and safety purposes. This PID has a detection range between 0.1 and 15,000 ppm and detects VOCs within three seconds. A Trimble GeoExplorer® GeoXT™ 3000 series was utilized to record GPS coordinates (latitude and longitude) of all sampled manholes and groundwater monitoring wells. A Cole Parmer Traceable® Remote-Probe Thermohygrometer was used to measure humidity and temperature of both ambient air and air inside the manhole. Data from the thermohygrometer was only collected at one site due to heavy rain on the day of sampler deployment. A Solinst Model 101 Water Level Meter was used to measure depth from manhole rim to the bottom and top of the channel within the manhole.

4   Results and Discussion

Field sampling completed as part of this project involved collection of sewer gas samples from sanitary sewer manholes at each of the four sites. The sampling period lasted from February 14 to February 20, 2018. Manhole sampling locations at each site have been shown on Figure 3-1, Figure 3-2, Figure 3-3, and Figure 3-4. Field sampling completed by consultants at each site has primarily consisted of groundwater monitoring, but soil gas monitoring has also been performed previously. However, only groundwater monitoring and sewer gas sampling results will be presented and discussed.

4.1   Precipitation During Sampling Period

Deployment of manhole samplers coincided with a rain event that lasted for much of the day. Rain events also occurred during the sampling period. A rain gauge located in downtown Lexington, Kentucky measured incremental rainfall depths in five-minute intervals. 2.68 in. of total precipitation fell during the sampling period (beginning with deployment of first sampler and ending with retrieval of last sampler) [76]. Figure 4-1, Figure 4-2, Figure 4-3, and Figure 4-4 show rainfall hyetographs for each of the first four days of sampling. A negligible amount of rainfall (0.01 in.) fell during the final days of sampling.

Table 4-1 shows daily rainfall during the sampling period. On February 14, the day of sampler deployment, 0.88 in. of precipitation fell. The majority of rainfall occurred in the morning, between 9 a.m. and 11 a.m. On February 15, 0.06 in. of precipitation fell between 7 a.m. and 9 a.m. On February 16, 1.13 in. of precipitation fell, which was the greatest amount of daily precipitation during the sampling period. All rainfall occurred in

the morning, between 4 a.m. and 2 p.m. On February 17, 0.60 in. of precipitation fell between 1 p.m. and 5 p.m.

Table 4-1: Rainfall during sampling period

Date	Daily Rainfall during Sampling Period (in.)	Cumulative Rainfall during Sampling Period (in.)
2/14/2018	0.88	0.88
2/15/2018	0.06	0.94
2/16/2018	1.13	2.07
2/17/2018	0.60	2.67
2/18/2018	0.00	2.67
2/19/2018	0.01	2.68
2/20/2018	0.00	2.68

Heavy rainfall occurred during sampler deployment at Site A. MH-A2, MH-A3, and MH-A4 were located along the edges of a street at the site. Stormwater collected at roadside channels and migrated toward storm drains. When covers were removed from manholes in the street to deploy samplers, stormwater infiltrated into the manholes. Stormwater infiltration at MH-A2 was too heavy to deploy a sampler safely, but samplers were safely installed in MH-A3 and MH-A4. Once samplers were deployed and manhole covers were replaced, stormwater appeared to bypass the manhole and continue toward storm drains.

The sanitary and storm sewer systems in Lexington are separate, meaning that sanitary sewers are not intended to receive significant additional flows of rainfall. Nevertheless, almost all sewer systems have some infiltration and/or inflow [77], so unintentional infiltration and inflow (I&I) of rainwater into the sampled sewers likely occurred during the sampling period. I&I rates were not measured for the sanitary sewers included in this study. Previous sanitary sewer assessments conducted by LFUCG involved

measurement of rainfall-derived I&I for a sample of sewer pipes in Lexington; none of the pipes sampled during this study were assessed. However, the results of the LFUCG assessment demonstrate that rainfall-derived I&I is common in sanitary sewer pipes in Lexington during and shortly after rainfall events [78-80]. The addition of rainfall-derived I&I complicates sewer gas sampling, as site-specific effects of additional flow on sewer gas VOC concentrations are unknown. Variables that could affect sewer gas VOC concentrations include, but are not limited to, sewer liquid velocity, sewer liquid VOC concentrations, and VOC volatilities.

It is unlikely that samplers were submerged during the sampling period. The samplers were deployed approximately one foot above the top of pipe at the bottom of manholes. This sampling depth is consistent with those used in other sewer gas studies nationally [11, 81]. LFUCG-DWQ also provided professional judgment that the samplers would not become submerged when placed in that position, even during precipitation events. During sampler deployment, which coincided with a precipitation event, sewer liquid flows in sampled manholes were not significant enough to be a submersion threat to the samplers.
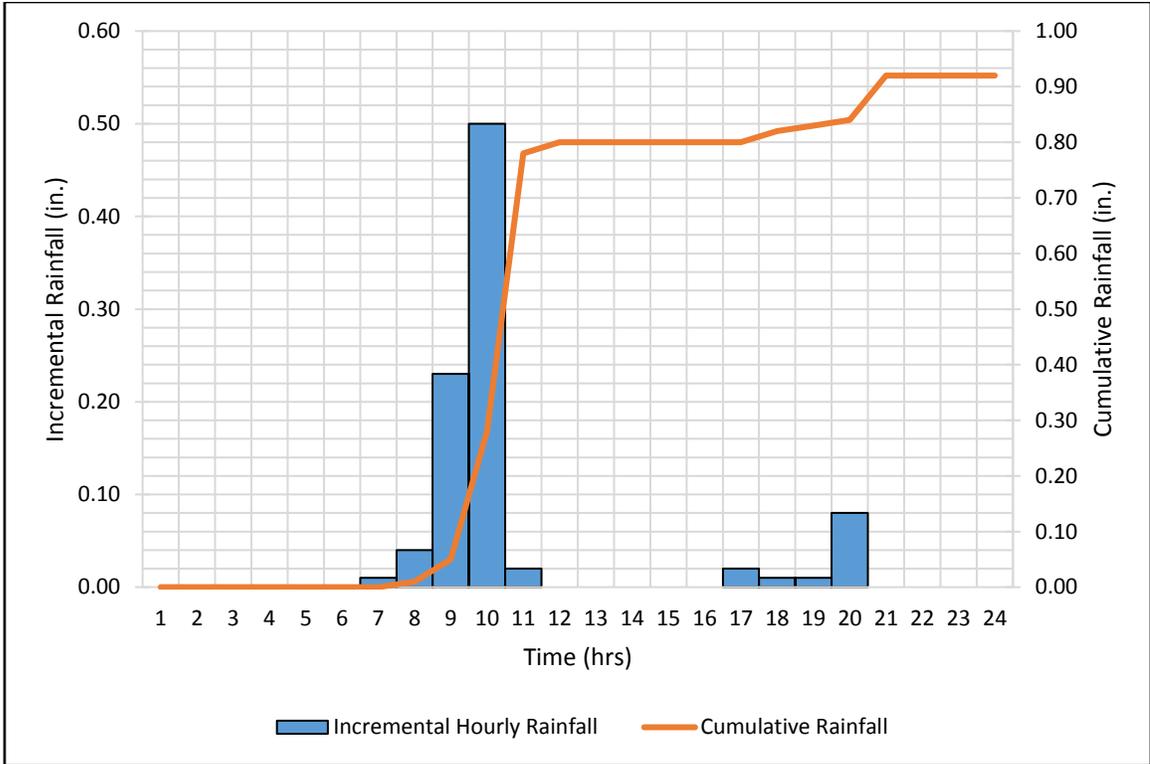
Figure 4-1: Rainfall hyetograph for February 14, 2018
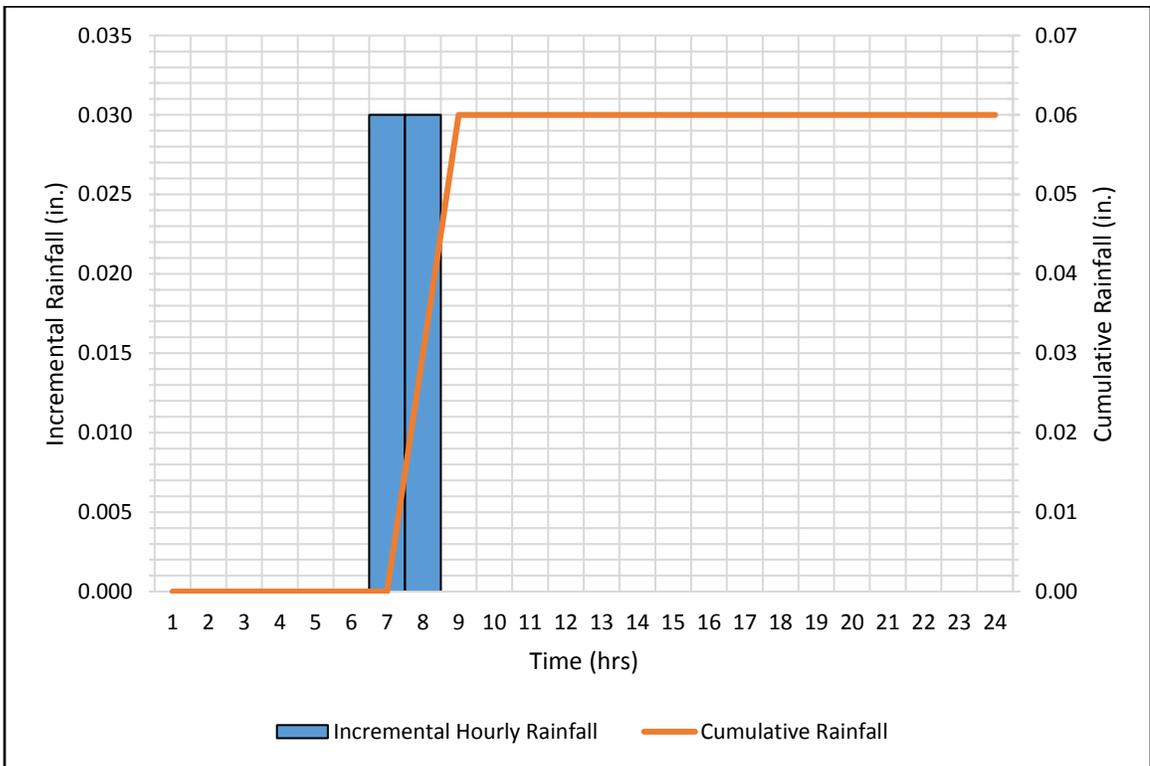
Figure 4-2: Rainfall hyetograph for February 15, 2018
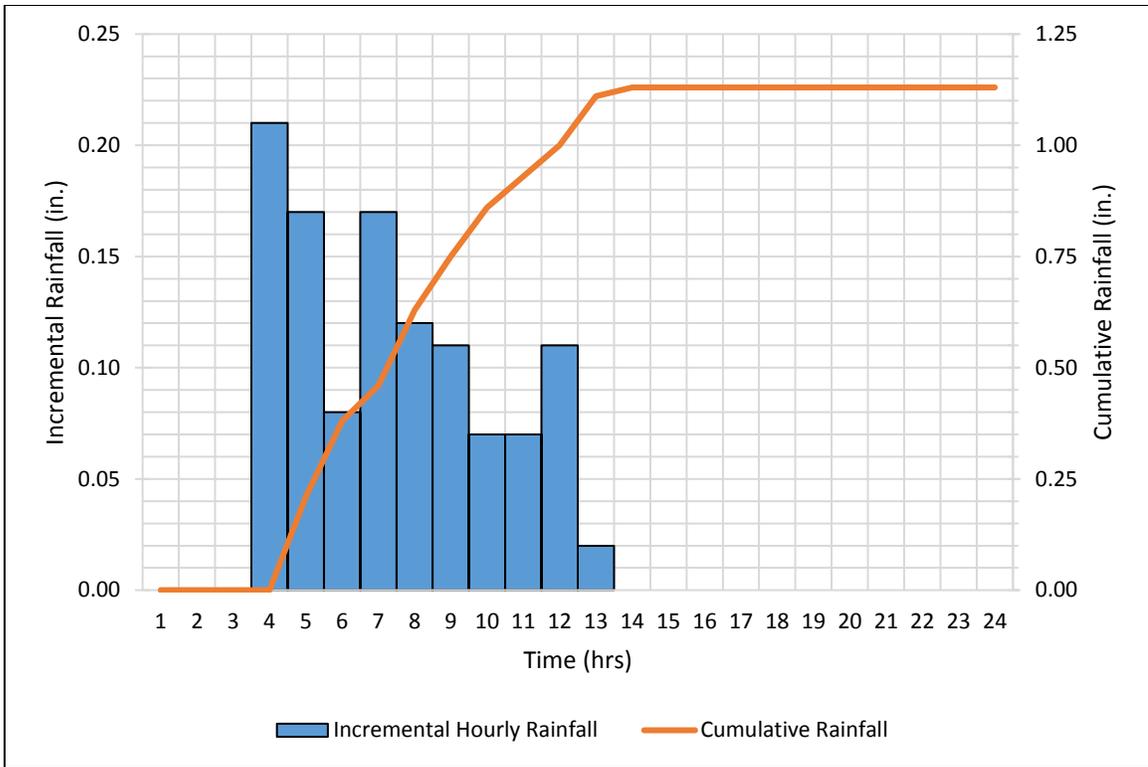
Figure 4-3: Rainfall hyetograph for February 16, 2018
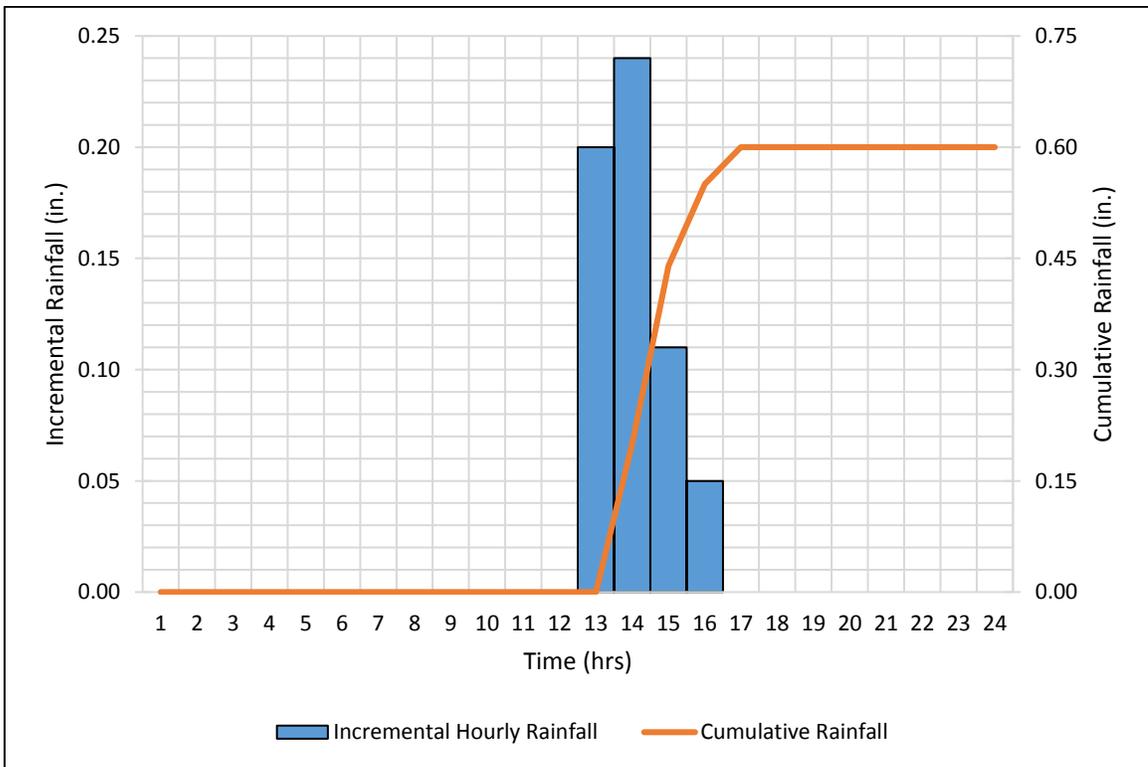
Figure 4-4: Rainfall hyetograph for February 17, 2018

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4.2 Trip and Field Blanks

One trip blank was sent back to Beacon's laboratory for analysis. The trip blank was an unopened sorbent tube never exposed to sampling procedures in order to assess artificial sources of contamination introduced by shipping, field handling, and analytical laboratory procedures. Concentrations of all targeted compounds were below LoDs for the trip blank.

Four field blanks (i.e., background atmospheric air samples) were deployed during the sampling period: one at each of the four sites. At Site A, benzene and PCE were detected below the LoQ but above the LoD. Toluene was detected at 3.3 $\mu g/m^3$. Concentrations of all other targeted compounds were below LoDs at this site. At Site B, toluene and PCE were detected below the LoQ but above the LoD. Concentrations of all other targeted compounds were below LoDs at this site. At Site C, toluene and PCE were detected below the LoQ but above the LoD. Concentrations of all other targeted compounds were below LoDs at this site. At Site D, toluene was detected below the LoQ but above the LoD. Concentrations of all other targeted compounds were below LoDs at this site.

PCE was detected at three sites, benzene was detected at one site, and toluene was detected at all four sites. Exact sources of background concentrations of these chemicals detected in atmospheric air at the sites are unknown; there are many potential sources, which have been discussed in Section 2.7. Interestingly, PCE was detected at Sites A, B, and C (i.e., inactive dry cleaning facilities) but not at Site D (i.e., the only active dry cleaning facility). All sites are located near parking lots and roads. On-road, combustion-related, mobile emission sources (e.g., automobiles, trucks, motorcycles, and other motor

vehicles) may account for background concentrations of benzene and toluene. Benzene and toluene are components of gasoline that can enter ambient air through vehicular exhaust due to incomplete combustion of gasoline. At Site C, where an active gasoline station abuts the property immediately to the east, toluene was detected but benzene was not.

4.3   Results of Sewer Gas Sampling and Recent Groundwater Monitoring

As mentioned previously in Section 3.4.2, some samples were diluted to bring the detected concentration of analytes into the calibration range of the GC/MS instrument. Equation 3-1 demonstrated that the calculated gas-phase concentration of a compound is proportional to the dilution factor. Therefore, when a sample is diluted, the LoD and LoQ of each analyte outside the initial calibration range in that sample increase by a magnitude equivalent to the dilution factor.

