One Alternate Exposure Pathway of VOC Vapors from Contaminated Subsurface Environments into Indoor Air – Legacy Sewer-Plumbing Systems

By James A. Jacobs, Olivia P. Jacobs, and Kelly G. Pennell

Abstract

Sewer-plumbing systems, land drains and subsurface utility conduits/lines/trenches are alternate exposure pathways for volatile organic compounds (VOCs) in the shallow subsurface to migrate into indoor air. Sewers which are well past their design life, or legacy sewers, allow for leakage into and out of the pipes. Legacy sewers that intercept VOC-contaminated groundwater or vapor likely contain VOCs in the sewer air. This article highlights an often overlooked implication of legacy sewers and their interception of VOC plumes—the potential for VOC-impacted sewer air to enter indoor air spaces.

Introduction

Sewer systems were designed to deliver residential, commercial, and industrial liquid wastes to treatment plants without loss of wastes in transit. Sewer-plumbing systems inside buildings were designed to properly vent sewer gases, preventing their entry into inhabited indoor space. Several decades, or even centuries, after the installation of sewer collection systems under the streets and the construction of vented plumbing in buildings, many components of sewer systems develop leaks, and some vapor seals designed to protect against sewer air intrusion into structures become compromised (pipes crack, fittings loosen, wax seals degrade and crack, and P-traps dry out). When compromised sewer and plumbing systems intercept contaminated groundwater plumes, indoor air becomes directly connected to sewer air that can contain VOCs.

Nationwide, legacy sewer lines are unintended conveyance systems for VOCs in sewer air. VOC-impacted groundwater (and vapor in the vadose zone) infiltrates leaky sewer trunk lines and laterals. The VOCs volatilize from the sewer/groundwater liquids into sewer air, which allows for migration throughout the sewer system, and into indoor air through failed vapor seals in plumbing systems.

This paper presents (1) currently used vapor intrusion conceptual models, (2) leakage and pipe damage as documented in a northern California sewage conveyance system, (3) two case studies demonstrating the presence of VOCs in indoor air resulting from the intersection of breached sewer systems with failed plumbing seals and PCE plumes, and (4) recommendations.

Indoor Air Quality Studies

There are many sources of indoor air pollution, but one that has captured the attention of regulators and managers of hazardous waste sites is the transport of subsurface vapors into indoor air spaces (i.e. vapor intrusion). U.S. EPA (2002) developed a series of models for estimating indoor-air concentrations of VOCs and the associated health risks from subsurface vapor intrusion into buildings. These vapor intrusion models were based on the analytical solutions of Johnson and Ettinger (1991) for contaminant partitioning and subsurface vapor transport into buildings. Figure 1 shows a common site conceptual model for VOC vapor intrusion, based on US EPA (2002) and modified by others. Since that time, several revisions to the vapor intrusion models have been made and a series of new models have been developed.

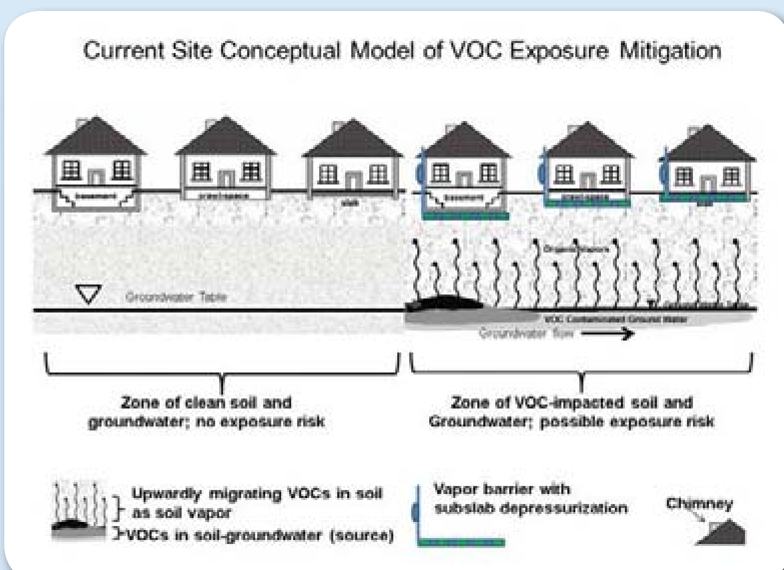

Figure 1: A common site conceptual VOC vapor intrusion model (modified after others; original from US EPA, 2002).

