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A conceptual model for vapor intrusion from groundwater through sewer lines

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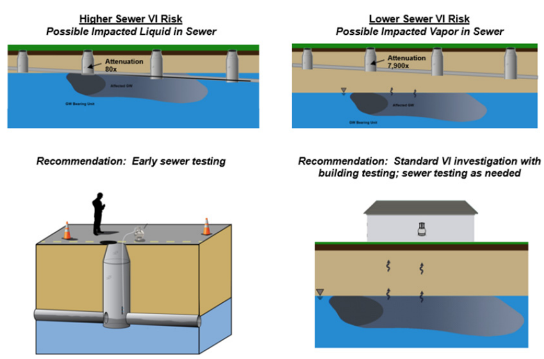
HIGHLIGHTS

- A variety of VOCs, e.g., chloroform, benzene, and tetrachloroethylene, are commonly detected in background sewer vapors.
- Sites at higher risk for sewer VI are those with direct interaction between sewers and contaminated groundwater.
- At direct interaction sites, median VOC attenuation was 80× from groundwater to sewer vapor, versus 7,900× at other sites.
- Within sewer lines, VOCs attenuate away from the source usually with >80% concentration decrease over a distance of 500 ft.
- At buildings impacted by sewer VI, 40 to 50× attenuation was seen between VOCs in the sewer line and the building.

GRAPHICAL ABSTRACT



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ABSTRACT

The role of sewer lines as preferential pathways for vapor intrusion is poorly understood. As a result, these pathways are often not considered when developing vapor intrusion investigation or mitigation plans. Neglecting this pathway can complicate data interpretation, which can result in repeated, and potentially unnecessary, rounds of sampling. Although a number of recent studies have highlighted the importance of sewers as preferential pathways at individual buildings, there is currently little specific technical or regulatory guidance on how to address it. The purpose of our study, therefore, was to conduct systematic testing to better understand the sewer vapor intrusion conceptual model. Through sampling at >30 different sites, the degree of interaction between impacted groundwater and the sewer lines were identified as the main factor when determining the degree of risk for sewer vapor intrusion at a given site. Higher risk sites are those with direct interaction between the subsurface volatile organic compound (VOC) source, such as groundwater, and the sewer line itself. This information can be used to prioritize sites and buildings to test for this particular exposure pathway.

1. Introduction

In the 1990s, vapor intrusion (VI) into homes and buildings was identified as a potential exposure pathway but was not routinely evaluated during site investigations because there were no accepted and

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validated assessment procedures. Today, the same is true for evaluation of contaminant transport through sewers and utility tunnels at sites undergoing VI assessments (McHugh et al., 2017b). In regulatory guidance, the conceptual model for VI focuses primarily on: i) volatile organic compounds (VOCs) partitioning from subsurface impacted soil or groundwater into soil gas, ii) diffusion of VOC-containing soil gas through unsaturated soil, and iii) further diffusion and advection into buildings through the building foundations (e.g., ITRC, 2007; NJDEP, 2011; USEPA, 2015). Although the need to evaluate preferential pathways is often mentioned in these regulatory guidance documents, there is little information detailing the conceptual model or prevalence of this pathway. There is also limited guidance on how to assess sites for the presence or absence of vapor transport through preferential pathways (Eklund et al., 2018; McHugh et al., 2017b).

One challenge for evaluating the importance of preferential pathways in vapor intrusion is that regulatory guidance defines the term very broadly. Most often, the term is defined to include natural features (e.g., fractured bedrock, gravel layers or lenses), manmade features confined within the footprint of a building (e.g., elevator shaft, sump, dry well), and manmade features such as sewer lines that extend beyond the footprint of a building (USEPA, 2015). In defining preferential pathways, ITRC (2007) explicitly excludes subsurface utility penetrations because they are present in almost all buildings; however, their definition still encompasses a broad range of natural and manmade features. These broad definitions make it difficult to focus on specific features that are more likely to enhance the migration of VOCs into a building relative to migration through bulk soil. Despite these broad definitions, the published examples of VI through preferential pathways almost exclusively identify VOC flux through the interior of sewers or utility tunnels as the preferential VOC migration pathway (McHugh et al., 2017b).