While cis-1,2-DCE and trans-1,2-DCE are sufficiently volatile to be of concern for vapor intrusion, no inhalation toxicity information (i.e., inhalation unit risk, reference concentration) is available for these chemicals. Thus, risk-based vapor intrusion screening levels cannot be calculated for cis-1,2-DCE and trans-1,2-DCE. Reference concentrations for inhalation exposure to trans-1,2-DCE were previously published by EPA but have been recently redacted due to inconsistencies in the conclusions about derivation of a reference concentration between two toxicity assessments [82, 83]. All sampled manholes were non-detect for trans-1,2-DCE, while cis-1,2-DCE was detected in 12 of 19 (63%) sampled manholes.

Groundwater monitoring results, sewer gas sampling results, and vapor intrusion screening levels (VISLs) are presented using a variety of tables and figures:

- Table 4-2 shows cancer and non-cancer VISLs for residential and commercial inhalation exposures to the targeted compounds, using a target cancer risk (TCR) of 10^{-6} (i.e., one per million) and a target hazard quotient (THQ) of 1. EPA generally recommends a TCR range of 10^{-6} to 10^{-4} when assessing potential cancer risks near hazardous waste sites. EPA prefers use of a conservative TCR of 10^{-6} as a starting point for site screening. EPA generally recommends using a THQ of 1 when assessing potential noncancer effects as part of hazardous waste site screening activities near hazardous waste sites [10]. A THQ of 0.1 is sometimes recommended when screening involves multiple COCs, but this may produce overly conservative VISLs. Thus, a THQ of 1 is used here.

- Table 4-3 shows groundwater screening levels for the targeted compounds. Groundwater screening levels include MCLs and target groundwater concentrations relevant for vapor intrusion. Target groundwater concentrations are calculated using target indoor air chemical concentrations corresponding with a TCR=10^{-6} and THQ=1, a generic groundwater-indoor air attenuation factor (α_{gw}) of 0.001, and the temperature-dependent Henry's Law constant of each chemical. Lexington, Kentucky has an average shallow groundwater temperature of approximately 15°C [84].

- Table 4-4, Table 4-5, and Table 4-6 show recent groundwater monitoring results for Sites B, C, and D, respectively. These tables show data for the three most recent groundwater sampling events at each site. No groundwater monitoring data is available for Site A.

- Table 4-7 and Table 4-8 show the sewer gas concentrations at all sample locations for CVOCs and BTEX compounds, respectively.

- Figure 4-5, Figure 4-6, Figure 4-7, and Figure 4-8 show the spatial distributions of sewer gas and groundwater (when available) CVOC concentrations at Sites A, B, C, and D, respectively.

- Figure 4-9 through Figure 4-17 show concentrations of targeted compounds at each of the manhole sample locations relative to other manholes and inhalation exposure screening levels. Sewer gas concentrations of trans-1,2-DCE are not provided in one of these figures because trans-1,2-DCE concentrations were non-detect at all sampling locations. Detection limits of targeted compounds for several samples exceed VISLs. Although non-detect concentrations on these figures are plotted as half the detection limit, these values may still appear to be greater than VISLs. These concentrations may, or may not, actually exceed VISLs, but it is not possible to confirm one way or the other with the data obtained.

- Figure 4-18, Figure 4-19, Figure 4-20, and Figure 4-21 show manhole invert and groundwater (when available) elevations at Sites A, B, C, and D, respectively. No groundwater elevation data is available for Site A. Approximate groundwater elevations at manholes were estimated with contour maps of water surface elevation created with Surfer® mapping software using water surface elevations at groundwater monitoring wells.

Table 4-2: Residential and commercial vapor intrusion (indoor air) screening levels [85]

Chemical	Henry's Law Constant @15°C (unitless)	Residential Screening Levels C_{res-ia} (µg/m³)		Commercial Screening Levels C_{w-ia} (µg/m³)	
		Cancer	Non-Cancer	Cancer	Non-Cancer
PCE	0.429	1.08E+01	4.17E+01	4.72E+01	1.75E+02
TCE	0.256	4.78E-01	2.09E+00	2.99E+00	8.76E+00
cis-1,2-DCE	0.110	-	-	-	-
trans-1,2-DCE	0.259	-	-	-	-
VC	0.895	1.68E-01	1.04E+02	2.79E+00	4.38E+02
Chloroform	0.100	1.22E-01	1.02E+02	5.33E-01	4.28E+02
Benzene	0.146	3.60E-01	3.13E+01	1.57E+00	1.31E+02
Toluene	0.165	-	5.21E+03	-	2.19E+04
Ethylbenzene	0.184	1.12E+00	1.04E+03	4.91E+00	4.38E+03
m-Xylene	0.167	-	1.04E+02	-	4.38E+02
o-Xylene	0.119	-	1.04E+02	-	4.38E+02
p-Xylene	0.161	-	1.04E+02	-	4.38E+02
Xylenes (total)	0.155	-	1.04E+02	-	4.38E+02

Note: Cancer screening levels correspond with TCR=1E-06. Non-cancer screening levels correspond with THQ=1. VISLs cannot be calculated for cis-1,2-DCE and trans-1,2-DCE because no inhalation toxicity information is available. Insufficient information exists to evaluate the carcinogenic potential of toluene, p- & m-xylenes, and o-xylene.

Carcinogenic VISLs for residential inhalation exposure to chemicals ($C_{res-ia-ca}$, in µg/m³) are calculated using Equation 4-1:

$$C_{res-ia-ca} = \frac{TCR \times AT_{res} \times LT}{EF_{res} \times ED_{res} \times ET_{res} \times IUR \times 1/24} \qquad (4\text{-}1)$$

where TCR = target cancer risk (10^{-6}, unitless), AT_{res} = resident averaging time - carcinogenic (365 days/year), LT = lifetime (70 years), EF_{res} = resident exposure frequency (350 days/year), ED_{res} = resident exposure duration (26 years), ET_{res} = resident air

exposure time (24 hours/day), IUR = chronic inhalation unit risk (contaminant-specific, $(\mu g/m^3)^{-1}$), and 1/24 = conversion factor between days and hours.

Noncarcinogenic VISLs for residential inhalation exposure to chemicals ($C_{res-ia-nc}$, in $\mu g/m^3$) are calculated using Equation 4-2:

$$C_{res-ia-nc} = \frac{THQ \times AT_{res-a} \times ED_{res} \times RfC \times 1000}{EF_{res} \times ED_{res} \times ET_{res} \times 1/24} \tag{4-2}$$

where THQ = target hazard quotient (1, unitless), AT_{res-a} = resident averaging time - noncarcinogenic (365 days/year), ED_{res} = resident exposure duration (26 years), RfC = chronic inhalation reference concentration (contaminant-specific, mg/m^3), 1000 = conversion factor between μg and mg, EF_{res} = resident exposure frequency (350 days/year), ET_{res} = resident air exposure time (24 hours/day), and 1/24 = conversion factor between days and hours.

Carcinogenic VISLs for commercial inhalation exposure to chemicals ($C_{w-ia-ca}$, in $\mu g/m^3$) are calculated using Equation 4-3:

$$C_{w-ia-ca} = \frac{TCR \times AT_w \times LT}{EF_w \times ED_w \times ET_w \times IUR \times 1/24} \tag{4-3}$$

where TCR = target cancer risk (10^{-6}, unitless), AT_w = worker averaging time - carcinogenic (365 days/year), LT = lifetime (70 years), EF_w = worker exposure frequency (250 days/year), ED_w = worker exposure duration (25 years), ET_{res} = worker air exposure time (8 hours/day), IUR = chronic inhalation unit risk (contaminant-specific, $(\mu g/m^3)^{-1}$), and 1/24 = conversion factor between days and hours.

Noncarcinogenic VISLs for commercial inhalation exposure to chemicals ($C_{w-ia-nc}$, in µg/m³) are calculated using Equation 4-4:

$$C_{w-ia-nc} = \frac{THQ \times AT_{w-a} \times ED_w \times RfC \times 1000}{EF_w \times ED_w \times ET_w \times \frac{1}{24}}$$

(4-4)

where THQ = target hazard quotient (1, unitless), AT_{w-a} = worker averaging time - noncarcinogenic (365 days/year), ED_w = worker exposure duration (25 years), RfC = chronic inhalation reference concentration (contaminant-specific, mg/m³), 1000 = conversion factor between µg and mg, EF_w = worker exposure frequency (250 days/year), ET_w = worker air exposure time (8 hours/day), and 1/24 = conversion factor between days and hours.

Mutagenic compounds, such as TCE and VC, are capable of producing genetic mutations in addition to carcinogenic and noncarcinogenic effects. Mutagenic VISL equations include age-dependent adjustment factors that account for increased childhood risk for mutagenic compounds. Mutagenic equations can be found online in EPA's VISL User's Guide [86]. Contaminant-specific IUR and RfC values, as well as additional information about chemical properties and toxicity, can be found online in EPA's VISL Calculator [85].

Table 4-3: Groundwater screening levels [85]

Chemical	Maximum Contaminant Level, MCL (mg/L)	Target Groundwater Concentration @T_{gw}=15°C (TCR=10^{-6} or THQ=1), C_{gw} (mg/L)	
		Residential	Commercial
PCE	0.005	0.0252*	0.11*
TCE	0.005	**0.00187***	0.0117*
cis-1,2-DCE	0.070	-	-
trans-1,2-DCE	0.100	-	-
VC	0.002	**0.000187***	0.00312*
Chloroform	0.080	**0.00122***	**0.00533***
Benzene	0.005	**0.00246***	0.0107*
Toluene	1.000	31.6**	133**
Ethylbenzene	0.700	**0.00609***	**0.0266***
m-Xylene	-	0.624**	2.62**
o-Xylene	-	0.873**	3.67**
p-Xylene	-	0.649**	2.73**
Xylenes (total)	10.000	**0.674***	**2.83***

Note: Bolded value indicates C_{gw} < MCL. * indicates carcinogenic toxicity basis. ** indicates noncarcinogenic toxicity basis. MCLs are available for total xylenes, but not xylene isomers (m-, o-, p-).

Target groundwater concentrations (C_{gw}, in mg/L) are calculated by Equation 4-5:

$$C_{gw} = \frac{C_{ia} \times 0.001}{\alpha_{gw} \times H' \times 1000} \qquad (4\text{-}5)$$

where C_{ia} = target indoor air concentration (µg/m³) (i.e., lower of the cancer and non-cancer screening levels for residential and commercial exposures in Table 4-2), α_{gw} = generic groundwater-indoor air attenuation factor (0.001, unitless), H' = temperature-adjusted Henry's Law constant (unitless) (i.e., provided in Table 4-2), 0.001 = conversion factor from µg to mg, and 1000 = conversion factor from L to m³.

Equation 4-5 incorporates Henry's Law and vapor attenuation between groundwater vapors and indoor air. Henry's Law, which defines liquid- and gas-phase

concentrations at static equilibrium, can also be used to calculate sewer liquid or sewer headspace VOC concentrations when one of the parameters is known. For example, when sewer headspace VOC concentration (C_g) is known, the sewer liquid VOC concentration (C_l) at equilibrium is given by Equation 4-6:

$$C_l = \frac{C_g}{H'} \tag{4-6}$$

where H' = temperature-adjusted Henry's Law constant (unitless). This relationship allows for approximation of sewer liquid and headspace concentrations, but dynamic equilibrium (i.e., steady state) between liquid- and gas-phases in the sewer system is difficult to achieve due to the inherent transient nature of sewer liquid and gas flows.

Table 4-4: Site B recent groundwater concentrations [55, 87, 88]

Sample Information		Method 8260B Groundwater Concentration, in mg/L				
Sample ID	Date	PCE	TCE	cis-1,2-DCE	trans-1,2-DCE	VC
MW-1	5/2/17	0.00299	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-1	5/9/16	0.00857	0.00214	0.00163	ND (<0.001)	ND (<0.001)
MW-1	5/8/15	0.011	0.0046	0.0034	ND (<0.001)	ND (<0.001)
MW-2	5/2/17	0.0306	0.0145	0.0228	ND (<0.001)	ND (<0.001)
MW-2	5/9/16	0.0616	0.0183	0.0345	ND (<0.001)	ND (<0.001)
MW-2	5/8/15	0.07	0.022	0.036	ND (<0.001)	ND (<0.001)
MW-3	5/2/17	NS	NS	NS	NS	NS
MW-3	5/9/16	NS	NS	NS	NS	NS
MW-3	5/8/15	NS	NS	NS	NS	NS
MW-4	5/2/17	NS	NS	NS	NS	NS
MW-4	5/9/16	NS	NS	NS	NS	NS
MW-4	5/8/15	NS	NS	NS	NS	NS
MW-5	5/2/17	NS	NS	NS	NS	NS
MW-5	5/9/16	NS	NS	NS	NS	NS
MW-5	5/8/15	NS	NS	NS	NS	NS
MW-6	5/2/17	NS	NS	NS	NS	NS
MW-6	5/9/16	NS	NS	NS	NS	NS
MW-6	5/8/15	NS	NS	NS	NS	NS
MW-7	5/2/17	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-7	5/9/16	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-7	5/8/15	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-8	5/2/17	NS	NS	NS	NS	NS
MW-8	5/9/16	NS	NS	NS	NS	NS
MW-8	5/8/15	NS	NS	NS	NS	NS
MW-9	5/2/17	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-9	5/9/16	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-9	5/8/15	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)

Note: ND = not detected above laboratory detection limit (shown in parentheses). NS = not sampled. Other analyte included in sampling but not detected at any of the monitoring wells during recent sampling events include chloroform (<0.005 mg/L), benzene (<0.001 mg/L), toluene (<0.001 mg/L), ethylbenzene (<0.001 mg/L), and total xylenes (<0.003 mg/L).

Table 4-5: Site C recent groundwater concentrations [60, 89, 90]

Sample Information		Method 8260B Groundwater Concentration (mg/L)				
Sample ID	Date	PCE	TCE	cis-1,2-DCE	trans-1,2-DCE	VC
MW-1	1/27/16	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-1	1/25/14	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-1	1/28/13	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-2	1/27/16	0.00387	0.131	1.27	ND (<0.025)	0.495
MW-2	1/25/14	ND (<0.001)	0.002	1.1	0.0015	0.28
MW-2	1/28/13	ND (<0.0037)	0.11	0.96	ND (<0.01)	0.31
MW-3	1/27/16	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-3	1/25/14	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-3	1/28/13	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-4	1/27/16	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	0.00492
MW-4	1/25/14	0.0073	0.0072	0.064	ND (<0.001)	0.15
MW-4	1/28/13	0.1	0.075	0.31	0.0084	0.43
MW-5	1/27/16	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-5	1/25/14	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-5	1/28/13	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-6	1/27/16	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-6	1/25/14	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-6	1/28/13	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-7	1/27/16	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-7	1/25/14	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-7	1/28/13	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-8	1/27/16	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	0.00341
MW-8	1/25/14	ND (<0.001)	ND (<0.001)	0.0013	ND (<0.001)	0.005
MW-8	1/28/13	ND (<0.001)	ND (<0.001)	0.0012	ND (<0.001)	0.0062
MW-9	1/27/16	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-9	1/25/14	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-9	1/28/13	ND (<0.001)	ND (<0.001)	0.0012	ND (<0.001)	ND (<0.001)

Note: ND = not detected above laboratory detection limit (shown in parentheses). Other analytes included in sampling but not detected at any of the monitoring wells during recent sampling events include chloroform (<0.005 mg/L), benzene (<0.001 mg/L), toluene (<0.005 mg/L), ethylbenzene (<0.001 mg/L), and total xylenes (<0.003 mg/L).

Table 4-6: Site D recent groundwater concentrations [65, 91, 92]

Sample Information		Method 8260B Groundwater Concentration (mg/L)				
Sample ID	Date	PCE	TCE	cis-1,2-DCE	trans-1,2-DCE	VC
MW-1	4/5/16	ND (<0.01)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-1	5/28/15	ND (<0.01)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-1	5/4/12	ND (<0.01)	ND (<0.001)	ND (<0.001)	ND (<0.001)	0.0014
MW-2	4/5/16	0.525	0.0575	0.1	0.000852	0.00194
MW-2	5/28/15	0.36	0.065	0.12	0.001	0.0029
MW-2	5/4/12	0.74	0.11	0.16	0.0018	0.0093
MW-3	4/5/16	0.0655	0.0209	0.0479	0.000481	0.000614
MW-3	5/28/15	0.1	0.015	0.031	ND (<0.001)	0.00033
MW-3	5/4/12	0.26	0.058	0.12	0.0017	0.0046
MW-4	4/5/16	NS	NS	NS	NS	NS
MW-4	5/28/15	0.019	0.0087	0.41	0.0014	ND (<0.001)
MW-4	5/4/12	0.29	0.05	0.13	0.0023	ND (<0.001)
MW-5	4/5/16	NS	NS	NS	NS	NS
MW-5	5/28/15	ND (<0.01)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-5	5/4/12	ND (<0.01)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-6	4/5/16	ND (<0.01)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-6	5/28/15	ND (<0.01)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-6	5/4/12	ND (<0.01)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-7	4/5/16	NS	NS	NS	NS	NS
MW-7	5/28/15	NS	NS	NS	NS	NS
MW-7	5/4/12	ND (<0.01)	ND (<0.001)	ND (<0.001)	ND (<0.001)	ND (<0.001)
MW-8	4/5/16	NS	NS	NS	NS	NS
MW-8	5/28/15	NS	NS	NS	NS	NS
MW-8	5/4/12	NS	NS	NS	NS	NS
MW-9	4/5/16	0.0276	0.00856	0.0588	0.00132	ND (<0.001)
MW-9	5/28/15	NS	NS	NS	NS	NS
MW-9	5/4/12	NS	NS	NS	NS	NS

Note: ND = not detected above laboratory detection limit (shown in parentheses). NS = not sampled. Chloroform was not detected (<0.005 mg/L) at all wells except for MW-4 on 5/28/15 (0.0012 mg/L) and MW-9 on 4/5/16 (0.00277 mg/L). Other analytes included in sampling but not detected at any of the monitoring wells during recent sampling events include benzene (<0.001 mg/L), toluene (<0.005 mg/L), ethylbenzene (<0.001 mg/L), and total xylenes (<0.003 mg/L).