Continued on the following page…

One Alternate Exposure Pathway of VOC Vapors from Contaminated Subsurface Environments into Indoor Air *– Continued*

After nearly two decades of indoor-air monitoring in structures above contaminant plumes, practitioners have developed a term, "alternate exposure pathways," to address contaminated vapor intrusion into indoor air from sources other than underlying groundwater plumes. Many regulatory documents reference trench backfill containing piping conduits as a potential pathway for contaminated vapor exposure, but few, if any, discuss the implications for the piping conduits (pipe interiors) themselves to serve as vapor exposure pathways. The current term alternate exposure pathways commonly refers to trenching and piping for sewer-plumbing systems, land drains, storm drains, abandoned pipelines, cable ducts, steam lines, utility lines, other pipes and other conduits. When these alternative exposure pathways enter, or are proximal to, structures, they may serve as unintended conveyance systems for VOCs. A land drain beneath a research house in northern Utah owned by Arizona State University was documented to be a VOC conduit for detected indoor air impacts (Johnson, 2014). Field investigations at Hill Air Force Base have shown some indoor air contamination to be the result of the connectivity of contaminated sewer air to indoor air (Gorder and Dettenmaier, 2011). Two other studies (Pennell et al., 2013; and Riis et al., 2010) documented tetrachloroethene (PCE) in sewer gas as an important source of indoor air contamination at two vapor intrusion study sites.

Based on these reports of sewer-plumbing systems as alternate pathways, an updated conceptual model to guide vapor intrusion studies is needed. Some of the combinations of factors related to plume location, vapor seal integrity, and possible VOC exposure in indoor air are shown in Figure 2. Not all permutations of foundation, subsurface depressurization system (SSD) and sewer configuration are shown. The rationale for this updated conceptual model is provided below.