Sewers and utility tunnels have been identified as important VOC transport pathways at a small but growing number of sites (e.g., Guo et al., 2015; McHugh et al., 2017a; Nielsen et al., 2014; Riis et al., 2010). In many cases, the importance of the preferential pathway at the site was identified only after extensive site characterization and vapor intrusion testing (e.g., McHugh et al., 2017a). Based on the absence of sewer testing during most vapor intrusion investigations, it is likely that there are additional sites where VOC transport through sewers and utility tunnels is important but has not been identified. This highlights the need for an improved understanding of VOC transport processes and the factors that make this transport significant at individual sites.

We have utilized field investigation results obtained through a Department of Defense (DoD)-funded study (McHugh and Beckley, 2018) along with information compiled from other published and unpublished sources to develop a conceptual model for the sewer preferential pathway as a mechanism for the migration of VOCs from groundwater into buildings. This conceptual model focuses on VOC migration through the interior of sewers (i.e., inside “pipes” rather than through utility backfill material). The conceptual model covers: i) typical background concentrations of VOCs in sanitary sewers, ii) migration of VOCs from groundwater into sewers, iii) higher risk and lower risk sewer preferential pathway sites, iv) migration of VOCs within sewers, and v) VOC migration from sewers into buildings. Many aspects of the conceptual model also apply to utility tunnels as preferential pathways. However, there are important differences in the migration of VOCs within utility tunnels (e.g., utility tunnels do not have a predictable slope to control the movement of liquids) and movement into buildings (e.g., unlike sanitary sewers, utility tunnel connections may not be designed to prevent vapor entry).

This paper focuses primarily on sewer lines rather than utility tunnels because sewer lines are ubiquitous in urban areas while utility tunnels are more likely to be confined to industrial facilities and are less common in other areas. We use the term “sewer VI” to distinguish our narrow focus from the broader definitions of “preferential pathways”.

Sewer vapor intrusion requires:

- A subsurface source of VOCs;
- A sewer line connecting the subsurface source to a building; and
- A mechanism for VOC entry from the sewer/utility tunnel into the building.

There are three main scenarios for subsurface sources of VOCs: impacted groundwater; non-aqueous phase liquid (NAPL) in the vadose zone; and permitted or non-permitted discharge of contaminated groundwater (e.g., recovered groundwater) into the sewer system. In this paper, we focus on risks of preferential pathway vapor intrusion from impacted groundwater to sewers.

2. Methods

A variety of field testing was conducted to develop the conceptual model for sewer VI. These data were supplemented with test results from published studies of sewer VI sites.

2.1. Selection of study sites

Field testing was conducted at a number of sites across the United States. Site selection criteria included the presence of documented VOC plumes in shallow groundwater and access to conduct the testing. The majority of sites had chlorinated VOC plumes. Sewer manhole testing was conducted at:

- Two established VI research sites: a DoD-sponsored site in Layton, Utah (Johnson et al., 2016) and a USEPA-sponsored site in Indianapolis, Indiana (USEPA, 2012);
- Two DoD facilities with previously-identified VI concerns: Moffett Field in California and NAS Corpus Christi in Texas; and
- Areas with documented VOC plumes in the uppermost groundwater-bearing unit: 10 dry cleaner sites in Houston, Texas and 2 dry cleaner sites in Austin, Texas enrolled in the Texas Dry Cleaner Remediation Program and 18 VOC-contaminated sites in California identified through review of the GeoTracker site remediation database (State of California, 2015).
- Supplemental sites in Indiana (2), Illinois (1), and California (1) with documented chlorinated VOC plumes in shallow groundwater.

A separate set of study sites was chosen to evaluate migration of VOCs from sewers into buildings. Communication between sewers and buildings is independent of whether groundwater contamination is present. Therefore, for this portion of the study, we focused on selecting a range of building types: residential/small commercial to industrial. Sewer to building tracer testing was conducted at:

- Two established VI research sites: a DoD-sponsored site in Layton, Utah and a USEPA-sponsored site in Indianapolis, Indiana;
- Buildings at three DoD facilities, the first of which had previously-identified VI concerns: Moffett Field in California, SPAWAR Systems Center in California, and NAS Corpus Christi in Texas;
- Business parks: One building in a business park in California and one building in a business park in Texas; and
- Private residences: two private residences in Texas and two private residences in California.

2.2. Measurement of VOC concentrations in sewer manholes

VOC concentrations in sewer lines were measured by collecting vapor samples from sewer manholes. Manholes are useful for characterizing VOC impacts to sewer lines because they i) provide physical access to main sewer lines at regular intervals along the lines, ii) extend to the depth of the deepest connected sewer line and iii) are commonly located in public rights-of-way.