Table 4-7: Sewer gas concentrations for chlorinated compounds

Sample Information		Method TO-17 Sewer Gas Concentration (µg/m³)				
Sample ID	Duration (days)	PCE	TCE	cis-1,2-DCE	trans-1,2-DCE	Chloroform
MH-A1	6.23	1.54 J	2.05 J	ND (<0.98)	ND (<0.98)	22.92
MH-A2	6.19	ND (<1.19)	ND (<1.14)	ND (<0.98)	ND (<0.98)	ND (<1.12)
MH-A3	NS	NS	NS	NS	NS	NS
MH-A4	6.22	ND (<1.19)	ND (<1.14)	ND (<0.98)	ND (<0.98)	ND (<1.12)
MH-A5	6.20	ND (<1.19)	ND (<1.14)	ND (<0.98)	ND (<0.98)	ND (<1.12)
MH-B1	6.19	3.23	ND (<1.15)	ND (<0.98)	ND (<0.98)	ND (<1.12)
MH-B2	NS	NS	NS	NS	NS	NS
MH-B3	6.18	ND (<1.20)	ND (<1.15)	ND (<0.99)	ND (<0.99)	ND (<1.12)
MH-B4	6.18	1.65 J	ND (<1.15)	2.42	ND (<0.99)	ND (<1.12)
MH-B5	6.17	459.97 D	14.2	35.21 D	ND (<0.99)	ND (<1.13)
MH-B6	NS	NS	NS	NS	NS	NS
MH-B7	6.18	10.7	ND (<1.15)	3.2	ND (<0.98)	ND (<1.12)
MH-C1	6.19	105.13 D	8.24	8.53	ND (<0.98)	ND (<1.12)
MH-C2	6.20	204.62 D	48.71 D	27.81	ND (<0.98)	ND (<1.12)
MH-C3	6.20	11.62	2.85	3.54	ND (<0.98)	ND (<1.12)
MH-C4	6.19	14.62	2.49	1.96 J	ND (<0.98)	ND (<1.12)
MH-C5	6.18	3.13	ND (<1.15)	ND (<0.99)	ND (<0.99)	ND (<1.12)
MH-D1	6.10	89.2 D	13.31	37.2	ND (<1.00)	30.41
MH-D2	6.10	10.83	1.28 J	2.75	ND (<1.00)	1.51 J
MH-D3	6.11	13.95	1.19 J	1.35 J	ND (<1.00)	ND (<1.14)
MH-D4	6.10	14.54	ND (<1.16)	1.72 J	ND (<1.00)	1.37 J
MH-D5	6.09	44.77	8.4	21.12	ND (<1.00)	27.73
OA-1	5.91	2.18 J	ND (<1.20)	ND (<1.03)	ND (<1.03)	ND (<1.17)
OA-2	6.19	1.59 J	ND (<1.14)	ND (<0.98)	ND (<0.98)	ND (<1.12)
OA-3	6.04	1.36 J	ND (<1.17)	ND (<1.01)	ND (<1.01)	ND (<1.15)
OA-4	6.11	ND (<1.21)	ND (<1.16)	ND (<1.00)	ND (<1.00)	ND (<1.14)
OA-5	6.04	ND (<1.22)	ND (<1.17)	ND (<1.01)	ND (<1.01)	ND (<1.15)

Note: NS = not sampled (MH-A3 not sampled due to heavy stormwater infiltration). MH-B2 and MH-B6 not sampled because they could not be located. ND = not detected above laboratory detection limit (shown in parentheses). D = sample diluted at the laboratory to achieve concentrations in calibration range. J = value below limit of quantification but above limit of detection. E = estimated value because concentration was above calibration range.

Table 4-8: Sewer gas concentrations for BTEX compounds

Sample Information		Method TO-17 Sewer Gas Concentration (µg/m³)				
Sample ID	Duration (days)	Benzene	Toluene	Ethylbenzene	p- & m-Xylenes	o-Xylene
MH-A1	6.23	1.83	3.62	ND (<1.24)	3.46	1.39 J
MH-A2	6.19	0.91 J	ND (<1.10)	ND (<1.25)	ND (<1.25)	ND (<1.25)
MH-A3	NS	NS	NS	NS	NS	NS
MH-A4	6.22	1.1 J	1.68 J	ND (<1.24)	ND (<1.24)	ND (<1.24)
MH-A5	6.20	ND (<0.85)	ND (<1.10)	ND (<1.24)	ND (<1.24)	ND (<1.24)
MH-B1	6.19	ND (<0.85)	1.23 J	ND (<1.25)	ND (<1.25)	ND (<1.25)
MH-B2	NS	NS	NS	NS	NS	NS
MH-B3	6.18	11.76	4.7	1.51 J	4.1	ND (<1.25)
MH-B4	6.18	1.05 J	1.16 J	ND (<1.25)	ND (<1.25)	ND (<1.25)
MH-B5	6.17	1.27 J	2.06 J	ND (<1.25)	ND (<1.25)	ND (<1.25)
MH-B6	NS	NS	NS	NS	NS	NS
MH-B7	6.18	2.82	7.37	ND (<1.25)	ND (<1.25)	ND (<1.25)
MH-C1	6.19	ND (<0.85)	ND (<1.10)	ND (<1.25)	ND (<1.25)	ND (<1.25)
MH-C2	6.20	1.06 J	1.46 J	ND (<1.24)	ND (<1.24)	ND (<1.24)
MH-C3	6.20	0.92 J	ND (<1.10)	ND (<1.24)	ND (<1.24)	ND (<1.24)
MH-C4	6.19	0.94 J	ND (<1.10)	ND (<1.25)	ND (<1.25)	ND (<1.25)
MH-C5	6.18	0.96 J	ND (<1.10)	ND (<1.25)	ND (<1.25)	ND (<1.25)
MH-D1	6.10	1.36 J	16.84	ND (<1.27)	1.34 J	ND (<1.27)
MH-D2	6.10	1.03 J	1.14 J	ND (<1.26)	ND (<1.26)	ND (<1.26)
MH-D3	6.11	1.24 J	1.35 J	ND (<1.26)	ND (<1.26)	ND (<1.26)
MH-D4	6.10	0.97 J	1.74 J	ND (<1.26)	ND (<1.26)	ND (<1.26)
MH-D5	6.09	1.39 J	122.47 D	ND (<1.27)	ND (<1.27)	ND (<1.27)
OA-1	5.91	1.22 J	3.3	ND (<1.30)	ND (<1.30)	ND (<1.30)
OA-2	6.19	ND (<0.85)	1.74 J	ND (<1.25)	ND (<1.25)	ND (<1.25)
OA-3	6.04	ND (<0.87)	1.51 J	ND (<1.28)	ND (<1.28)	ND (<1.28)
OA-4	6.11	ND (<0.86)	1.41 J	ND (<1.26)	ND (<1.26)	ND (<1.26)
OA-5	6.04	ND (<0.87)	ND (<1.13)	ND (<1.28)	ND (<1.28)	ND (<1.28)

Note: NS = not sampled (MH-A3 not sampled due to heavy stormwater infiltration). MH-B2 and MH-B6 not sampled because they could not be located. ND = not detected above laboratory detection limit (shown in parentheses). D = sample diluted at the laboratory to achieve concentrations in calibration range. J = value below limit of quantification but above limit of detection. E = estimated value because concentration was above calibration range.

Figure 4-5: Site A map of sewer gas CVOC concentrations

Figure 4-6: Site B map of sewer gas and groundwater CVOC concentrations

Legend

	Dry cleaning facility
	Groundwater monitoring well
⬤	Sampled sewer manhole
○	Non-sampled sewer manhole
→	Sewer line & flow direction
MW-1 (mg/L)	Groundwater concentration
MH-C1 (µg/m³)	Sewer gas concentration

N

0   100   200
SCALE IN FEET

MW-9 (mg/L)
ND for all analytes

MW-8 (mg/L)

PCE	<0.001
TCE	<0.001
cis-DCE	<0.001
trans-DCE	<0.001
VC	**0.00341**
Chloroform	<0.005

MW-4 (mg/L)

PCE	<0.001
TCE	<0.001
cis-DCE	<0.001
trans-DCE	<0.001
VC	**0.00492**
Chloroform	<0.005

MW-1 (mg/L)
ND for all analytes

MW-2 (mg/L)

PCE	**0.00387**
TCE	**0.131**
cis-DCE	**1.27**
trans-DCE	<0.025
VC	**0.495**
Chloroform	<0.125

MH-C3 (µg/m³)

PCE	**11.62**
TCE	**2.85**
cis-DCE	**3.54**
trans-DCE	<0.98
Chloroform	<1.12

MW-3 (mg/L)
ND for all analytes

MW-6 (mg/L)
ND for all analytes

Former Dry Cleaning Facility

MH-C5 (µg/m³)

PCE	**3.13**
TCE	<1.15
cis-DCE	<0.99
trans-DCE	<0.99
Chloroform	<1.12

MW-5 (mg/L)
ND for all analytes

MH-C4 (µg/m³)

PCE	**14.62**
TCE	**2.49**
cis-DCE	**1.96**
trans-DCE	<0.98
Chloroform	<1.12

MH-C2 (µg/m³)

PCE	**204.62**
TCE	**48.71**
cis-DCE	**27.81**
trans-DCE	<0.98
Chloroform	<1.12

MW-7 (mg/L)
ND for all analytes

MH-C1 (µg/m³)

PCE	**105.13**
TCE	**8.24**
cis-DCE	**8.53**
trans-DCE	<0.98
Chloroform	<1.12

Note: Only groundwater samples collected by GeoScience Consultants, Inc. during the most recent sampling event (January 27, 2016) are shown. "<" indicates concentration below the detection limit. Bold value emphasizes concentration above the detection limit. "ND for all analytes" denotes non-detect for groundwater sampling analytes: PCE, TCE, 1,2-DCE (cis- and trans-), VC, and chloroform. Manhole sewer gas samples were collected February 14-20, 2018 but were not analyzed for VC.

**Figure 4-7: Site C map of sewer gas and groundwater CVOC concentrations**

**MH-D5 (µg/m³)**

PCE	44.77
TCE	8.4
cis-DCE	21.12
trans-DCE	<1.00
Chloroform	27.73

MH-D1 (µg/m³)

PCE	89.2
TCE	13.31
cis-DCE	37.2
trans-DCE	<1.00
Chloroform	30.41

Legend

	Dry cleaning facility
	Groundwater monitoring well
	Sampled sewer manhole
	Non-sampled sewer manhole
	Sewer line & flow direction
MW-1 (mg/L)	Groundwater concentration
MH-D1 (µg/m³)	Sewer gas concentration

MW-6 (mg/L)

ND for all analytes

MW-1 (mg/L)

ND for all analytes

MW-3 (mg/L)

PCE	0.0655
TCE	0.0209
cis-DCE	0.0479
trans-DCE	0.000481
VC	0.000614
Chloroform	<0.005

MH-D3 (µg/m³)

PCE	13.95
TCE	1.19
cis-DCE	1.35
trans-DCE	<1.00
Chloroform	<1.14

MW-2 (mg/L)

PCE	0.525
TCE	0.0575
cis-DCE	0.100
trans-DCE	0.000852
VC	0.00194
Chloroform	<0.005

Current Dry Cleaning Facility

MH-D4 (µg/m³)

PCE	14.54
TCE	<1.16
cis-DCE	1.72
trans-DCE	<1.00
Chloroform	1.37

MW-9 (mg/L)

PCE	0.0276
TCE	0.00856
cis-DCE	0.0588
trans-DCE	0.00132
VC	<0.001
Chloroform	0.00277

MH-D2 (µg/m³)

PCE	10.83
TCE	1.28
cis-DCE	2.75
trans-DCE	<1.00
Chloroform	1.51

Note: Only groundwater samples collected by Amec Foster Wheeler during the most recent sampling event (April 5, 2016) are shown. "<" indicates concentration below the detection limit.
Bold value emphasizes concentration above the detection limit. "ND for all analytes" denotes non-detect for groundwater sampling analytes: PCE, TCE, 1,2-DCE (cis- and trans-), VC, and chloroform.
Manhole sewer gas samples were collected February 14-20, 2018 but were not analyzed for VC.