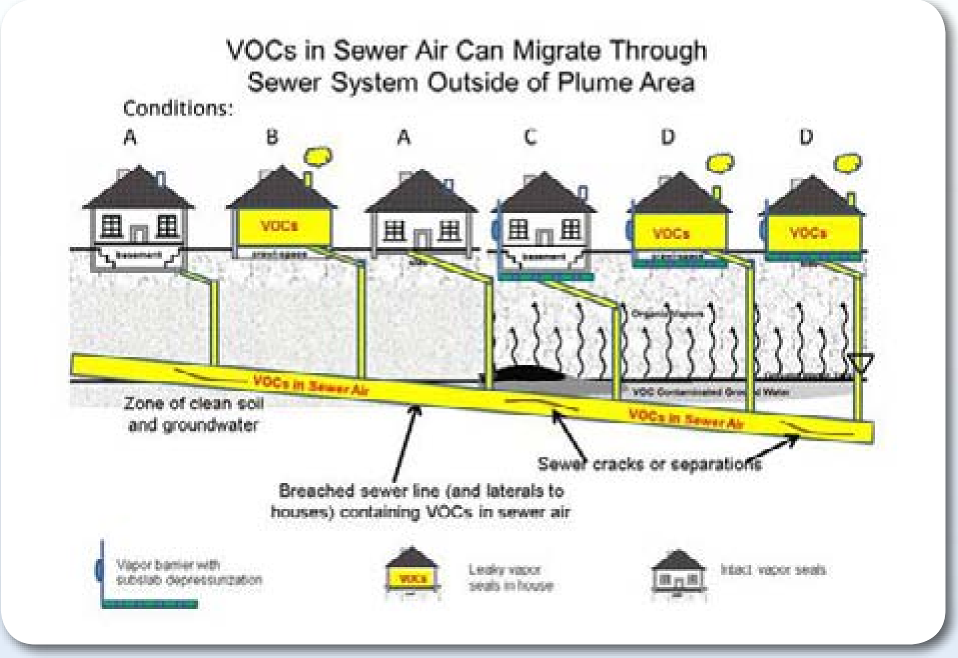

Figure 2: An example of an alternate exposure pathway model showing sewer gases and VOCs entering indoor air through ineffective plumbing vapor seals. Note: VOCs are released to the indoor air and through the vent line on roof. VOC data (Riis et al., 2010; Pennell et al., 2013) support this alternate VOC exposure pathway into indoor air. Conditions in the houses reflect exposure pathways. A) Intact vapor seals and not over VOC plume (exposure pathway not completed); B) Leaky vapor seals and not over VOC plume (exposure pathway completed); C) Intact vapor seals and working SSD over VOC plume (exposure pathway not completed); D) Leaking vapor seals and working SSDs over VOC plume (exposure pathway completed)

Note that in Figure 2, the SSD protects buildings overlying VOC-contaminated groundwater plumes from VOCs rising through the vadose zone into indoor air. SSDs cannot protect indoor air quality in buildings where VOCs in sewer air leak into indoor air through failed plumbing seals.

Legacy Sewers, Mains, Laterals and Plumbing Systems meet VOC plumes

There are hundreds of thousands of shallow VOC groundwater plumes in urban areas in North America. Urban sewer systems installed 50–100 years ago are well past their design life. These legacy sewers develop cracks, separations and other damage over time associated with earth subsidence, corrosive substances, pipe settling, biological intrusion and pipe material failure. Video camera inspections of sewers show that breaches are common in or between concrete, clay or transite pipes, and from corrosion in cast iron pipes. Tree and plant roots grow into the sewer system and commonly damage sewer pipe integrity. Pipe connections, junctions, manholes, etc., likewise develop structural damage resulting in both leaks of sewage from the pipes/structures and inflow of groundwater and vapors (Jacobs et al., 2014).

Legacy sewer system pipes experience a baseline of infiltration and inflow (I&I)

Continued on the following page…

One Alternate Exposure Pathway of VOC Vapors from Contaminated Subsurface Environments into Indoor Air – *Continued*

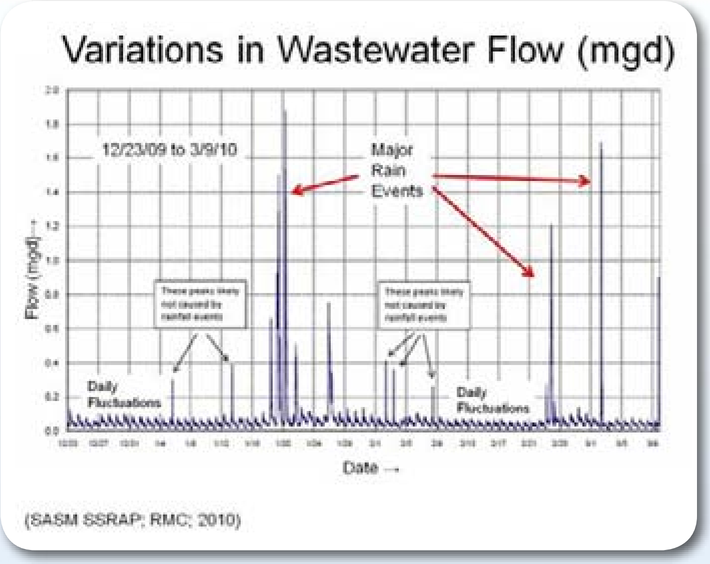

Figure 3: Variations in wastewater flow within a sewer pipeline (modified after SASM, 2010).