For this study, vapor samples were collected from one or more manholes located within or immediately downstream of the footprint of each VOC plume in groundwater. The priority for manhole selection was to choose the manhole closest to the plume source area (but downstream relative to liquid flow in the sewer). In addition, vapor samples were collected from a number of background manhole locations. These background manholes were on sewer lines that did not intersect any known VOC plumes or were at least 400 ft upstream of any known plumes, a distance sufficient to ensure that the sample results were not impacted by the localized entry of VOC-containing groundwater associated with the plume.

Vapor samples were collected from sewer manholes using the following steps. To minimize disturbance of the sewer vapors, sampling was conducted without removing the manhole cover (if the manhole cover had vent holes or other openings allowing sample collection) or by partially removing the cover to allow access while minimizing the opening created. Preliminary sewer vapor sampling at different depths in three manholes indicated that VOC concentrations were either higher near the bottom, or were comparable at different depths (Fig. 1). Therefore, manhole vapor samples for the study were collected near the bottom to avoid low bias. The depth to water and bottom of the manhole were measured using a water level meter or weighted measuring tape. Eighth-inch outer diameter nylon tubing was measured and cut to a length that allowed sample collection one foot above the manhole bottom or one foot above the liquid level, whichever was shallower. A weight was attached to the down-hole end of the tubing so that it would hang vertically for more accurate depth placement. A gas-tight three-way valve was attached to the end of the tubing at the surface to allow for line purging and sample collection. To collect the vapor samples, the tubing was lowered to the target depth and purged of at least three line-volumes. The sample line was attached to the sample container (i.e., 1-liter Summa canister or 1-liter Tedlar bag) and the assembly was tested for leaks by using a syringe to induce a vacuum on the sample line and maintaining that vacuum for 30 to 60 s (ITRC, 2014). After verifying the assembly was leak-free, the sample was collected as a grab sample (i.e., no flow controller). The majority of samples were analyzed by USEPA Method TO-15 at the TestAmerica laboratory in West Sacramento, California. A smaller number of samples were analyzed on-site using a calibrated portable HAPSITE GC/MS instrument.

2.3. VOC concentrations in groundwater

At each site where VOC concentrations were measured in sewer manholes, the VOC concentration in groundwater was determined by review of recent test results from sampling conducted by other parties and documented in site investigation reports submitted to regulatory authorities. We defined chemicals of concern (COCs) associated with each site as the chemical found at the highest concentration in groundwater (i.e., the primary COC) plus other chemicals detected at concentrations of at least 15% of the primary COC concentration. At 23 of the 34 groundwater sites, tetrachloroethene (PCE) or trichloroethene (TCE) was the primary COC. At each site, the representative source area VOC concentration in groundwater was determined by i) selecting the monitoring well with the highest concentration of the primary VOC and ii) selecting the groundwater sampling date(s) closest to the manhole vapor sampling events.

2.4. Calculation of groundwater to sewer attenuation factors

Sewer vapor concentrations from the manhole closest to the plume source area were paired with groundwater concentrations from the highest source area monitoring well. Although the separation distance between wells and manholes will vary from site to site, this pairing is the most practical way to line up the data. For each paired measurement of VOC concentration in groundwater and sewer manhole, the attenuation factor for each COC was calculated as the sewer vapor concentration divided by the equilibrium vapor concentration in groundwater. The equilibrium vapor concentration in groundwater was calculated as the groundwater concentration multiplied by the dimensionless Henry's constant.

2.5. Tracer testing to define sewer to building attenuation

Tracer testing was done to get a better understanding of gas exchange between sewers and buildings across a range of settings. Different types of buildings were tested including eight residential or small commercial buildings and seven large commercial/industrial buildings. At two of the buildings, prior available information suggested VOC entry into the building through a sewer.

The tracer testing involved deploying arrays of tracer gas emitters and samplers at each test site. Perfluorinated tracers (PFTs) and analytical methods developed by Brookhaven National Laboratory were used. PFTs are totally fluorinated cyclic carbon compounds. Background sources and concentrations of these compounds are negligible. The tracer compounds are released using passive, constant-rate emitters, and are sampled using capillary adsorption tube samplers (CATS) that are deployed in duplicate (i.e., two sorbent tubes at each sample location). While the emitters release only one PFT compound, the CATS sample for multiple tracer compounds. For each of the tests, the CATS were deployed from 3.5 to 11 days.