**Figure 4-8: Site D map of sewer gas and groundwater CVOC concentrations**

Figure 4-9: Sewer gas PCE concentrations detected in manholes

Figure 4-10: Sewer gas TCE concentrations detected in manholes
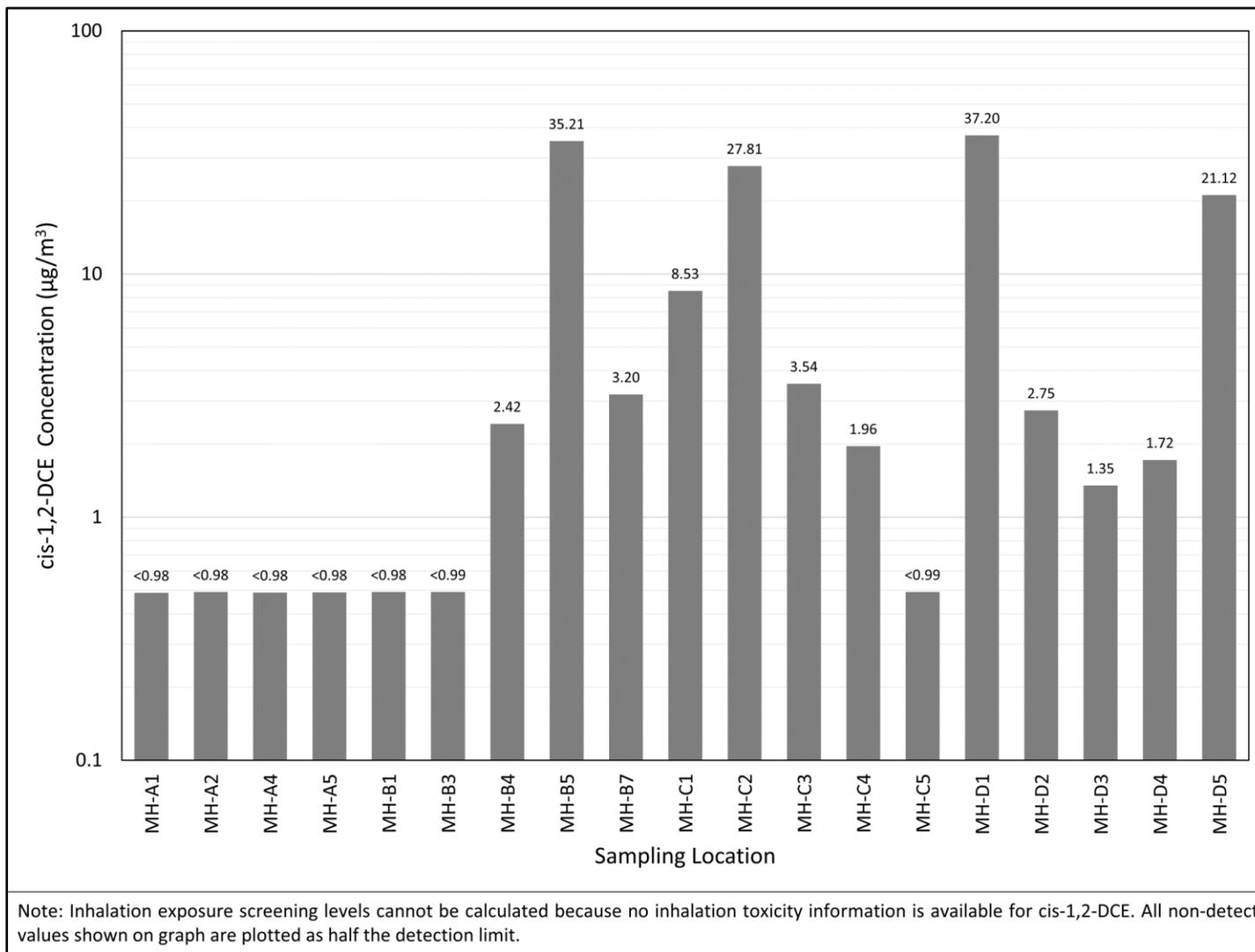
**Figure 4-11: Sewer gas cis-1,2-DCE concentrations detected in manholes**
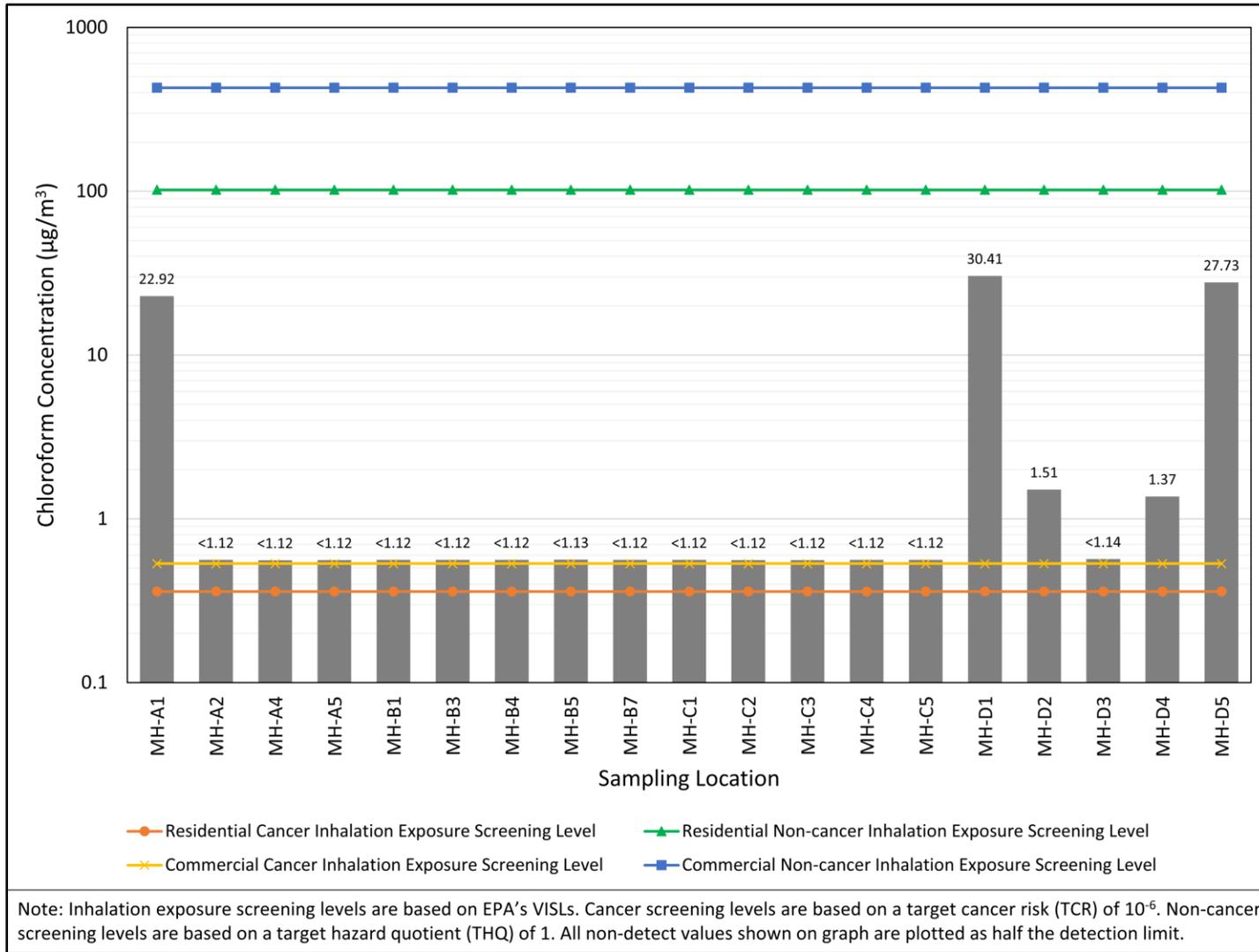
**Figure 4-12: Sewer gas chloroform concentrations detected in manholes**
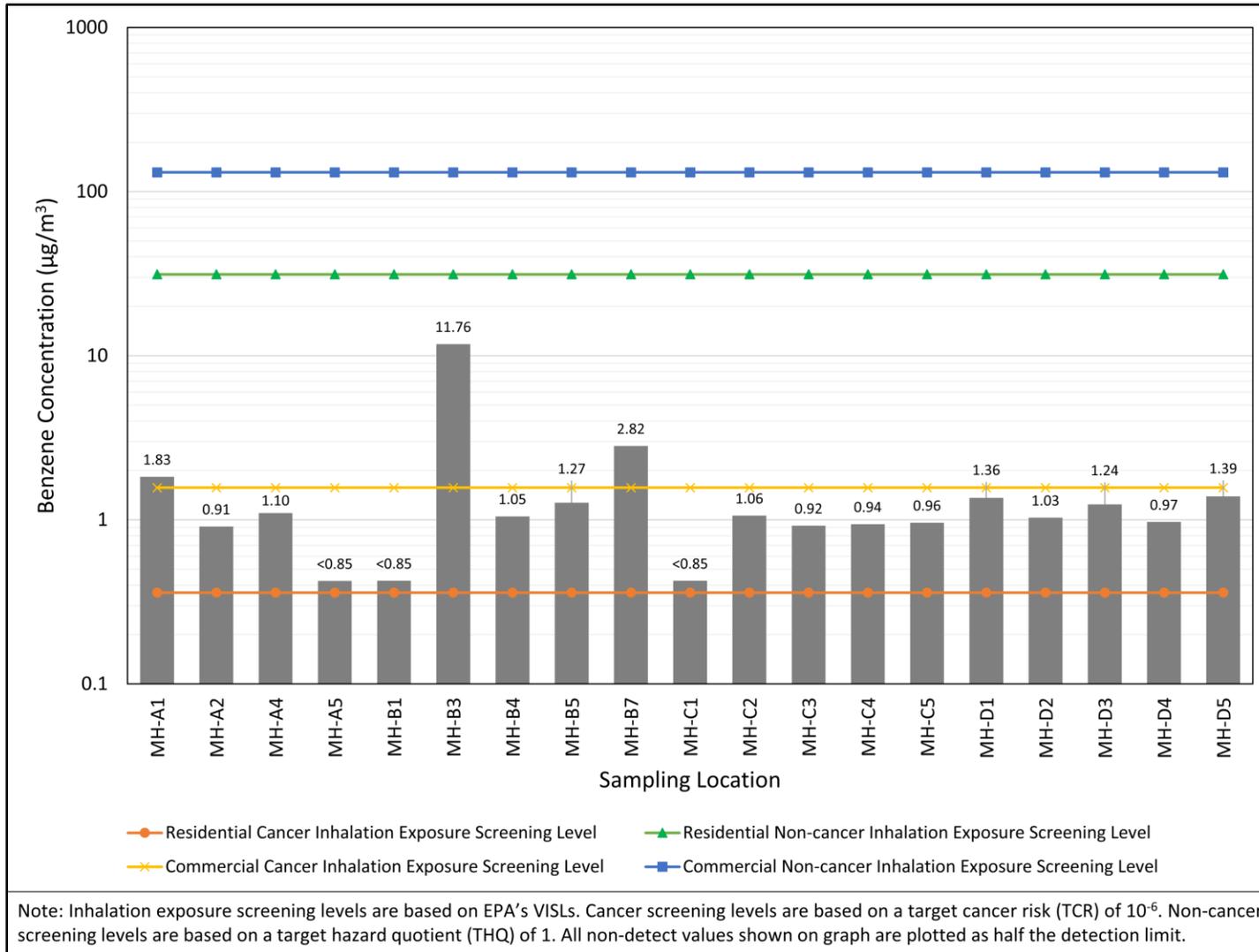
**Figure 4-13: Sewer gas benzene concentrations detected in manholes**
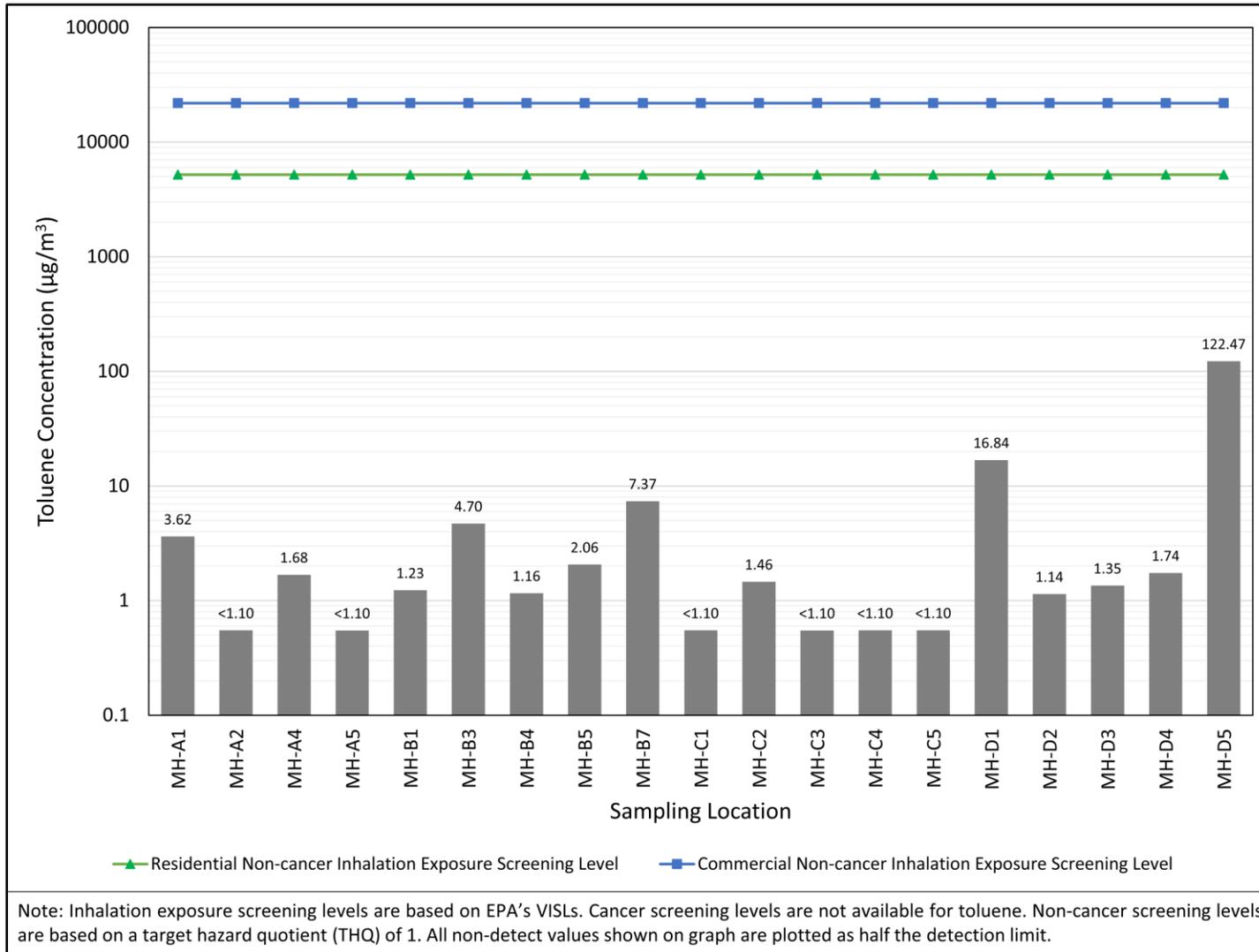
Figure 4-14: Sewer gas toluene concentrations detected in manholes
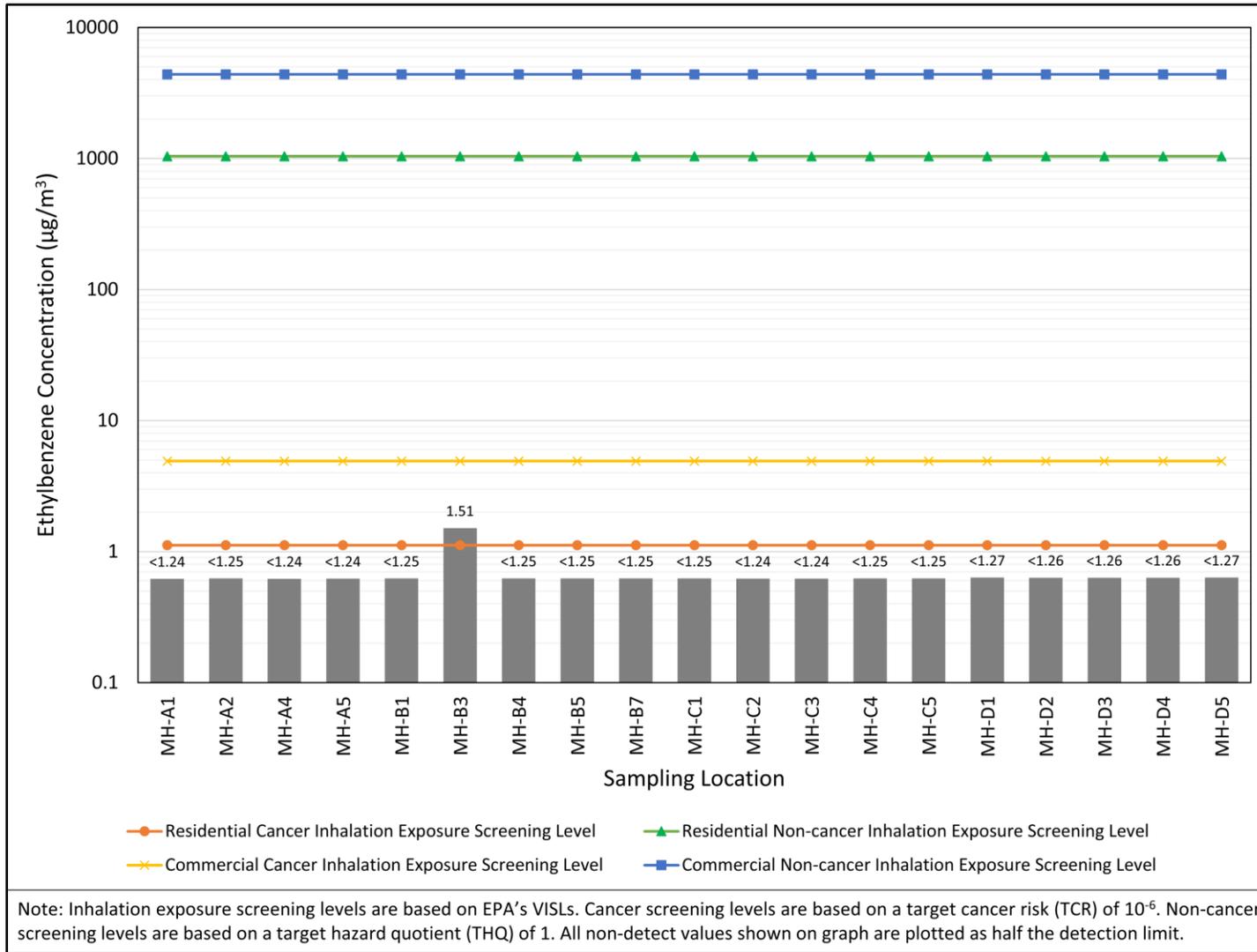
Figure 4-15: Sewer gas ethylbenzene concentrations detected in manholes
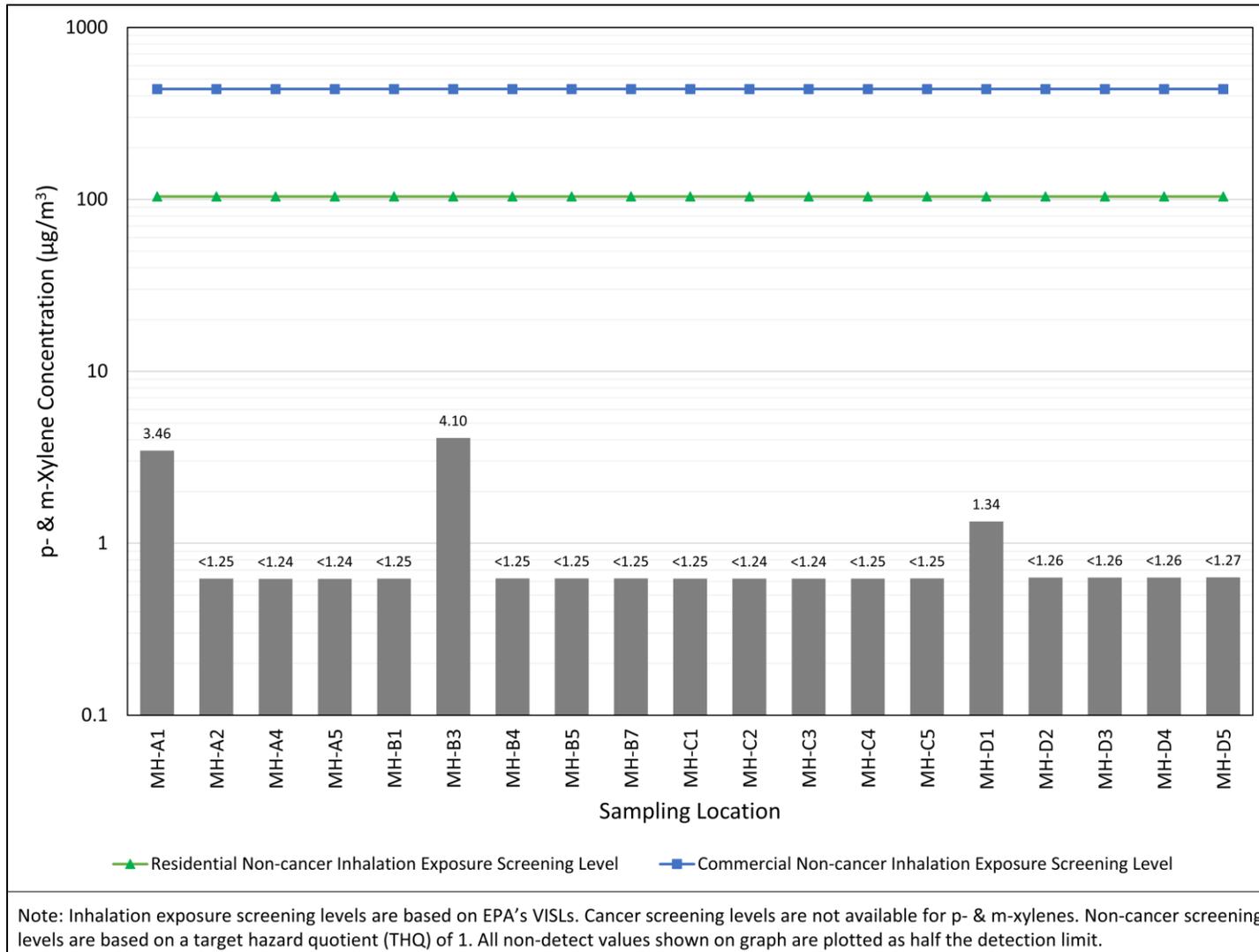
**Figure 4-16: Sewer gas p- & m-xylenes concentrations detected in manholes**
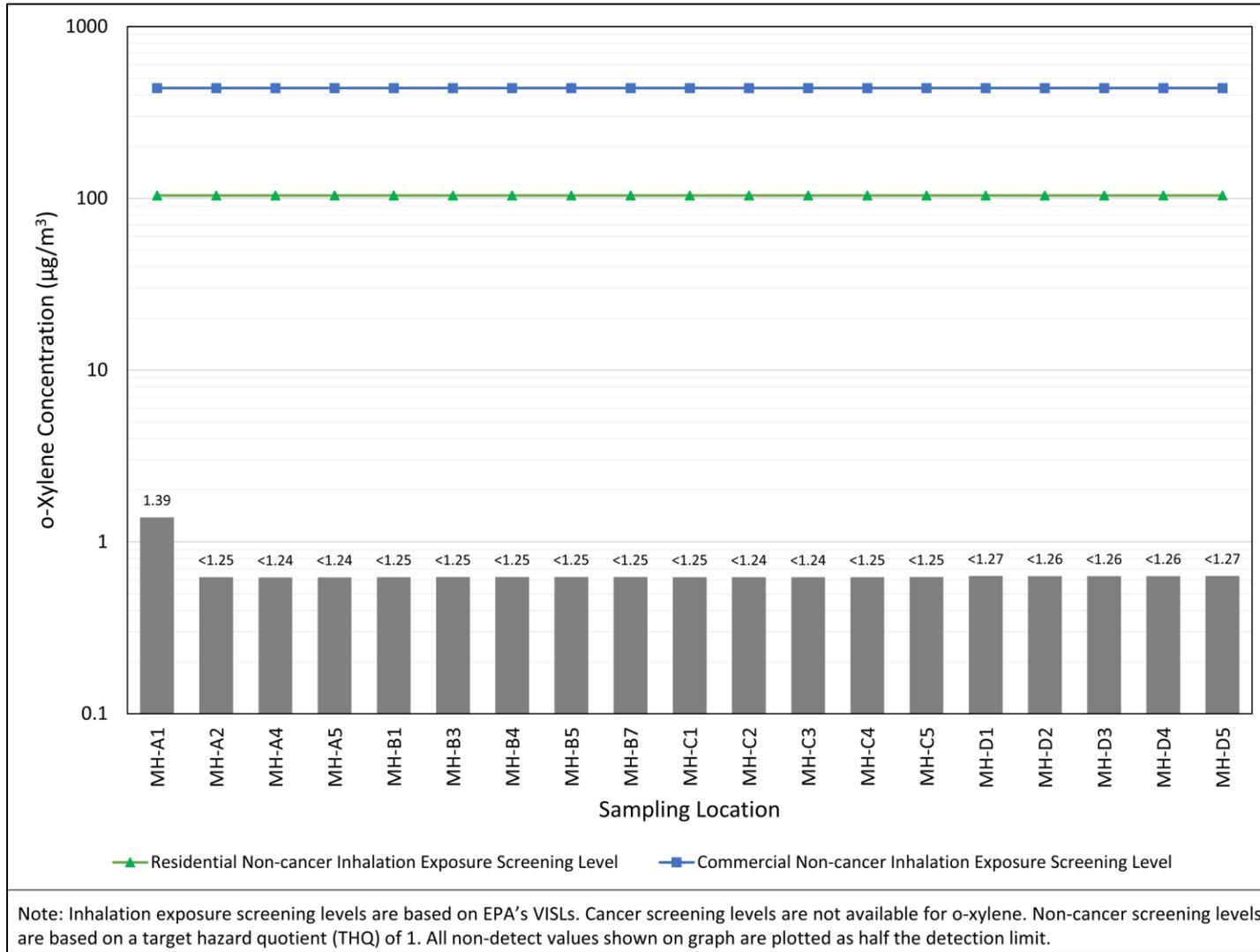
Figure 4-17: Sewer gas o-xylene concentrations detected in manholes
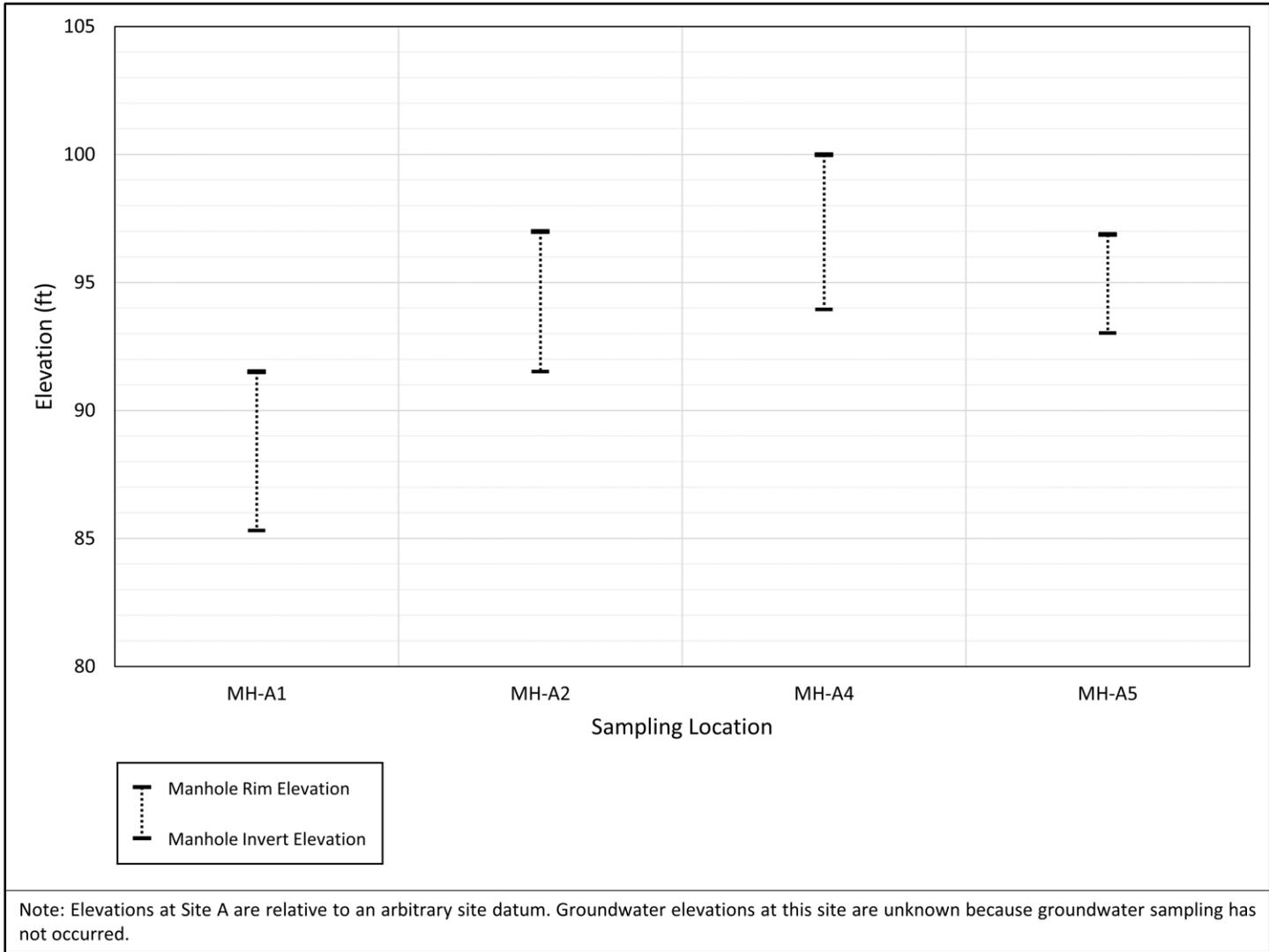
**Figure 4-18: Site A sanitary sewer manhole elevations**
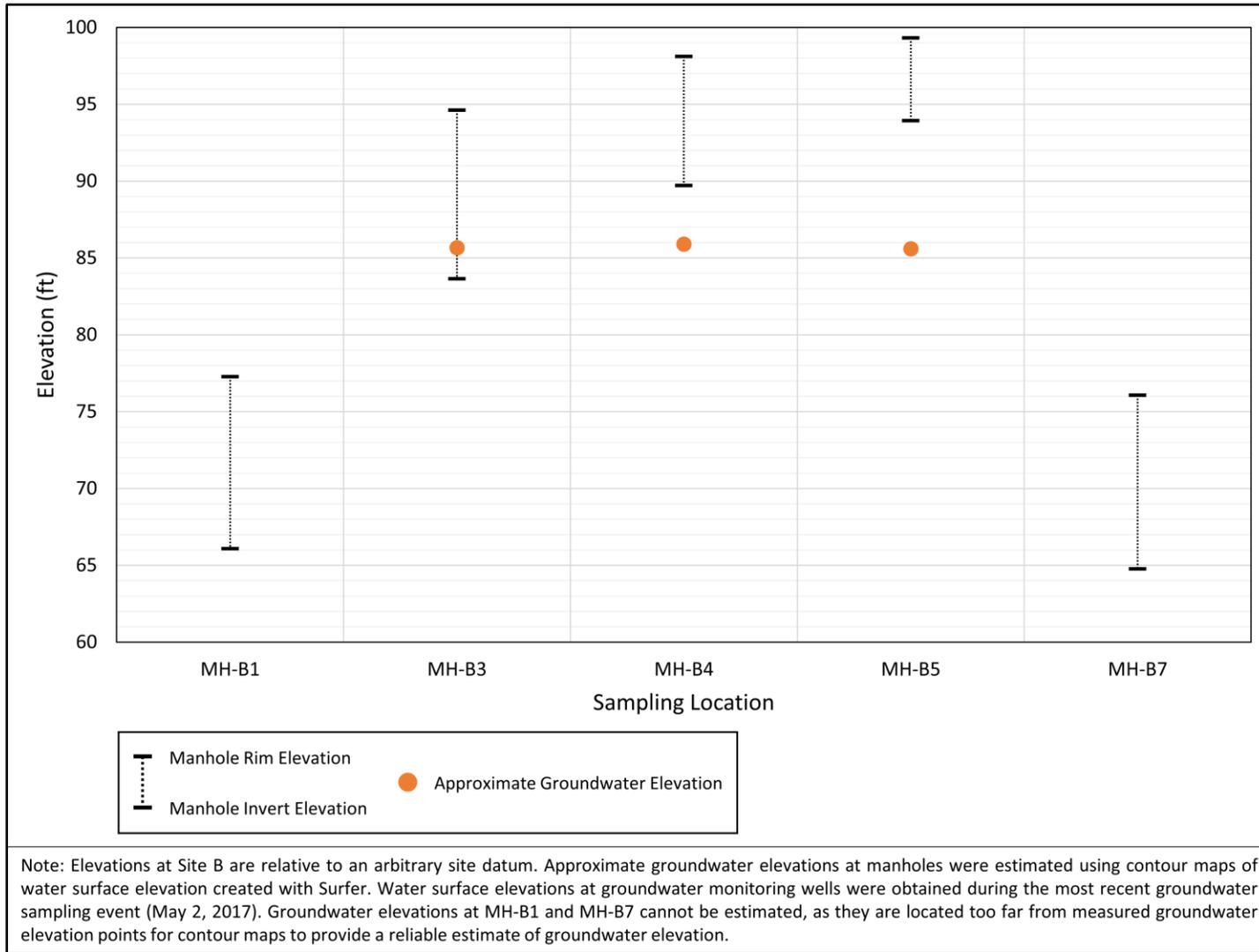
Figure 4-19: Site B sanitary sewer manhole and groundwater elevations
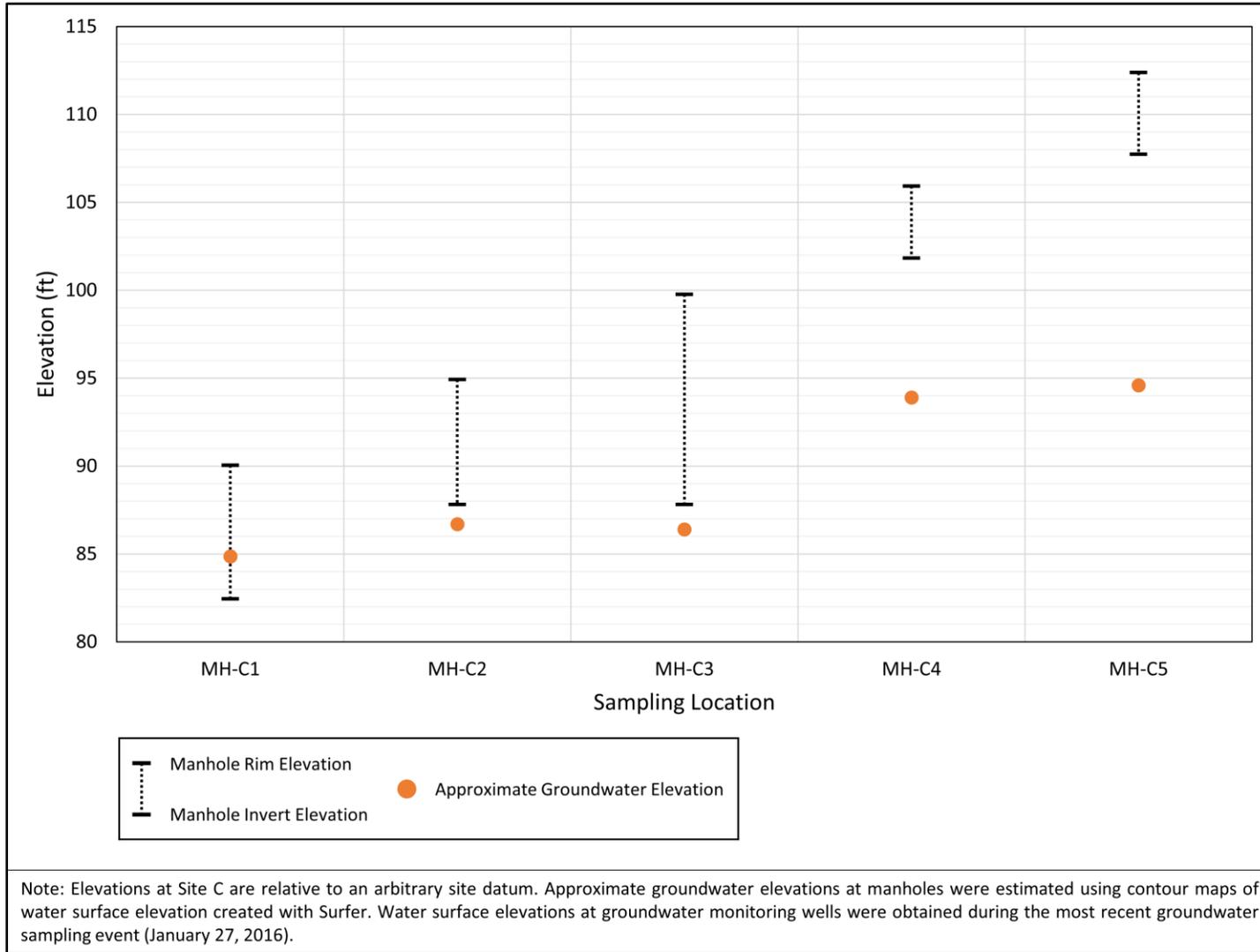
Figure 4-20: Site C sanitary sewer manhole and groundwater elevations
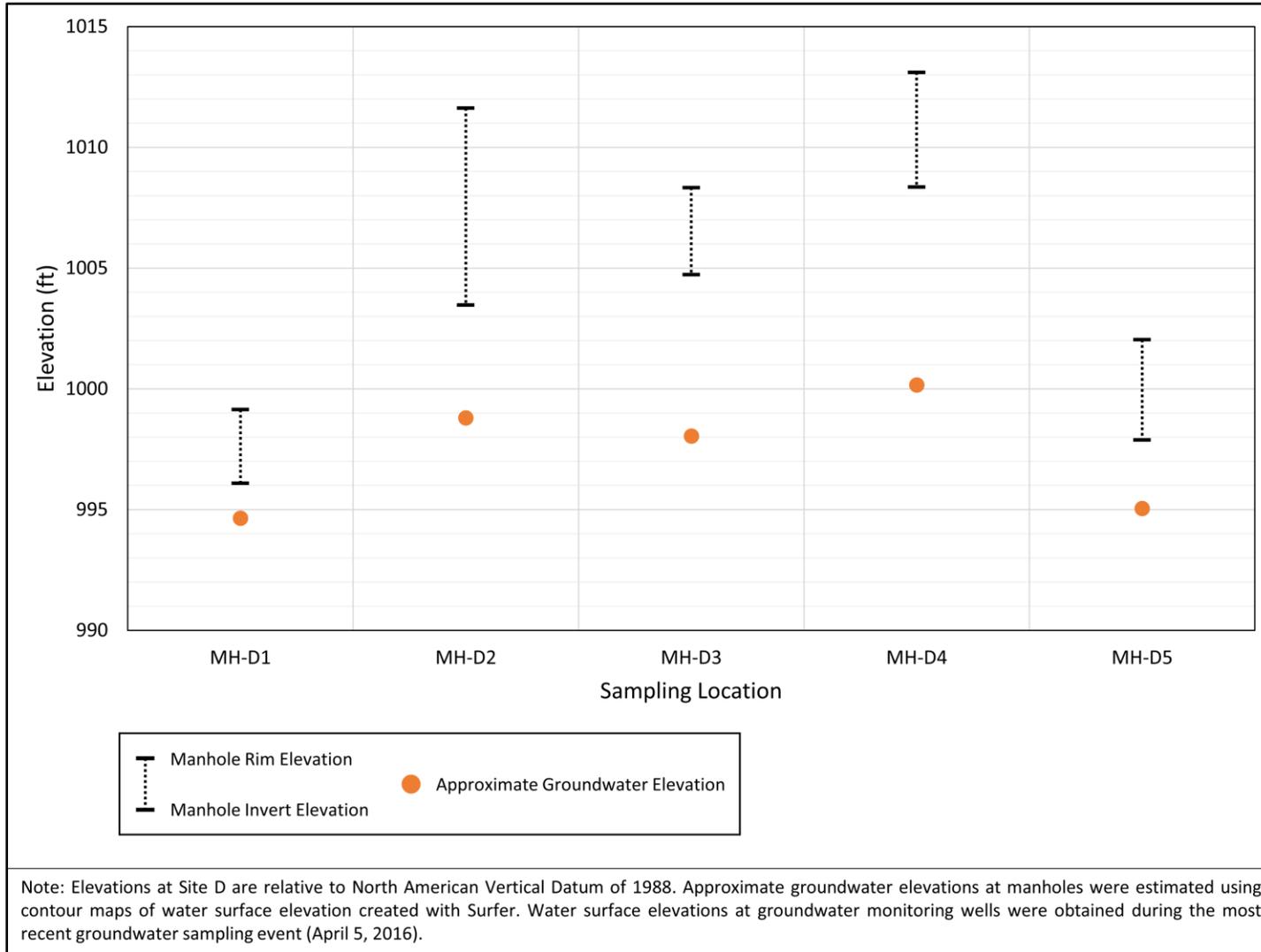
Figure 4-21: Site D sanitary sewer manhole and groundwater elevations