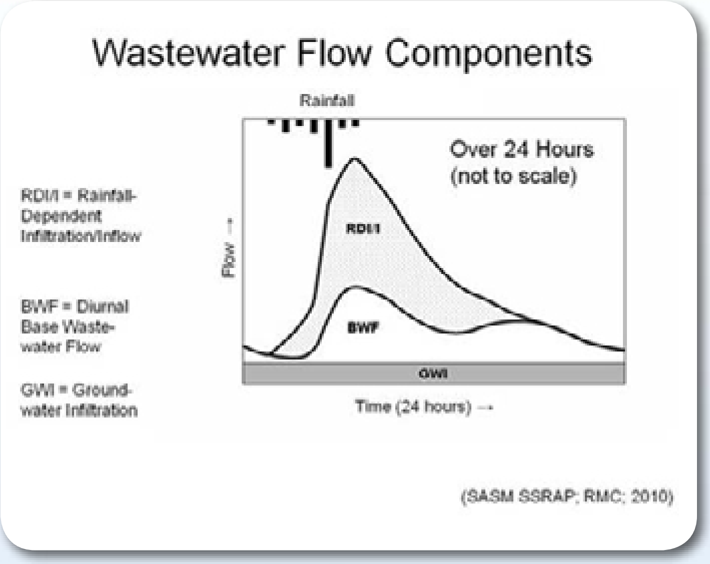

Figure 4: Conceptual diagram showing wastewater flow components (modified after SASM, 2010).

of groundwater throughout the year, but experience significant increases in groundwater I&I during the rainy season (Figure 3). I&I within a wastewater pipeline system in northern California was shown to contribute 8 to 33 times the amount of daily sewer flow shortly after a strong storm (SASM, 2010). This wastewater system, including the trunk lines and sewer laterals, was originally installed 6 or more decades ago. Figure 4 is a conceptualized diagram showing the wastewater flow components of rainfall-dependent infiltration/inflow (RDI/I) into sewer pipes, and illustrates the lag between the timing of rainfall and its infiltration into the sewer pipes. Unlike storm-induced increases in wastewater flow, diurnal base wastewater flow (BWF) shows increases only during early-morning and dinner through evening hours. During dry weather, groundwater infiltration (GWI) into sewer pipes is relatively constant during the day in an area with no tidal influences. I&I leakage in sewer sections in northern California is frequently confirmed using smoke testing, flow meters and video inspections. These inspections consistently indicate that breaches of unpressurized sewer lines are common, and that failed sewer lines provide opportunities for vapors and groundwater to enter and exit the sewer system.

Leakage into and out of the sewer system (from the inside drain to the wastewater plant) is not limited to subsurface fixtures. Within buildings, examples of ineffective vapor seals in plumbing systems include dry P-traps, breached toilet wax rings, cracked pipes, loose pipe fittings and gaskets, improper repairs or additions, and settlement. Examples of vapor leak locations (Figure 5), a close-up of a P-trap (Figure 6) and the migration pathway of sewer gas and VOCs into indoor air (Figure 7) illustrate how VOCs in sewer air can migrate into indoor air.

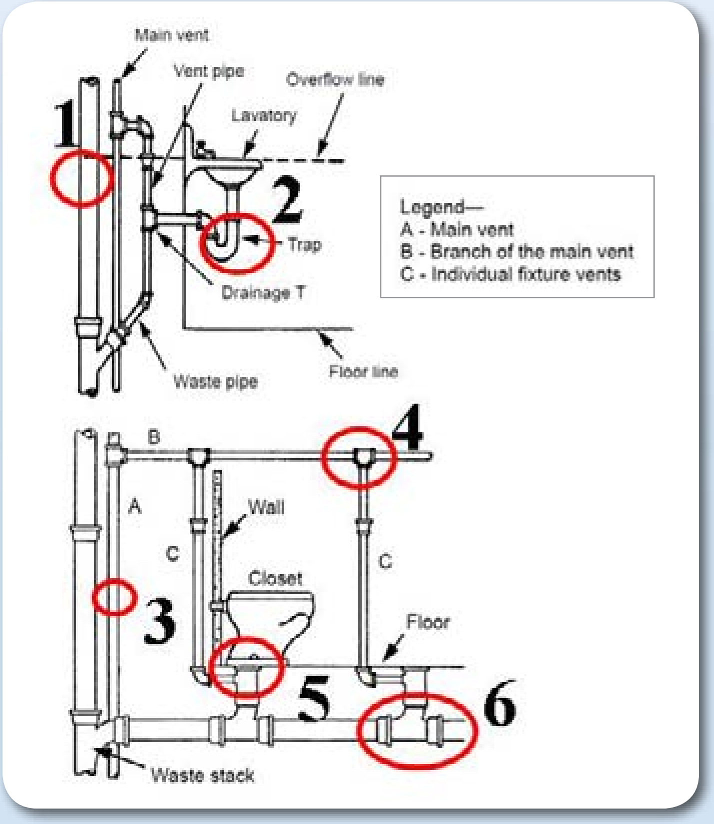

Figure 5: Examples of vapor leak locations (modified after U.S. Department of the Army, 2001). 1) Cracked waste stack; 2) Dry P-trap; 3) Cracked main vent; 4) Loose fittings; 5) Faulty wax ring seal; 6) Leaking joints