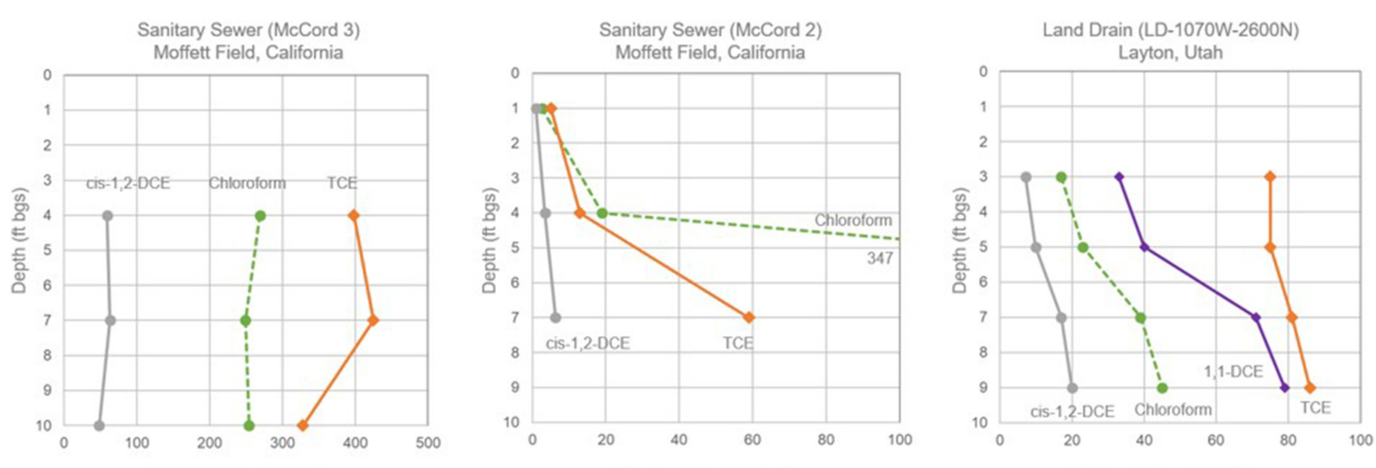

Fig. 1. Vertical VOC concentration profiles in manholes.

Table 1
Typical background VOC concentrations in sewers.

Analyte	No. manholes tested	No. samples	Det freq (%)	10th (ug/m^3)	Median (ug/m^3)	90th (ug/m^3)	Maximum (ug/m^3)	Screening level based on AF 0.03 (μg/m^3)
Common chlorinated VOCs at remediation sites								
Tetrachloroethene	20	31	90%	0.35	3.2	68	**550**	360
Trichloroethene	19	30	70%	ND (0.56)	2.6	**16**	**85**	16
Dichloroethene, cis-1,2-	20	31	55%	ND (0.35)	0.67	7.5	20	n/a
Common petroleum VOCs at remediation sites								
Benzene	55	98	79%	ND (0.32)	1.1	4.3	**89**	12
Toluene	56	99	98%	1.5	20	280	3300	170,000
Ethylbenzene	56	99	74%	ND (0.27)	1.4	8.9	**190**	37
Xylene, m,p-	57	100	83%	ND (0.82)	3.4	21	57	3500
Xylene, o-	58	101	78%	ND (0.34)	1.2	4.4	16	3500
Other VOCs								
Acetone	56	99	100%	15	47	200	4000	1,100,000
Bromodichloromethane	58	101	86%	ND (0.44)	**16**	**86**	**540**	2.5
Butanone, 2- (MEK)	57	100	86%	1.9	4.3	14	66	170,000
Carbon disulfide	58	101	99%	3	20	180	940	24,000
Carbon tetrachloride	58	101	60%	ND (0.41)	0.73	4.4	6	16
Chloroform	103	249	82%	1	**26**	**360**	**4000**	4.1
Chloromethane	58	101	94%	1.1	2	12	100	3100
Dibromochloromethane	58	101	69%	0.67	5.2	33	99	n/a
Dichlorodifluoromethane	58	101	77%	1.2	2.3	9.8	38	3500
Methylene chloride	58	101	97%	0.74	5.1	35	110	3400
Trichlorofluoromethane	58	101	53%	1.1	1.8	11	8.4	n/a

Notes: 1) Table includes VOCs detected at least 50% of the time. See Appendix A Table A.1 for results from full list of compounds analyzed. 2) Bold-underline indicates values greater than generic screening levels based on an attenuation factor of 0.03 (e.g., USEPA screening levels for sub-slab soil gas to indoor air assuming residential exposure and a target risk of 10e-6 and hazard quotient of 1 (USEPA, 2018)).