4.3.1 Site A

Figure 4-5 shows a map of sewer gas CVOC concentrations detected at manholes at Site A. This site had relatively low concentrations for most CVOCs, with the exception of a chloroform concentration of 22.92 $\mu g/m^3$ at MH-A1. MH-A4 and MH-A5, the manholes closest to the former dry cleaning facility, were non-detect for all CVOCs. MH-A2, located two manholes downstream of MH-A5 and across the street from the former dry cleaning facility, was also non-detect for all CVOCs. MH-A1, located several manholes downstream and across the street from the former dry cleaning facility, had detections for PCE, TCE, and chloroform. The PCE concentration (1.54 $\mu g/m^3$) at MH-A1 did not exceed any health-relevant VISLs, as shown on Figure 4-9. The TCE concentration (2.05 $\mu g/m^3$) at MH-A1 exceeded the residential cancer VISL and nearly exceeded the residential non-cancer VISL. The chloroform concentration (22.92 $\mu g/m^3$) at MH-A1 was the third-highest chloroform concentration of all sampled manholes. The concentration was 188× and 43× greater than the residential cancer and commercial cancer VISLs, respectively.

Figure 4-13 through Figure 4-17 show sewer gas BTEX concentrations detected at manholes at Site A. The residential cancer VISL for benzene is low at 0.36 $\mu g/m^3$. The detection limit for sewer gas samples actually exceeded this level. Benzene concentrations were relatively low across Site A, with detections at MH-A1, MH-A2, and MH-A3. The benzene concentration at MH-A1 (1.83 $\mu g/m^3$) was the third-highest benzene concentration of all sampled manholes. The concentration exceeded residential cancer and commercial cancer VISLs, but by less than one order of magnitude. Sewer gas concentrations of toluene, ethylbenzene, and xylenes were low for manholes at Site A. No manholes had concentrations of these compounds greater than VISLs.

Figure 4-18 shows elevations of the sampled sanitary sewer manhole rims and inverts at Site A. Since there is no available information related to groundwater depth at this site, it is not possible to compare groundwater and sewer depths to determine if groundwater infiltration to the sewer may be occurring. The sampled manholes close to the former dry cleaning facility were non-detect for all CVOCs. If the groundwater around the dry cleaning facility is impacted by CVOCs and intersects the sanitary sewer line, then detections of CVOCs in sewer gas at nearby manholes could be expected. MH-A1, located several manholes downstream and a significant distance away from the site, had detections for PCE and TCE, but these concentrations were low. These concentrations may stem from historic releases of CVOCs to the sanitary sewer line from the dry cleaning facility but could also derive from a different source entirely. Considering the low and non-detect CVOC concentrations at Site A, further evaluation of potential vapor intrusion impacts stemming from dry cleaning chemical releases is not necessary.