Continued on the following page…

One Alternate Exposure Pathway of VOC Vapors from Contaminated Subsurface Environments into Indoor Air – *Continued*

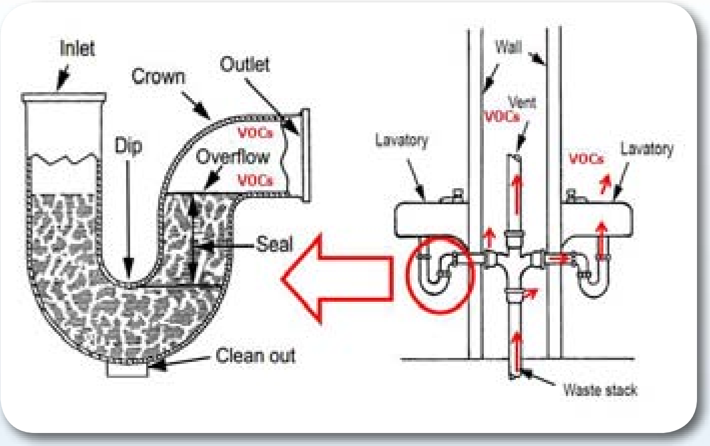

Figure 6: Anatomy of a P-trap vapor seal in cross-section. Water in P-trap seals VOCs from entering indoor air. If water evaporates, or is siphoned to below the upper part of the trap dip, sewer air can be released into indoor air. (Modified after U.S. Department of the Army, 2001).

Breached Sewer Lines Intersecting Subsurface VOC Plumes

When breached sewer collection pipes intersect VOC-contaminated soil and groundwater, water and vapor containing VOCs infiltrate the breached sewer pipes. While VOC-containing fluids flow downgradient in the sewer pipes toward the wastewater treatment plant, the VOCs contained in the groundwater, pipe debris/solids and soil vapor have an opportunity to volatilize into the sewer air. Once in the sewer air, the contaminants can migrate within the connected sewer pipes independently from the liquid waste stream. Sewer air movement is dependent on a number of variables, but VOCs in vapor form are not exclusively gravity-driven, and could exit the sewer at any point where the sewer or plumbing is not vapor tight.

Sewer Air Considered with Respect to Indoor Air Quality Investigations

Indoor air quality degradation caused by vapor intrusion of VOCs into structures has been a health concern investigated by US EPA and other agencies for decades. However, public sewer and private plumbing systems have not been evaluated systematically for their role as vapor conduits in the standard site conceptual models for indoor air quality developed by US EPA (2002) and others.

Recent PCE-specific vapor intrusion studies in Denmark and Boston document PCE indoor air concentrations resulting from failed plumbing-sewer systems that intersect mapped PCE groundwater plumes (Riis et al., 2010; Pennell et al., 2013). In both studies, iterative testing of indoor air (after PCE was detected indoors) led to direct sewer-air testing. The findings established that the sewer air contained PCE and that the sewer intersected a PCE groundwater plume. The sampling also established that the sewer air was contributory to the presence of VOCs in the indoor air. In both cases, the concentrations of PCE detected inside the buildings were orders of magnitude higher than levels generally considered safe for long-term indoor air exposure.

In the Denmark study (Riis et al., 2010), PCE was reported in the cabinet under a kitchen sink at levels as high as 810 µg/m³. In the Boston study, the concentration of PCE detected in bathroom air was 37 µg/m³. A faulty plumbing connection to the toilet was presumed to be the source of PCE. The concentration of PCE detected in the sewer gas (sampled directly from the sewer pipe connected to the toilet) was 58 µg/m³. When the toilet connection was sealed, the PCE concentration in the bathroom air decreased to 2.6 µg/m³. It was documented in the Boston case that variability of VOC concentrations in sewer air between sampling events depended on many factors, including the integrity of the sewer seals.