For each test building, emitters and samplers were set up in a minimum of two zones: sanitary sewer manhole and inside a nearby building. The tracer compound was released into the main sewer line at a manhole near the test building, typically by attaching the emitter to a weighted string and suspending it inside the manhole. CATS were installed in the same manhole to measure the concentration of tracer within the manhole. In a few cases, the tracer concentration in the manhole had to be estimated because the samplers were compromised (i.e., got inundated) or were not recovered (i.e., missing at the end of the test). In these cases, the tracer concentration in the manhole was estimated as the average tracer concentration from the manholes where valid concentration measurements were obtained. Because the tracer compound emitters release tracer at a constant rate, the resulting manhole concentrations were similar across sites and, therefore, the average of valid measurements provided a reasonable estimate for the manholes with missing measurements. Although uncertainty associated with the proxy values may be as high as approximately 10× in the worst case, strong vs. weak sewer to building connections could still be distinguished.

Each test also included use of different tracer compounds inside the buildings by setting out emitters in different rooms (e.g., kitchen counter, bathroom shelf), with CATS placed across the room. This was done to evaluate air exchange between the sewer and different sections of the buildings. After each test was completed, the CATS were shipped to Brookhaven National Laboratory for analysis using a GC-ECD method certified through the New York State Department of Health Environmental Laboratory Approval Program.

2.6. Calculation of sewer to building attenuation factors

Sewer to building attenuation factors were calculated by dividing the concentration of the tracer compound measured at each indoor measurement location by the tracer concentration in the sewer manhole. For each building, tracer concentrations were measured at two to four locations, typically including a bathroom and an office or living room. Separate attenuation factors were calculated for indoor tracer measurement location resulting in a range of attenuation factors for each building tested.

3. Results

Field sampling took place from 2016 to 2018. The results from the field sampling program and literature review have been utilized to develop a general conceptual model of VOC transport within sewer lines including: i) background VOC concentrations in sewers, ii) attenuation in VOC concentrations between groundwater plumes and sewer lines, iii) movement and attenuation of VOCs within sewer lines, and iv) movement and attenuation from sewer lines into buildings.

3.1. Background concentrations of VOCs in sanitary sewer lines

In addition to acting as preferential pathways for VI, sanitary sewers may contain VOCs from other sources such as the permitted or non-permitted disposal of VOC-containing waste. In addition, because of the prevalence of VOC plumes in groundwater within urban areas, VOCs detected within sewer lines may be associated with subsurface

Table 2
Groundwater concentration summary.

Analyte	No. monitoring wells	No. samples	Det freq (%)	10th (μg/L)	Median (μg/L)	90th (μg/L)	Maximum (μg/L)
Tetrachloroethene	19	52	100	22	230	17,000	36,000
Trichloroethene	21	54	100	14	50	3600	170,000
Dichloroethene, cis-1,2-	18	60	100	13	170	2500	19,000

Table 3
Manhole vapor concentration summary.

Analyte	No. manholes	No. samples	Det freq (%)	10th (μg/m^3)	Median (μg/m^3)	90th (μg/m^3)	Maximum (μg/m^3)
Tetrachloroethene	19	52	90	0.81	16	810	5600
Trichloroethene	24	54	83	1.1	26	900	1500
Dichloroethene, cis-1,2-	20	60	70	0.35	13	310	1600

sources unrelated to the specific site under investigation. As discussed in Section 2 (Methods), background VOCs were defined as VOCs not associated with the specific groundwater plume of interest at the site. No effort was made during sampling to distinguish between VOCs originating from direct discharge into the sewer and VOCs originating from unidentified VOC plumes that may have been present in groundwater. To augment the dataset, other manholes were considered to be background for all of the VOCs not detected in the groundwater plumes. For example, if the groundwater plume contained only benzene and no other VOCs, then all of the manholes sampled at the site were considered background locations for the purpose of characterizing concentrations of all VOCs in the TO-15 reporting list except benzene.