4.3.2 Site B

Figure 4-6 shows a map of sewer gas and groundwater CVOC concentrations at Site B. On average, this site did not have highly elevated concentrations of CVOCs in sewer gas. However, MH-B5, the manhole closest to the former dry cleaning facility and current groundwater plume of CVOCs, had the highest PCE concentration, second highest TCE concentration, and second highest cis-1,2-DCE concentration of all sampled manholes. The PCE concentration at MH-B5 (459.97 µg/m^3) exceeds all VISLs; the detected concentration is nearly one and a half orders of magnitude (43×) greater than the residential cancer VISL, and one order of magnitude (11×) greater than the residential non-cancer VISL.

The TCE concentration at MH-B5 (14.2 $\mu g/m^3$) exceeds all VISLs; the detected concentration is 1.1 orders of magnitude (30×) greater than the residential cancer VISL, and 0.8 orders of magnitude (6.8×) greater than the residential non-cancer VISL. No inhalation toxicity information is available to assess how the cis-1,2-DCE concentration (35.21 $\mu g/m^3$) compares to VISLs.

MH-B4, located just downstream of MH-B5 and the former dry cleaning facility, had detections for PCE (1.65 $\mu g/m^3$) and cis-1,2-DCE (2.42 $\mu g/m^3$) but these concentrations were below all respective VISLs. MH-B3, the next manhole downstream, was non-detect for all CVOCs. However, MH-B3 did have detections for benzene, toluene, ethylbenzene, and p- & m-xylenes. The benzene concentration (11.76 $\mu g/m^3$) at MH-B3 was the highest of all sampled manholes, exceeding the residential cancer and commercial cancer VISLs; the detected concentration is 1.5 orders of magnitude (33×) greater than the residential cancer VISL and 0.9 orders of magnitude (7.5×) greater than the commercial cancer VISL. MH-B3 also had the only detected concentration of ethylbenzene (1.51 $\mu g/m^3$) of all sampled manholes. This concentration just marginally exceeded the residential cancer VISL for ethylbenzene. Additionally, MH-B3 had the highest concentration of p- & m-xylenes (4.10 $\mu g/m^3$) of all sampled manholes, but this concentration was below all VISLs.

MH-B1 and MH-B7, located several manholes downstream and a significant distance away from the former dry cleaning facility had detections for PCE (3.23 $\mu g/m^3$ and 10.7 $\mu g/m^3$, respectively), but these concentrations are less than VISLs. MH-B7 receives sewer liquid flow from a tributary that runs to the south of the study area.

Figure 4-19 shows elevations of the sampled sanitary sewer manholes relative to groundwater at Site B. Elevations at Site B are relative to an arbitrary site datum set by the consultants who have conducted groundwater monitoring at the site. Approximate groundwater elevations at manholes were estimated using contour maps of water surface elevation created with Surfer®. Water surface elevations at groundwater monitoring wells were obtained during the most recent groundwater sampling event, which occurred on May 2, 2017. Groundwater elevations at MH-B1 and MH-B7 cannot be estimated because they are located too far from measured groundwater elevation points for contour maps to provide a reliable estimate of groundwater elevation.

MH-B3 is below the groundwater table. No recent groundwater monitoring has occurred near MH-B3. The sewer gas concentrations of all CVOCs were non-detect at MH-B3, but this manhole had some of the highest concentrations of all sampled manholes for BTEX compounds. Since this manhole is below the groundwater table, there is a potential for groundwater infiltration into the sewer. Depending on the concentrations of chemicals in nearby groundwater, infiltration could dilute or increase chemical concentrations in sewer gas. At MH-B3, it is possible that nearby groundwater does not contain elevated levels of CVOCs but does contain elevated levels of BTEX compounds.

Conversely, MH-B4 and MH-B5 are above the groundwater table. MH-B5, which had high concentrations of PCE, TCE, and cis-1,2-DCE, is located close to two groundwater monitoring wells (MW-1 and MW-2) that had detections for PCE and/or TCE during the most recent groundwater sampling event. Since infiltration is not expected to occur at MH-B5, it is probable that CVOCs are present within the sewer system due to historical releases from the former dry cleaning facility and in nearby groundwater due to

exfiltration from leaks in the sewer. This may contribute to an accumulation of vapors at this manhole. The CVOCs may also be sorbed to sludge in the sewer or to the sewer pipe material itself. MH-B5 appeared to be significantly clogged with debris and seemingly viscous substances when opened for sampler deployment and retrieval. Additionally, no sewer liquid flow was evident in the manhole. This manhole is located directly adjacent to the former dry cleaning facility and is likely located very close to the sewer lateral that connects the building to the sewer. The debris in the manhole may serve as a derivative source of CVOCs that volatilize from the material to sewer air.

While PCE and cis-1,2-DCE were detected at MH-B4, these concentrations were significantly lower than those detected at MH-B5. Since groundwater infiltration into the sewer line between these two manholes is not expected to occur, dilution of sewer gas concentrations due to groundwater infiltration is unlikely. Ventilation of sewer gas between the two manholes may be responsible for the decrease in sewer gas CVOC concentrations. Sewer laterals connected to the sewer main between manholes MH-B4 and MH-B5 may provide transport pathways for sewer gas contaminants to exit the sewer system and migrate to indoor air of nearby buildings, thereby exposing inhabitants of these buildings to volatilized contaminants.

Additionally, the sewer laterals may provide significant sewer liquid flow to the sewer main that helps to dilute chemical concentrations. However, sewer ventilation processes are complicated. Many factors can influence sewer ventilation. While there are several possible explanations of the spatial distribution of sewer gas concentrations at Site B, additional sampling and further evaluation of potential vapor intrusion impacts at this site are necessary.

4.3.3 Site C

Figure 4-7 shows a map of sewer gas and groundwater CVOC concentrations at Site C. PCE was detected in all sampled manholes, with the highest concentrations being found in MH-C2 (204.62 µg/m^3) and MH-C1 (105.13 µg/m^3). Similarly, the highest TCE concentrations were also found in MH-C2 (48.71 µg/m^3) and MH-C1 (8.24 µg/m^3). The PCE and TCE concentrations at MH-C2 exceed all VISLs, while the PCE and TCE concentrations at MH-C1 exceed all VISLs aside from those for commercial non-cancer. MH-C3, the manhole closest to the former dry cleaning facility and groundwater plume containing CVOCs, had lower sewer gas concentrations of PCE, TCE, and cis-1,2-DCE than MH-C2 and MH-C1. MH-C4 and MH-C5, located across the street from the former dry cleaning facility and upstream of MH-C2, had similar CVOC concentrations to MH-C3.

These counterintuitive results are difficult to explain using recent groundwater monitoring data at the site. During the groundwater sampling event in January 2016, MW-2 had elevated concentrations of PCE, TCE, cis-1,2-DCE, and VC. MW-2 is located just in front of the former dry cleaning facility at Site C and close to a sanitary sewer pipe. At MW-4, located close to MH-C3, groundwater concentrations were non-detect for all CVOCs except for VC. At MW-6, located close to MH-C2, groundwater concentrations were non-detect for all analytes.

Figure 4-20 shows elevations of the sampled sanitary sewer manholes relative to groundwater at Site C. Elevations at Site C are relative to an arbitrary site datum set by the consultants who have conducted groundwater monitoring at the site. Approximate groundwater elevations at manholes were estimated using contour maps of water surface

elevation created with Surfer®. Water surface elevations at groundwater monitoring wells were obtained during the most recent groundwater sampling event, which occurred on January 27, 2016.

MH-C1 is below the groundwater table. The groundwater monitoring wells closest to MH-C1 were non-detect for all analytes during the most recent sampling event. The groundwater table likely intersects the sewer main connecting MH-C2 and MH-C1 since MH-C2 is above the groundwater table. There is therefore a potential for groundwater infiltration into this sewer pipe. Infiltrating groundwater may help explain the dilution of sewer gas CVOCs between MH-C2 and MH-C1. MH-C3, MH-C4, and MH-C5 are above the groundwater table as well. However, MH-C2 and MH-C3 are close enough to the groundwater table that seasonal groundwater fluctuations may reasonably be expected to cause intersection between the sewer and groundwater at these locations.

The sewer gas concentrations detected at MH-C2 and MH-C3 are difficult to explain using groundwater. Since infiltration is not expected to occur at these manholes on a continual basis, it is probable that CVOCs are present within the sewer system at the site due to historical releases from the former dry cleaning facility and in nearby groundwater due to exfiltration from leaks in the sewer. This may contribute to an accumulation of vapors at this manhole. The CVOCs may also be sorbed to sludge in the sewer or to the sewer pipe material itself. The higher sewer gas concentrations found at MH-C2 could possibly be explained by the presence of a drop structure at this manhole. A drop structure (i.e., where sewer liquid drops from a higher elevation to a lower elevation) would promote volatilization of volatile chemicals present in sewer liquid and/or sludge. Once these chemicals migrate to the sewer headspace, they will preferentially migrate in the same

direction as sewer liquid due to drag between the water surface and air in the headspace. This may also help explain why higher PCE, TCE, and cis-1,2-DCE concentrations were found at MH-C1 than MH-C3. The capability of sewer gas to also migrate upstream towards MH-C4 and MH-C5 may also explain the CVOC concentrations detected at these manholes, but other sources could contribute CVOCs to the sewer system near these manholes.

MH-C2 also receives flow from two sewer tributaries, whereas MH-C3 receives flow from only one. Turbulence created from sewer liquid mixing at MH-C2 is another possible explanation for the elevated sewer gas concentrations found at this manhole. However, turbulence and chemical volatilization processes in the sewer are complicated. There are many factors that can impact chemical volatilization and sewer gas migration. While there are several possible explanations of the spatial distribution of sewer gas concentrations at Site C, additional sampling and further evaluation of potential vapor intrusion impacts at this site are necessary.

4.3.4 Site D

Figure 4-8 shows a map of sewer gas and groundwater CVOC concentrations at Site D. PCE was detected in all sampled manholes, with the highest concentrations being found in MH-D1 (89.2 $\mu g/m^3$) and MH-D5 (44.77 $\mu g/m^3$). The PCE concentration at MH-D1 exceeds all VISLs for PCE except for the commercial non-cancer VISL, exceeding the residential cancer VISL by 0.92 orders of magnitude (8.26×). The PCE concentration at MH-D5 exceeds residential cancer and non-cancer VISLs by 0.62 (4.15×) and 0.03 (1.08×) orders of magnitude, respectively. These two manholes also had the highest

concentrations of all other compounds detected at Site D, including TCE, cis-1,2-DCE, chloroform, benzene, toluene, and p- & m-xylenes.

The TCE concentration at MH-D1 (13.31 µg/m^3) exceeds all VISLs, and the TCE concentration at MH-D5 (8.4 µg/m^3) exceeds all VISLS except for the commercial non-cancer VISL. MH-D1 had the highest cis-1,2-DCE concentration (37.2 µg/m^3) of any manhole across the four study sites. Chloroform concentrations at MH-D1 (30.41 µg/m^3) and MH-D5 (27.73 µg/m^3) exceed the residential cancer VISL by 2.4 (249.3×) and 2.36 (227.3×) orders of magnitude, respectively. Benzene concentrations at MH-D1 (1.36 µg/m^3) and MH-D5 (1.39 µg/m^3) also exceed the residential cancer VISL by a little more than 0.5 orders of magnitude. Toluene and p- & m-xylenes concentrations did not exceed respective VISLs, but the highest toluene concentration across the four study sites was detected at MH-D5 (122.47 µg/m^3). Construction activities that have been completed in the vicinity of this manhole may account for this elevated toluene concentration, as incidental leakage of fuel from equipment used during construction could have occurred.

MH-D2, MH-D3, and MH-D4 had lower concentrations than MH-D1 and MH-D5 for all analytes. These three manholes are located along sewer mains that run directly behind the current dry cleaning facility. MH-D3 is actually located just behind (i.e., to the south of) the facility. There are other sewer pipes and manholes located just west of the facility, but these were not accessible for sampling. It is unknown whether the dry cleaning facility's sewer lateral connects to these inaccessible pipes, or if the lateral connects to the pipes containing MH-D2, MH-D3, and MH-D4.

Groundwater monitoring wells MW-2, MW-3, and MW-9 had elevated groundwater concentrations of CVOCs during the most recent groundwater sampling event

in April 2016. Interestingly, these three wells are located close to sewer lines around the dry cleaning facility. MW-2 and MW-3 are located close to the inaccessible sewer pipes, while MW-9 is located close to the pipes containing MH-D2, MH-D3, and MH-D4. MW-2 and MW-3 had higher concentrations of CVOCs than MW-9, with the highest overall concentrations being detected in MW-2. Thus, the hot spot of the groundwater plume is likely located in the vicinity of MW-2 and MW-3. The locations of these monitoring wells close to sewer lines may provide evidence that groundwater contamination in the area originates from exfiltration from sewer pipes and that the dry cleaning facility's lateral connects to the inaccessible sewer pipes.

Figure 4-21 shows elevations of the sampled sanitary sewer manholes relative to groundwater at Site D. Elevations at Site D are relative to the North American Vertical Datum of 1988. Approximate groundwater elevations at manholes were estimated using contour maps of water surface elevation created with Surfer®. Water surface elevations at groundwater monitoring wells were obtained during the most recent groundwater sampling event, which occurred on April 5, 2016.

All of the sampled manholes at Site D are located above the groundwater table. Groundwater infiltration into sewer pipes and manholes is not expected to occur. Therefore, it is probable that CVOCs are present within the sewer system at the site due to releases from the dry cleaning facility and in nearby groundwater due to exfiltration from leaks in the sewer. Sorption of CVOCs to sewer sludge or the sewer pipe material could allow the CVOCs to remain in the local sewer pipes for extended durations. The elevated concentrations of CVOCs in sewer gas at MH-D1, which is located at the end of the

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inaccessible section of sewer pipes, may provide additional evidence that the dry cleaning facility's sewer lateral connects to this inaccessible sewer section.

MH-D1 receives flow from three sewer tributaries. Mixing at MH-D1 may generate turbulence that facilitates volatilization of chemicals from sewer liquid to air in the headspace. It is more difficult to develop a possible explanation for the concentrations of CVOCs found at MH-D5. The groundwater monitoring wells closest to this manhole were non-detect for all analytes during the most recent sampling event, and this manhole receives no inflow from a sewer main. One possible explanation is that another source is adding CVOCs to the sewer system using a sewer lateral located close to MH-D5. Another possible explanation is that mechanically-forced pressure differences caused volatilized gas-phase chemicals at MH-D1 to migrate upstream to MH-D5, opposite of the flow of sewer liquid. While there are several possible explanations of the spatial distribution of sewer gas concentrations at Site D, additional sampling and further evaluation of potential vapor intrusion impacts at this site are necessary.

5   Conclusions

This research project involved the development and use of a screening-level method to identify hazardous waste sites where additional evaluation of vapor intrusion pathways may (and may not) be warranted. Geospatial evaluation of sanitary sewers and hazardous waste sites was accomplished using spatial data and metadata available from city and regulatory databases. Most of this information was not readily available online and required interaction with local wastewater authorities (i.e., LFUCG-DWQ) and hazardous waste site regulators (i.e., KYDEP). Submittal of open records requests was vital for preliminary data collection for this study.

Sites with groundwater contamination stemming from vapor-forming chemicals, such as PHCs and chlorinated solvents, were identified as having a greater potential for vapor intrusion issues. Dry cleaning facilities were targeted as sites of particular concern due to the numerous petroleum-based and chlorinated solvents that have been used historically for dry cleaning operations, and because these facilities are often located within populated residential and commercial areas. Four dry cleaning sites were selected for further evaluation by sewer gas sampling. Considerations 1 and 2, discussed in Section 3.1, were successfully addressed during this study. Consideration 3, however, necessitates further evaluation.

Screening of sanitary sewer pipes and groundwater VOC concentration data at the selected study sites revealed a great potential for the sewer system to be deteriorated and therefore susceptible to infiltration of contaminated groundwater (when the sewer is below the groundwater table) and vapors. At each site, sewer gas sampling of VOCs occurred at four to five sanitary sewer manholes, both close to and away from known groundwater

VOC plumes. Passive sorbent samplers were deployed at deep depths in the manholes using a novel sampling train and subsequently analyzed by Method TO-17. Many sampled manholes were found to be situated above the groundwater table based on site surveying.

While geospatial screening of the sanitary sewer system around the dry cleaning facility at Site A indicated deterioration of sewer pipes and potential for groundwater infiltration, no information was known about historic or recent groundwater VOC concentrations. Sewer gas concentrations of CVOCs and BTEX were low or non-detect at Site A. Considering these results, no further evaluation of potential vapor intrusion impacts stemming from dry cleaning chemical releases is necessary at Site A.

However, elevated sewer gas concentrations of certain CVOCs and BTEX compounds were detected at Site B, Site C, and Site D. Elevated concentrations of PCE and TCE greater than health-protective indoor air VISLs were detected at several manholes at these three sites. cis-1,2-DCE concentrations may also be an issue at these sites, but the detected concentrations cannot be compared against indoor air VISLs since no inhalation toxicity information yet exists for this chemical.

The locations of sewer gas concentrations did not always correspond with the locations of groundwater VOC hot spots. There are several possible explanations for the spatial distributions of sewer gas concentrations found at the sites. Factors that affect air flow in sewer systems include water drag, air pressure, drop structures, buoyancy effects, storage tunnels, and siphons [93]. Interplay between these different factors, as well as a lack of knowledge about the design of a sewer system, can make it difficult to understand sewer gas concentrations at a site. Furthermore, temporal variability is expected for sewer gas VOCs, especially considering the rainfall events during the sampling period.

Additional sampling and further evaluation of potential vapor intrusion impacts at Site B, Site C, and Site D are necessary.

Further evaluation of the study sites would ideally include collection of gas samples from sewer mains, sewer laterals, and indoor air. While gas-phase VOC concentrations in sewer mains provide information about the distribution of contamination in sewer mains, sewer lateral and indoor air samples are important for ultimately assessing human health risks associated with preferential sewer pathways for vapor intrusion. In order for receptors to be exposed to contaminants via inhalation of indoor air, the contaminants must be transported into the sewer air.

Plumbing systems are an important vapor transport pathway. Vapors can migrate from sewer mains to sewer laterals, then from sewer laterals to plumbing fixtures, and then from leaky plumbing fixtures into indoor air. Attenuation factors between detected sewer main gas concentrations and indoor air depend significantly on the characteristics and condition of a building's plumbing system. Alternatively, vapors can exfiltrate from sewer mains and/or laterals near a building's foundation and migrate into indoor air through cracks in the foundation.