Regulatory Levels

The concentrations of PCE measured at these two sites, compared to the Massachusetts Department of Environmental Protection (MassDEP) threshold (risk) value of 1.4 µg/m³, were 1 to 2 orders of magnitude higher. The California Department of Toxic Substances Control's (DTSC) Human and Ecological Risk (HERO) recommended values for residential air screening for PCE, calculated using the Regional Screening Level (RSL)

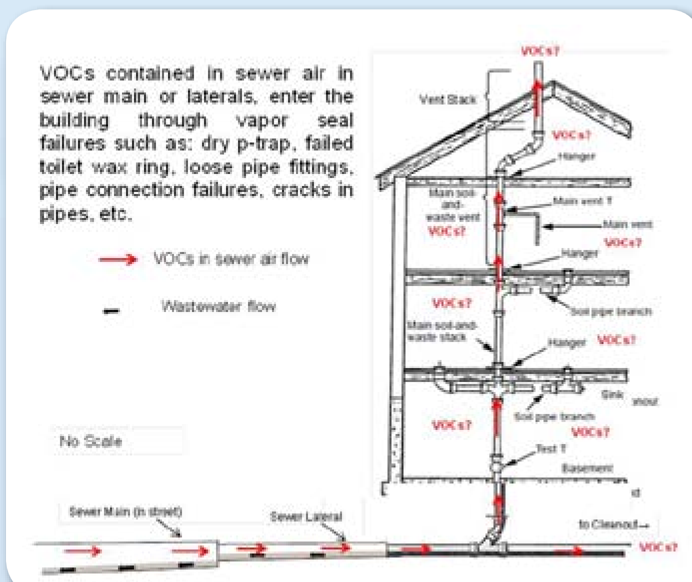

Figure 7: Migration pathway of sewer gas and VOCs into indoor air (modified after U.S. Department of the Army, 2001).

Continued on the following page…

One Alternate Exposure Pathway of VOC Vapors from Contaminated Subsurface Environments into Indoor Air – *Continued*

calculator, are 0.41 μg/m³ for cancer risk and 37 μg/m³ for non-cancer risk (DTSC, 2010). The San Francisco Bay Regional Water Quality Control Board's (RWQCB, 2013) Environmental Screening Level (ESL) for PCE in residential indoor air is 0.41 μg/m³.

The levels of PCE detected in indoor air (Riis et al., 2010; Pennell et al., 2013) are small compared to those immediately dangerous to life and health (IDLH) for an instantaneous exposure of PCE. However, exposure to a low-concentration carcinogen (such as PCE and other VOCs) over a long period of time is a clear health risk; the hypothesis of sewer air exposure should be tested to document the incidence of VOC exposure through vapor seal failures (see Figure 7) and to minimize the VOC exposure to unsuspecting occupants.

Recommendations

Alternate vapor exposure pathways should be considered in environmental indoor air assessments. The scientific and regulatory community needs to update vapor intrusion models and consider alternate exposure pathways in health risk evaluations and regulatory decision making. To establish the risk of exposure of individual building inhabitants to VOCs, we recommend screening (PID and sorbent tubes), or laboratory testing (passive sorbents and air samples) of nearby sewer manholes and building sewer system cleanouts or vent stacks. Further evaluation of inside vapor seals and plumbing connections can be performed using smoke testing.

To clear high VOCs in sewer pipe air, active venting in manholes has been shown effective. The remedy for the vapor seal failure may be as simple as filling a dry P-trap with water or replacing toilet wax seals. For leaking underground sewer system repair, the capital costs, including leak inspection and testing, pipe engineering design, and installation is millions of dollars for municipalities or sewer agencies. Ultimately, the breached pipe network should be fixed in order to prevent VOC intrusions into indoor air.

Nationwide, U.S. EPA's focus on I&I issues of sewer systems has been as a major source of sewer overflows of untreated wastes onto land and into water bodies. Prioritizing sewer replacement projects in areas where known shallow VOC groundwater plumes co-exist with breached sewer systems would decrease the potential for VOCs to enter sewer air and reduce the risk of indoor air exposure.