Manhole vapor was sampled in urban areas that included residential and commercial settings. Typically, the land use was mixed, such as dry cleaners and shopping centers adjacent to residential neighborhoods. A total of 50 analytes were reported for this study. Nineteen (19) were detected in >50% of the samples (Table 1; see Appendix A Table A.1 for a summary of all 50 analytes). These included a variety of chlorinated, petroleum hydrocarbon, and other VOCs. Compounds such as PCE, toluene, and acetone were detected in 90% or more of the samples indicating that direct disposal of VOCs into sewers is an important source of the VOCs detected. *Cis*-1,2-dichloroethene (*cis*-1,2-DCE) was detected in 55% of samples. This compound is a product of biodegradation of TCE in the subsurface (Wiedemeier et al., 1999) and is not strongly associated with manufactured products. This suggests that unidentified subsurface VOC sources are also an important source of VOC detections in background sewer manholes. For the VOCs that are most commonly risk drivers at corrective action sites (e.g., benzene, PCE, TCE), the detected background concentrations were typically low (e.g., median less than screening levels of 12, 360, and 16 μg/m^3, respectively, based on a sewer to indoor air AF of 0.03).

3.2. Groundwater to sewer attenuation and classification of sites as “higher risk” or “lower risk” for sewer vapor intrusion

To examine groundwater to sewer attenuation, we paired groundwater and manhole vapor concentrations. The majority of the study sites had chlorinated VOCs in shallow groundwater. Principal contaminants included PCE, TCE, and cis-1,2-DCE. The median groundwater concentrations across the sites were 230, 50, and 170 μg/L, respectively (Table 2). Median manhole vapor concentrations were 16, 26, and 13, respectively (Table 3). The dataset used to calculate attenuation factors is provided in Appendix A, Table A.2.

One fundamental difference between the sites included in the study was the interaction between the sewer line and the VOC plume in groundwater. The sewers fell into two general categories: i) sites with sewer lines at or below the water table resulting in a direct interaction with impacted groundwater and ii) sites with sewers lines in a vadose zone above the water table and thus no direct interaction with the VOC plume in groundwater. In order to characterize the relationship between VOC concentrations in groundwater plumes and VOC (vapor) concentrations in near-by sewer lines, paired VOC concentration measurements from 34 different VOC plumes were used to evaluate groundwater to sewer attenuation. The paired measurements were grouped by categories (Table 4).

The median attenuation (i.e., the median decrease in VOC concentration from groundwater to sewer vapors) was approximately 100× higher for sewer lines above the water table compared to sewer lines at or below the water table. In addition, for sewer lines at or below the water table, infiltration of contaminated groundwater may result in the migration of VOC-containing liquids downstream within the sewer line beyond the footprint of the VOC plume in groundwater. As VOCs partition between the liquid and vapor phases, this creates a risk for sewer VI outside the footprint of the groundwater plume in the downstream sewer direction (Fig. 2). Based on these two factors, sites where sewer lines may act as preferential pathways can be grouped into higher risk sites and lower risk sites. Higher risk sites are characterized by direct interaction between the subsurface source and the preferential pathway (e.g., the sewer line is below the water table) while lower risk sites are characterized by an indirect interaction between the subsurface source and the preferential pathway (i.e., the sewer line is located in the vadose zone above the groundwater plume or other VOC source). At the direct interaction sites, attenuation factors are generally large (i.e., resulting in higher VOC concentrations inside the sewer lines). However, significant migration of VOCs from groundwater plumes into the sewer can occur at both higher risk sites and lower risk sites (see Table 4).

3.3. VOC attenuation within sewer lines

Temporally matched vapor samples within individual sewer lines were used to evaluate the attenuation of VOC vapors along sewer lines moving away from the footprint of the VOC plume in groundwater.

VOCs in the sewer vapor phase can result from partitioning from contaminated liquids entering the sewer line or from direct vapor entry (i.e., entry of contaminated soil gas). Once in the vapor phase,

Table 4
Groundwater to sewer attenuation factors.