Vapor intrusion through preferential sewer pathways can be remediated by preventing intrusion of contaminants into the sewer system and preventing intrusion of contaminated sewer gas into indoor air. Remediation techniques that could potentially be used to remediate this vapor intrusion pathway include replacement of the sewer line, lining (i.e., repair) of the sewer line, increased sewer ventilation, and sealing of leaky plumbing fixtures. Sub-slab depressurization, a remediation technique commonly used to address

typical vapor intrusion, may be utilized in scenarios where sewer gases exfiltrate from pipes and accumulate below building foundations.

The results of this project demonstrate that preferential vapor intrusion pathways such as sewers can help facilitate the distribution of VOCs beyond source areas of contamination. Vapor migration along these pathways can spread vapor intrusion exposure risks over larger geographic areas than those resulting from typical vapor intrusion processes (i.e., upward transport of vapors through the vadose zone and into buildings directly overlying subsurface plumes). The study sites evaluated for this project have relatively small contaminated groundwater plumes that are fairly localized within the vicinity of the dry cleaning facilities. Intersection between contaminated groundwater plumes and degraded sanitary sewer pipes, as well as historical solvent releases to the sewer system, may be responsible for detected sewer gas CVOC concentrations. Although sewer as-built drawings were not reviewed as part of this study, they can provide important site-specific information about the construction of sewer pipes and whether the pipes are located near the groundwater table where infiltration could occur.

Potential future research at the study sites could investigate temporal variability of sewer gas VOC concentrations and evaluate Consideration 3 (i.e., what are the conditions and characteristics of plumbing systems in buildings near the sites?) for indoor air exposure risks. Sewer gas to indoor air attenuation is likely, and attenuation may vary depending on site- and building-specific characteristics, such as the presence and extent of plumbing leaks. Additional evaluation of Consideration 3 may also include tracer gas studies to determine sewer gas to indoor air attenuation, smoke testing of plumbing systems in nearby buildings to determine if leakage occurs, and indoor air sampling of VOC concentrations.

Appendix: Health and Safety Plan

SANITARY SEWER STUDY
MANHOLE SAMPLING
PASSIVE SEWER AIR SAMPLING WORKPLAN

February 2018
Field Sampling of Sewers to Assess Inhalation Exposure Risks

Scope of Work (check all that apply):

    __X___   Travel

    __X___   Installation of Samplers (IS)

    __X___   Retrieval of Samplers (RS)

Field Dates	Type of Work	Site Safety Officer	Project Manager
02/14/2018	IS	Kelly Pennell	Evan Willett
02/20/2018	RS	Kelly Pennell	Evan Willett

Field Dates	Type of Work	Site Safety Technician(s)
02/14/2018	IS	Mohammadyousef Roghani
		Elham Shirazi
02/20/2018	RS	Mohammadyousef Roghani
		Elham Shirazi

PURPOSE

This Site Safety Plan (SSP) establishes the safety guidelines and requirements for installing passive vapor sorbent samplers in sanitary sewer manholes at four sites in Lexington, Kentucky.

This SSP addresses the expected potential hazards that may be encountered during this project.

The work tasks are as follows:
- o Establishing traffic control (cones) as needed prior to installing or retrieving the samplers in the street;
- o Removing manhole covers;
- o Installing/retrieving the samplers at/from the manholes;
- o Donning gloves and decontaminating between each sampling point;
- o Documenting conditions and installation details;
- o Taking other scientific measurements;
- o Replacing manhole covers;
- o Removing traffic control (as needed);
- o Transporting and packaging the samplers for shipment to analytical laboratory.

The provisions in this SSP will apply to University of Kentucky (UK) employees and students working at the job sites. All personnel working for UK must read this SSP and sign the attached Compliance Agreement prior to engaging in work at any of the sites.

PROPOSED ACTIVITY

Field sampling will take place at four sites. Passive samplers will be deployed in sanitary sewer manholes located on property owned by and accessible to Lexington-Fayette Urban County Government, as verified by the Division of Water Quality. Sampler deployment activities are anticipated to be completed in one workday, but two workdays may be necessary if inclement weather or unexpected field conditions are encountered. The samplers will remain in the manholes at each site for up to seven calendar days, at which time sampler retrieval activities will commence. Samplers cannot be left in the manholes for longer than seven days or the data becomes invalid.

JOB HAZARD ANALYSIS

Chlorinated solvents (e.g., tetrachloroethylene, trichloroethylene) and other similar industrial chemicals or degradation compounds may be present in the sewer air. It is not anticipated that concentrations of hazardous materials in the breathing zone will exceed safety guidelines.

Chemical Hazards

Chlorinated solvents, PHCs, water disinfection byproducts, and other industrial chemicals or degradation compounds may be present in sanitary sewer air. Hydrogen sulfide (H_2S) is commonly found in sewer gas at low concentrations. Human identification of sewer gas is determined by an individual's capacity to recognize H_2S odor. The estimated odor

threshold of H_2S ranged from 0.004 to 0.03 mg/m^3, while adverse health effects of H_2S occur at a much greater concentration in indoor environments [94]. For many chlorinated solvents, however, low concentrations are specified for protection from adverse health effects associated with indoor air exposures. Odor thresholds for chlorinated solvents are generally much higher than that of H_2S. Therefore, sewer gas odor can be an effective indicator of a completed sewer gas to indoor air pathway and the potential presence of VOCs in indoor air [8]. Nevertheless, the absence of sewer gas odor does not necessarily indicate an incomplete sewer gas pathway and absence of VOCs.

For the purposes of this study, the chlorinated solvents of concern are tetrachloroethylene, trichloroethylene, 1,2-dichloroethylene (cis and trans isomers), and vinyl chloride. PHCs of concern are benzene, toluene, ethylbenzene, and xylenes (BTEX). Chloroform is the lone water disinfection byproduct of concern due to its high volatility. Permissible exposure limits (PELs) (i.e., acceptable concentrations) of these chemicals in workplace air are set by the Occupational Health and Safety Administration (OSHA) in 29 Code of Federal Regulations 1910.1000, which was most recently amended in 2006. PELs are published as 8-hr time-weighted average (TWA) concentrations and acceptable ceiling concentrations. During an 8-hr period, an employee's exposure to a chemical cannot exceed the 8-hr TWA limit, nor can exposure exceed the acceptable ceiling concentration limit at any time.

Information about the usage and health effects of the chemicals shown in Table 2-1 has been summarized from chemical-specific toxicity reports prepared by the Environmental Protection Agency (EPA) and the Agency for Toxic Substances and Disease Registry (ATSDR).

The potential breathing zone concentrations of drycleaning solvent or petroleum hydrocarbon vapors are not expected to reach the permissible exposure limits (PEL) or the threshold limit values (TLV). The potential exposure pathways are **inhalation** and **skin contact**. Gloves will be used at each sampling location. The personnel protective equipment (PPE) specified in this SSP will be mandatory for field personnel.

Tetrachloroethylene
Tetrachloroethylene is a nonflammable, colorless liquid that evaporates readily into air and has a sharp, sweet odor. It is a manufactured chemical that is widely used for dry cleaning of fabrics and metal degreasing. It is also used to manufacture other chemicals and is used in some consumer products. Other names for tetrachloroethylene include perchloroethylene, PCE, perc, perchlor, and tetrachloroethene. Most people can smell tetrachloroethylene in air at a concentration of 1 part per million (1 ppm) or more [95].

As of September 2017, completed exposure pathways for tetrachloroethylene have been found at 226 NPL sites [96]. Acute effects of human inhalation exposure to high concentrations of tetrachloroethylene include dizziness, headaches, sleepiness, incoordination, confusion, nausea, unconsciousness, and even death. Chronic effects include kidney cancer (strong evidence), liver cancer (some evidence), and malignant

lymphoma (some evidence). EPA has determined that tetrachloroethylene is "likely to be carcinogenic in humans" by all routes of exposure [97].

Under anaerobic conditions, certain types of bacteria known as *Dehalococcoides* are able to degrade halogenated compounds. Anaerobic conditions exist in the subsurface in groundwater, soils, and sanitary sewer systems. During this process, the halogenated compound serves as the electron acceptor while hydrogen typically serves as the electron donor. When the compound being degraded is a chlorinated solvent, the process is known as reductive dechlorination. The figure below shows the reductive dechlorination of PCE to TCE to DCE (cis or trans isomers) to VC to ethene.
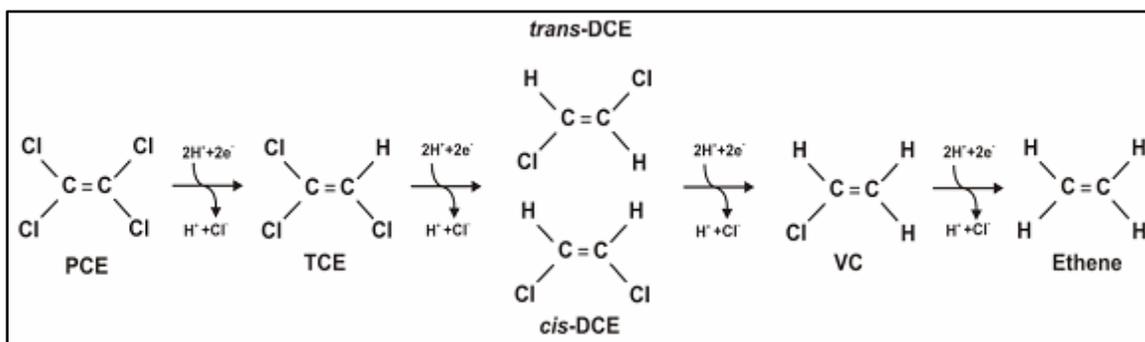
Reductive dechlorination of chlorinated ethenes [98]

Sequential removal of chloride ions occurs during reductive dechlorination of chlorinated compounds. Reductive degradation rates are faster for the more oxidized chlorinated compounds (i.e., PCE and TCE) than for those that are less oxidized (i.e., DCE and VC). Conversely, compounds that are less chlorinated/oxidized are more receptive to aerobic biodegradation. For example, TCE biodegrades anaerobically or occasionally aerobically, while VC easily biodegrades both anaerobically and aerobically [99]. Compared to trans-DCE, cis-DCE is more frequently detected as a groundwater contaminant [100], most likely because cis-DCE is a more common intermediate than trans-DCE during biodegradation of TCE [101]. PCE and TCE are highly toxic to humans, but VC is even more toxic [102]. Ethene has very low toxicity to humans.

Trichloroethylene
Trichloroethylene is a nonflammable, colorless liquid with a sweet odor. It is a combustible liquid and is incompatible with strong caustics and alkalis. It is a manufactured chemical that is used primarily as a metal degreasing solvent, but it is also used as an extraction solvent, as a chemical intermediate for the production of other chemicals, as a refrigerant, as an ingredient in consumer products, and in dry cleaning as a spot stain remover. It is also produced as an intermediate during reductive dechlorination of tetrachloroethylene. Synonyms and trade names for trichloroethylene include ethylene trichloride, TCE, trichloroethene, and trilene [103].

As of September 2017, completed exposure pathways for trichloroethylene have been found at 312 NPL sites [96]. Acute effects of human inhalation exposure to very high

concentrations of trichloroethylene include dizziness, headaches, sleepiness, incoordination, confusion, nausea, unconsciousness, liver damage, kidney damage, and even death. Chronic effects include kidney cancer, liver cancer, malignant lymphoma, and testicular cancer. For pregnant women, there is evidence that exposure to trichloroethylene may cause adverse development effects in children, including congenital heart defects, central nervous system defects, small birth weight, and spontaneous abortion. EPA has determined that trichloroethylene is "carcinogenic to humans" by all routes of exposure by a mutagenic mode of action [104]. Age-dependent adjustment factors are used when estimating age-specific cancer risks for trichloroethylene [105].

1,2-Dichloroethylene

1,2-Dichloroethylene is a highly flammable, colorless liquid (usually a mixtures of cis and trans isomers) with a sharp, harsh odor. It is used in chemical mixtures and to produce solvents. It is also produced as an intermediate during reductive dechlorination of tetrachloroethylene and trichloroethyelene. 1,2-Dichloroethylene readily evaporates into air, and humans can smell very small amounts (about 17 ppm) of it in air. Synonyms and trade names for 1,2-dichloroethylene include 1,2-dichloroethene, 1,2-DCE, and acetylene dichloride. The cis isomer is commonly referred to as cis-1,2-DCE or simply cis-DCE, and the trans isomer is often referred to as trans-1,2-DCE or trans-DCE [106].

As of September 2017, completed exposure pathways for cis- and trans-1,2-dichloroethylene have been found at 43 and 46 NPL sites, respectively [96]. Acute effects of human inhalation exposure to very high concentrations of 1,2-dichloroethylene include drowsiness, malaise, nausea, liver damage, lung damage, heart damage, and even death. Chronic effects are currently unknown. EPA has determined that there is "inadequate information to assess the carcinogenic potential" of both cis-1,2-dichloroethylene and trans-1,2-dichloroethylene [107].

Vinyl chloride

Vinyl chloride is a colorless gas or liquid (below 7°F) with a pleasant odor at high concentrations. It burns easily and it is not stable at high temperatures. It is a manufactured substance that does not occur naturally. It can be formed when other substances such as tetrachloroethylene, trichloroethylene, and 1,2-dichloroethylene are reductively dechlorinated. Synonyms and trade names for vinyl chloride include chloroethene, chloroethylene, ethylene monochloride, monochloroethene, monochloroethylene, VC, and vinyl chloride monomer [108].

As of September 2017, completed exposure pathways for vinyl chloride have been found at 99 NPL sites [96]. Acute effects of human inhalation exposure to very high concentrations of vinyl chloride include dizziness, sleepiness, unconsciousness, and even death. Chronic effects include permanent liver damage, immune reactions, and nerve damage. EPA classifies vinyl chloride as a "known human carcinogen" by the inhalation and oral routes of exposure, and as a highly likely carcinogen by the dermal route of exposure. Vinyl chloride acts by a mutagenic mode of action [109].

Benzene

Benzene is a colorless liquid with a sweet odor. It evaporates into the air very quickly and dissolves slightly in water. It is highly flammable and is formed from both natural processes and human activities. Benzene is widely used in industry; some industries use benzene to make other chemicals which are used to make plastics, resins, and nylon and other synthetic fibers. Benzene is also used to make some types of rubbers, lubricants, dyes, detergents, drugs, and pesticides. Benzene is also a natural part of crude oil, gasoline, and cigarette smoke. Synonyms and trade names for benzene include benzol and phenyl hydride [110].

As of September 2017, completed exposure pathways for chloroform have been found at 94 NPL sites [96]. Acute effects of human inhalation exposure to very high concentrations of benzene include cause drowsiness, dizziness, and unconsciousness, headaches, rapid heart rate, and even death. Chronic effects include bone marrow damage, anemia, and leukemia. EPA classifies benzene as a "known human carcinogen" by all routes of exposure [111].

Toluene

Toluene is a clear, colorless liquid with a distinctively sweet, pungent, benzene-like odor. It is a good solvent. Toluene occurs naturally (e.g., in crude oil) and is manufactured in the process of making gasoline and other fuels from crude oil and in making coke from coal. Toluene is used in making a variety of consumer products and is also used in the manufacture of other chemicals, nylon, and plastics. It is added to gasoline along with benzene, ethylbenzene, and xylene to improve octane ratings. Synonyms and trade names for toluene include methylbenzene, methyl benzol, phenyl methane, and toluol [112].

As of September 2017, completed exposure pathways for toluene have been found at 65 NPL sites [96]. Acute effects of human inhalation exposure to very high concentrations of toluene include malaise, confusion, weakness, drunken-type actions, memory loss, nausea, and loss of appetite. Chronic effects hearing loss, color vision loss, nerve damage, and brain damage. EPA has determined that there is "inadequate information to assess the carcinogenic potential" of toluene [113].

Ethylbenzene

Ethylbenzene is a colorless, flammable liquid that smells like gasoline. It is naturally found in coal tar and petroleum and is also found in manufactured products such as inks, pesticides, and paints. Ethylbenzene is used primarily to make another chemical, styrene. Other uses include as a solvent, in fuels, and to make other chemicals. Ethylbenzene moves easily into the air from water and soil. Synonyms and trade names for ethylbenzene include ethylbenzol and phenylethane [114].

As of September 2017, completed exposure pathways for ethylbenzene have been found at 39 NPL sites [96]. Acute effects of human inhalation exposure to ethylbenzene include dizziness and throat and eye irritation. Chronic effects, studied in animals, include hearing loss and kidney damage. EPA has determined ethylbenzene to be "not classifiable as to human carcinogenicity" [115], and the International Agency for Research on Cancer (IARC) classifies ethylbenzene as "possibly carcinogenic to humans" [116].

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Xylenes

There are three forms of xylene in which the methyl groups vary on the benzene ring: *meta*-xylene, *ortho*-xylene, and *para*-xylene (*m*-, *o*-, and *p*-xylene). These different forms are referred to as isomers. Xylene is a colorless, sweet-smelling liquid that catches on fire easily. It occurs naturally in petroleum and coal tar. Chemical industries produce xylene from petroleum. Xylene is used as a solvent and in the printing, rubber, and leather industries. It is also used as a cleaning agent, a thinner for paint, and in paints and varnishes. It is found in small amounts in airplane fuel and gasoline. Synonyms and trade names for the various forms of xylene are as follows:

- o m-Xylene: 1,3-Dimethylbenzene, meta-Xylene, m-Xylol
- o o-Xylene: 1,2-Dimethylbenzene, ortho-Xylene, o-Xylol
- o p-Xylene: 1,4-Dimethylbenzene, para-Xylene, p-Xylol [117]

As of September 2017, completed exposure pathways for xylenes (total) have been found at 38 NPL sites [96]. Acute effects of human inhalation exposure to very high concentrations of xylenes include headaches, lack of muscle coordination, dizziness, confusion, changes in one's sense of balance, dermal irritation, loss of memory, nausea, and even death. Chronic effects are currently unknown. EPA and IARC have both determined xylenes to be "not classifiable as to human carcinogenicity" [116, 118].

Chloroform

Chloroform is a colorless liquid with a pleasant, nonirritating odor and a slightly sweet taste. It evaporates easily into the air and will burn only when it reaches very high temperatures. Chloroform is used to make other chemicals and can also be formed in small amounts when chlorine is added to water. Synonyms and trade names for chloroform include methane trichloride, methyl trichloride, and trichloromethane [119].