More research is needed into assessment and mitigation methods to address the presence of VOCs in sewer-plumbing systems and their migration into indoor air.

References Cited

California Department of Toxic Substances Control (DTSC). 2010. Human Health Risk (HERO), Office of Human and Ecological Risk Overview; Retrieved January 20, 2014; https://www.dtsc.ca.gov/assessingrisk/humanrisk2.cfm

Gorder, K. and Dettenmaier, E. 2011. Portable GC/MS Methods to Evaluate Sources of cVOC Contamination in Indoor Air. Groundwater Monitoring & Remediation, National Groundwater Association, Fall, Vol. 31, Issue 4, p. 113-119.

Jacobs, J.A., Jacobs, O.P., and K.G. Pennell. 2014. Geologists and Site Conceptual Models: VOCs and Sewer Gas in Indoor Air Resulting from Migration from Breached Sewer Conveyance Systems, American Institute of Professional Geologists National Meeting, Abstracts, p. 73-74.

Johnson, P. C, and R. A. Ettinger. 1991. Heuristic model for predicting the intrusion rate of contaminant vapors in buildings. Environ. Sci. Technol. 25: 1445-1452.

Johnson, P. C. 2014. Vapor Intrusion: Lessons-Learned from Four Years of Intensive

Monitoring of a House Over a Dilute Chlorinated Solvent Plume, GRACast Web Seminar

Series on Vapor Intrusion, Part 2, Groundwater Resources Association of California, Sacramento, California, June 25.

Massachusetts Department of Environmental Protection (MassDEP). 2011. Interim final vapor intrusion guidance, WSC#11-435. Boston, Massachusetts: MassDEP.

Pennell, K.G., Scammell, M.K., McClean, M.D., Arnes, J., Weldon, B., Friguglietti, L., Suuberg, E.M., Shen, R., Indeglia, P.A., and W.J. Heiger-Bernays. 2013. Sewer Gas: An Indoor Air Source of PCE to Consider During Vapor Intrusion Investigations, Groundwater Monitoring & Remediation; Volume 33, Issue 3, Summer 2013, p. 119–126.

Riis, C.E., A.G. Christensen, M.H. Hansen, and H. Husum. 2010. Vapor Intrusion through sewer systems: Migration pathways of chlorinated solvents from groundwater to indoor air. Presented at the Seventh Battelle International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey. http://indoorairproject.files.wordpress.com/2011/03/ sgs-attachment-1.pdf (accessed August 1, 2014).

San Francisco Bay Regional Water Quality Control Board (RWQCB). 2013. 2013 Tier 1 ESLs, Summary Table F, December, 19 p.

Sewerage Agency of Southern Marin (SASM), 2010, Sewage Spill Reduction Action Plan; Annual Report on Flow Monitoring, Prepared by RMC, October, Mill Valley, CA, 31 p.

United States Department of the Army. 2001. Plumbing, Pipe Fitting, and Sewerage, Field Manual FM 3-34.471 (FM 5-420), Headquarters, Washington, D.C., August 31, 276 p.

United States Environmental Protection Agency (US EPA). 2011. Background indoor air concentrations of volatile organic compounds in north American residences (1990–2005): A compilation of statistics for assessing vapor intrusion. EPA 530-R-10-001. Washington, DC: Office of Solid Waste and Emergency Response (OSWER).

United States Environmental Protection Agency (US EPA). 2002. OSWER Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance), November 2002.

About the Authors

James A. Jacobs, P.G., C.P.G., C.H.G. is a geologist with over three decades of experience. He is a Fulbright Scholar and has been an elected director of a sewer board since 2002. He can be reached at jjacobs@clearwatergroup.com or www.clearwatergroup.com.

Olivia Jacobs, C.E.M., is a Thomas J. Watson Fellow (subject was waste use). She brings experience with I&I modeling to decades of environmental science experience. President of Clearwater Group, she can be reached at oj@clearwatergroup.com.

Kelly G. Pennell, PhD, PE is an Assistant Professor in the Department of Civil Engineering at the University of Kentucky. She has over 15 years combined environmental engineering experience as a consultant, governmental liaison and faculty member. She can be reached at kellypennell@uky.edu.