As of September 2017, completed exposure pathways for chloroform have been found at 94 NPL sites [96]. Acute effects of human inhalation exposure to chloroform include dizziness, fatigue, headaches. Chronic effects include damage to the liver and kidneys. EPA has classified chloroform as a "probable human carcinogen" by all routes of exposure [120].

Hydrogen sulfide

Hydrogen sulfide is a flammable, colorless gas that smells like rotten eggs. People usually can smell hydrogen sulfide at low concentrations in air ranging from 0.0005 to 0.3 ppm. Hydrogen sulfide occurs naturally in crude petroleum, natural gas, volcanic gases, and hot springs. Since it can also form from bacterial breakdown of organic matter, it is essentially ubiquitous in sewer gas. Industrial sources of hydrogen sulfide include petroleum refineries, natural gas plants, petrochemical plants, coke oven plants, food processing plants, and tanneries. It is used primarily in the production of sulfur and sulfuric acid. Synonyms and trade names for hydrogen sulfide include sewer gas, dihydrogen monosulfide, hydrosulfuric acid, and sulfuretted hydrogen [121].

As of September 2017, completed exposure pathways for hydrogen sulfide have been found at four NPL sites [96]. Acute effects of human inhalation exposure to hydrogen

sulfide include dermal irritation, headaches, memory loss, malaise, balance problems, unconsciousness, and even death. Chronic effects are currently unknown. EPA has determined that "data are inadequate for an assessment of the carcinogenic potential of hydrogen sulfide" [94].

Instrumentation

A photo ionization detector (PID) with an 11.6ev lamp will be used to measure organic vapors in the breathing zone throughout the workday. The PID will be calibrated daily using 100 parts per million (ppm) iso-butylene calibration gas and recorded in the daily field log. The PID will monitor the work zone at the breathing zone height of approximately five fet above the ground surface. Measurements will be read and recorded during each sampling event in the daily field log.

Permissible Exposure Limits

Permissible exposure limits (PELs) (i.e., acceptable concentrations) of these chemicals in workplace air are set by the Occupational Health and Safety Administration (OSHA) in 29 Code of Federal Regulations 1910.1000, which was most recently amended in 2006. PELs are published as 8-hr time-weighted average (TWA) concentrations and acceptable ceiling concentrations. During an 8-hr period, an employee's exposure to a chemical cannot exceed the 8-hr TWA limit, nor can exposure exceed the acceptable ceiling concentration limit at any time. The American Conference of Government Industrial Hygienists (ACGIH) has set recommended threshold limit values (TLVs) as recently as 2017. ACGIH exposure limits are provided as threshold limit values. TLVs are provided as 8-hour time weighted averages (TWAs), short term exposure limits (STELs), and ceilings (C). ACGIH recommended limits are generally more stringent than OSHA regulatory limits. Regulatory and recommended limits are provided below for each of the chemical hazards previously discussed [122].

| Chemical | OSHA PEL (ppm) | | ACGIH 2017 TLV (ppm) |
	8-hour TWA	Acceptable Ceiling Concentration	8-hour TWA (ST) STEL[a] (C) Ceiling[b]
Tetrachloroethylene	100	200	25 (ST) 100
Trichloroethylene	100	200	--
1,2-Dichloroethylene	200	--	200
Vinyl chloride	1	5	1
Benzene	10	25	0.5 (ST) 2.5
Toluene	200	300	20
Ethylbenzene	100	--	20
Xylenes	100	--	100 (ST) 150
Chloroform	--	50	10
Hydrogen sulfide	--	20	1 (ST) 5

Note: [a] STEL is a 15-minute TWA exposure that should not be exceeded at any time during a workday, even if the 8-hour TWA is within the TLV–TWA. [b] Ceiling is the concentration that should not be exceeded during any part of the working exposure.

The use of respiratory protection is not planned.
The PID measures the total amount of solvents and PHCs in the breathing space and cannot distinguish between the various contaminants (solvents, benzene, toluene, etc.). Therefore, the most conservative concentration (10 ppm for benzene) is selected as the action level. It is not expected that respiratory protection will be needed.

Exposure Controls
The levels of any organic compounds will not require the use of exposure controls such as fans. Should PID readings be elevated or strong odors in the breathing zone be noted, workers should move away from the source of the exposure until the levels dissipate into outdoor air. Use the PID to measure organic vapors.

Physical Hazards
The potential physical hazards expected at the job site are addressed below:
- The potential for physical injury exists from working with the manholes and cleanouts. Proper precaution should be used prior to inserting or retrieving the samplers.
- Use of brightly colored vests will be required when in the work area.
- Traffic should be carefully watched in sampler locations in or near the streets. Place cones around each work area near or in the streets to alert drivers of the field activity.

- The work area will be maintained free of trash or loose debris.
- With a "buddy" work team, each member is responsible for the awareness/safety of the other team member(s).

Heat Stress

The potential for heat stress is present if the air temperature exceeds 80°F, clothing prevents sweat from evaporating, or shade is not available. The field desk set up should be set up in the shade. Some signs and symptoms of heat stress are discussed below:
- Heat cramps are caused by heavy sweating with inadequate electrolyte replacement. Signs and symptoms include: muscle spasms, heavy sweating, dizziness, nausea, and fainting.
- Heat exhaustion occurs from increased stress on various body organs, including inadequate blood circulation due to cardiovascular insufficiency or dehydration. Signs and symptoms include pale, cool, moist skin; heavy sweating; dizziness; nausea; and fainting.
- Heat stroke is the most serious form of heat stress. Temperature regulation fails, and the body temperature rises to critical levels. Immediate action must be taken to cool the body before serious injury or death occurs. Competent medical help must be obtained. Signs and symptoms of heat stroke are red, hot, unusually dry skin; lack of or reduced perspiration; nausea; dizziness and confusion; strong, rapid pulse; and coma.

Heat Stress Monitoring

All personnel (including subcontractors) at the job site shall be monitored for heat stress. Workers at the job site are expected to wear cotton or synthetic work clothes. Monitoring for heat stress will consist of personnel constantly observing each other for any of the heat stress symptoms discussed above. The **Site Safety Officer** shall mandate work slowdowns as needed.

Heat Stress Prevention

Heat stress can be avoided by taking the following precautions:
- Adequate liquid intake
- Cooling by water misting
- Shade
- Working early and/or late in the day

Fire and Explosive Hazards

It is not expected that an explosion will occur, however, the potential for fire or explosion exists whenever flammable liquids or vapors are present above lower explosions limit (LEL) concentrations and sufficient oxygen (<19.5; >23.5%) is present to support combustion.

In the event of a fire or explosion, all personnel shall be evacuated and the local fire department or emergency response agency shall be called by dialing 911. No one shall re-enter the area until it has been cleared by qualified safety and firefighting personnel.

Electrical Hazards
No electrical enclosures will be opened. The absence of electrical power will be verified with a meter prior to working on any circuits. The generator and electrical equipment will comply with all local, state, and federal regulations. Ground fault circuit breakers will be installed on all electrical equipment of 50 volts or greater.

Biological Hazards
Potential biological hazards such as bacteria from the sewer, spiders, insects, or animals may occur onsite. Personnel shall use caution when entering areas that may shelter indigenous creatures. Gloves shall be donned and doffed with special care to prevent exposure of skin to sewer material. Black widow spiders are likely to exist in or near the cleanout vaults and manholes. Eating, drinking, smoking, or chewing gum/tobacco, or other substances, while working will not be permitted within the work area.

General Public Hazards
Use cones to define the work zone and prevent the ingress of pedestrians or vehicles.

EMERGENCY RESPONSE PROCEDURES

The Site Safety Officer has the responsibility and authority for coordinating all emergency response activities until emergency response authorities arrive and assume control of the site.

Emergency Medical Procedures
For severe injuries, illnesses, or contaminant exposure:
- o Remove the injured or exposed person(s) from immediate danger.
- o If possible, partial decontamination should be completed. Wash, rinse, and/or cut off protective clothing and equipment and re-dress the victim in clean overalls.
- o If decontamination cannot be done, wrap the victim in blankets or plastic sheeting to reduce contamination of other personnel.
- o Render emergency first aid, and immediately call an ambulance for transport to the local hospital.
- o Evacuate other personnel on site to a safe place until the Site Safety Officer determines that it is safe to resume work.

For minor injuries or illnesses:
- o Complete a full decontamination.
- o Administer first aid. Minor injuries may be treated on site, but trained medical personnel will examine all injuries.
- o Notify the Project Manager and Site Safety Officer immediately.

First Aid – Chemical Exposure

The following first aid procedures are to be initiated as soon as possible for chemical injuries:

Eye Exposure	If a contaminated solid or liquid gets into the eyes, wash eyes immediately with sterile saline solution, lifting the lower and upper lids occasionally. Continue washing the eye for 15 minutes. Cover the eye with a dry pad and obtain medical attention immediately.
Skin Exposure	If a contaminated solid or liquid gets on the skin, promptly wash contaminated skin for 15 minutes using soap or mild detergent and water. If solids or liquids penetrate the clothing, remove the clothing immediately and wash the skin using soap or mild detergent and water. Obtain medical attention immediately if symptoms warrant.

First Aid – Physical Injury

The following first aid procedures are to be initiated as soon as possible for physical injuries:

Animal Bites	Thoroughly wash the wound with soap and water. Flush the area with running water and apply a sterile dressing. Immobilize affected part until a physician has examined the victim. See that the animal is kept alive and in quarantine. Obtain name and address of the owner of the animal.
Minor Burns	Do not apply vaseline or grease of any kind. Apply cold water until pain subsides. Cover with a wet sterile gauze dressing. Do not break blisters or remove tissues. Seek medical attention.
Severe Burns	Do not remove adhered particles or clothing. Do not apply ice or immerse in cold water. Do not apply grease, vaseline, or ointment of any kind. Cover burns with thick sterile dressings. Keep burned feet or legs elevated. Seek medical attention immediately.
Cuts	Apply pressure with sterile gauze dressing and elevate the area until bleeding stops. Apply a bandage and seek medical attention.
Eyes	Keep the victim from rubbing the eye. Flush the eye with clean water. If flushing fails to remove the object, apply a dry, protective dressing and consult a physician.
Fainting	Bring the victim out of the sun. Keep the victim lying down with feet elevated. Loosen tight clothing. If victim vomits, roll them onto their side or turn their head to the side. If necessary, wipe out their mouth. Maintain an open airway. Bathe face gently with cool water. Unless recovery is prompt, seek medical attention.
Fracture	Deformity of an injured part usually means a fracture. If a fracture is suspected, splint the part as it lies. Do not attempt to move the injured part of the person. Seek medical attention immediately.
Insect Bites	Remove the stinger. Keep affected part below the level of the heart. Apply ice bag. For minor bites and stings, apply soothing lotions, such as Calamine.

Puncture Wounds	If puncture wound is deeper than skin surface, seek medical attention. Serious infection can arise unless proper treatment is received.
Sprains	Elevate injured part and apply ice bag or cold packs. Do not soak in hot water. If pain and swelling persist, seek medical attention.
Unconscious-ness	Do not attempt to give any fluid or solid by mouth. Keep victim flat and maintain an open airway. If victim is not breathing, provide artificial mouth-to-mouth resuscitation and call for an ambulance immediately.

PERSONAL PROTECTIVE EQUIPMENT

Level D personal protective equipment (PPE) is expected to be the highest protective level required for this project. Modified Level C PPE may be required at the discretion of the Site Safety Officer. The following lists summarize the PPE that shall be used by all field personnel in the work zone:

Level D Protection (shall be worn at all times)
- o Brightly colored safety vest
- o Boots with steel toes (light shoes like sneakers are not safe for this project because manhole covers will have to be removed)
- o Safety glasses (not required for this project)
- o Hard hat (not required for this project)
- o Latex gloves (mandatory except for scribe)
- o Long-legged trousers (recommended)
- o Long-sleeved shirt (recommended, due to cold temperatures and potential wind)
- o Chemical splash goggles or face shield for the grout/cement mixer operator (not required for this project)
- o Respiratory protection (not required for this project)

TRAINING REQUIREMENTS

University of Kentucky personnel will be required to have completed OSHA HAZWOPER 24-hour training to assist in field work for this project, in compliance with OSHA Standard 29 CFR 1920.120, Hazardous Waste Operations and Emergency Response. All site personnel are required to participate annually in OSHA HAZWOPER 8-hour refresher training.

EMERGENCY RESPONSE PLAN

In the event of an accident resulting in physical injury, first aid will be administered and the most able-bodied and immediately available person will transport the injured worker to the University of Kentucky Albert B. Chandler Hospital in Lexington, Kentucky. Severely injured personnel will be transported by ambulance to the hospital.

In the event of a fire or explosion, dialing 911 will call local fire or emergency response agencies. The Project Manager should be notified next.

Emergency Telephone Numbers:

Fire and Police..**911**
University of Kentucky Albert B. Chandler Hospital – Pavilion A
1000 South Limestone
Lexington, KY 40536-0602..**859-323-5901**

KEY SAFETY PERSONNEL AND RESONSIBILITIES

All personnel working for the University of Kentucky at the job site are responsible for project safety. Specific individual responsibilities are listed below:

> Project Manager: **Evan Willett**
> Site Safety Officer: **Kelly Pennell**

The **Project Manager** is responsible for preparation of this Site Safety Plan. He/she has the authority to provide for the auditing of compliance with the provisions of this Site Safety Plan, suspend or modify work practices, and to report to the Site Safety Officer any individual whose conduct does not meet the provisions presented in this Site Safety Plan. The **Site Safety Officer** is responsible for disseminating the information contained in this Site Safety Plan to all University of Kentucky personnel working at the job site, and to the responsible representative(s) of each subcontractor working for the University of Kentucky at the job site.

The Site Safety Officer is responsible for ensuring that the following items are documented after these items have been addressed:
- Inspection of tools, drilling equipment, and safety equipment
- Safety supplies and equipment inventory
- Site-specific training/hazard communication
- Accident/incident reporting
- Decontamination/contamination reduction procedures

The Site Safety Officer and all site personnel shall take the necessary steps to ensure that all personnel are protected from physical hazards, which could include:
- Falling objects such as tools or equipment
- Fall from elevations
- Tripping over hoses, pipes, tools, or equipment
- Slipping on wet or oily surfaces
- Insufficient or faulty protective equipment
- Insufficient or faulty operations, equipment, or tools
- Noise
- Vehicular traffic

The Site Safety Officer has the authority to suspend work anytime he/she determines the safety provisions set forth in this Site Safety Plan are inadequate to ensure worker safety. The Site Safety Officer or Project Manager must be present during all phases of the site work.

DOCUMENTATION

All personnel shall sign the compliance agreement. All personnel training documents, including medical certifications, will be kept with the onsite Site Safety Officer. A daily log, completed by the Site Safety Officer in his/her field notebook, shall provide daily documentation. The Site Safety Officer shall record the names of all personnel working for the University of Kentucky, its subcontractors, and any site visitor(s). The Site Safety Officer shall also record accidents, illness, and other safety related matters.

Site Safety Plan prepared by: Evan Willett   Date: January 8, 2018

Site Safety Plan approved by: Kelly Pennell   Date: February 7, 2018

COMPLIANCE AGREEMENT

I have read the Site Safety Plan and understand its contents and conditions. I will comply with the safety requirements set forth in this document by signing below. I agree to notify Kelly Pennell, the Site Safety Officer, should any unsafe acts be witnessed by me while I am on the job site(s).

Print Name	Company	Signature (Initials)	Date
Kelly Pennell	UK	KP	02/07/18
Evan Willett	UK	EW	02/07/18
Mohammadyousef Roghani	UK	MR	02/07/18
Elham Shirazi	UK	ES	02/07/18

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VITA

Evan James Willett

Place of Birth:

Louisville, Kentucky, United States of America

Education:

M.S. Civil Engineering, University of Kentucky (*In Progress, Expected 2018 Graduation*)
   GPA: 4.0/4.0
   Emphasis: Environmental Engineering

B.S. Civil Engineering, University of Kentucky (2016)
   GPA: 4.0/4.0 (*Summa Cum Laude*)
   Certificate of Honors in the Honors Program

Professional Experience:

Graduate Research Assistant, Department of Civil Engineering, University of Kentucky (2016 – present)

Graduate Teaching Assistant, Department of Civil Engineering, University of Kentucky (2017)

Undergraduate Research Assistant, Department of Civil Engineering, University of Kentucky (2014 – 2016)

Honors & Awards:

James and Sharon Weinel Chi Epsilon National Graduate Fellowship (2018)

First Place, Student Poster Competition, KY/TN Water Professionals Conference (2017)

AEESP 2017 Student Travel Award, Sponsored by AECOM (2017)

Honorable Mention, NSF Graduate Research Fellowship Program (2017)

University of Kentucky Otis A. Singletary Fellowship (2016)

John A. Focht Chi Epsilon National Undergraduate Scholarship (2016)

University of Kentucky Most Outstanding Civil Engineering Junior Award (2015)

Tau Beta Pi Engineering Honor Society (2014)

Chi Epsilon National Civil Engineering Honor Society (2013)

Chellgren Student Fellows Program (2013)

Benjamin A. Gilman International Scholarship (2013)

Foundation for Global Scholars Scholarship (2013)

University of Kentucky Education Abroad Scholarship (2013)

Kevin and Sherri Collins Endowment for Education Abroad Award (2013)

University of Kentucky Honors Program Kate Johnson Scholarship (2013)

University of Kentucky Dean's List (2012 – 2016)

University of Kentucky Otis A. Singletary Scholarship (2012)

Professional Organizations:

Graduate Student Representative, University of Kentucky Civil Engineering Education Team

Graduate Trainee, University of Kentucky Superfund Research Center

Member, University of Kentucky Water Professionals Student Chapter

Member, Chi Epsilon Civil Engineering Honor Society

Member, Tau Beta Pi Engineering Honor Society

Student Member, Environmental & Water Resources Research Institute

Student Member, American Water Works Association

Student Member, Water Environment Federation

Student Member, American Society of Civil Engineers

Former Member, University of Kentucky Student Sustainability Council

Former Member, Engineers Without Borders

Former Member, Kentucky Society of Professional Engineers

Certifications:

Engineer in Training, Kentucky State Board of Licensure for Professional Engineers and Land Surveyors

Hazardous Waste Operations and Emergency Response (HAZWOPER) 24-Hour Training, Occupational Safety and Health Administration

Publications:

Roghani, M., Jacobs, O.P., Miller, A., Willett, E.J., Jacobs, J.A., Viteri, C.R., Shirazi, E., and Pennell, K.G. Occurrence of Chlorinated Volatile Organic Compounds (VOCs) in a Sanitary Sewer System: Implications for Assessing Vapor Intrusion Alternative Pathways. *Science of the Total Environment*, *616-617*, 1149-1162.

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Conference Presentations:

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