Site category	No. plumes	No. AFs	Attenuation factor	Attenuation
			Median (10th – 90th percentiles) [Note 1]	Median (10th – 90th percentiles) [Note 2]
A: direct interaction (sewer at or below water table)	6	59	1.3E−02 (6.7E−05–7.3E−02)	80× (15,000×–14×)
B: indirect interaction (sewer above water table)	28	137	1.3E−04 (1.9E−06–5.5E−03)	7900× (520,000×–180×)

Notes: 1) Attenuation factor calculated as sewer vapor concentration divided by equilibrium groundwater concentration. 2) Attenuation is the inverse of attenuation factor.

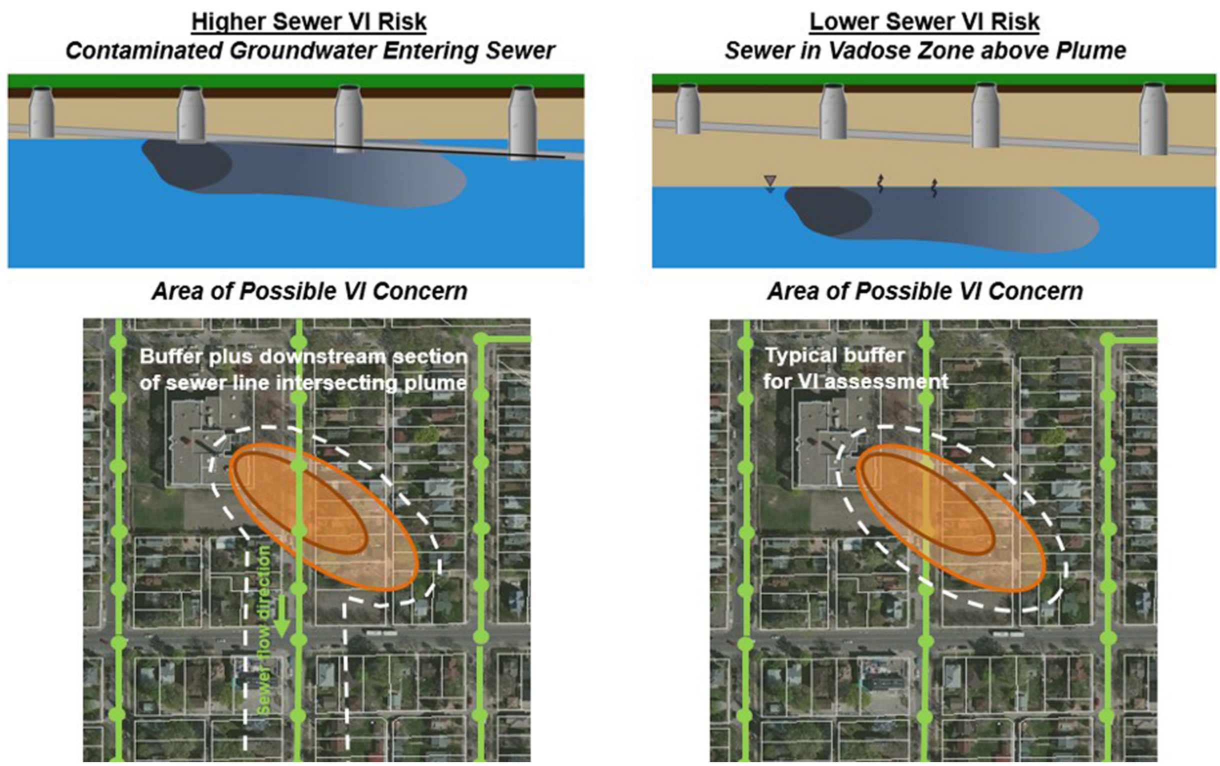

Fig. 2. Relative risk scenarios for sewer vapor intrusion.

the direction of movement within a sewer is somewhat less predictable compared to the liquids. If there are liquids in the sewer, these liquids will flow downslope under the influence of gravity. Friction at the liquid surface commonly creates an advective flow of air within the sewer in the direction of liquid flow (i.e., drag) (Lowe, 2016). Thus, attenuation within sewer lines was evaluated for two cases: i) moving downstream from the plume footprint in vadose zone sewer lines and ii) moving downstream from the plume footprint in water table sewer lines. In addition, transient pressure gradients can drive air flow upstream or through sewer laterals. Therefore, a third case was tested: moving upstream from the plume footprint in water table sewer lines. These three sets of evaluations were done by collecting sewer vapor samples from consecutive manholes along a given sewer line.

For the vadose zone sewer scenario, the median concentration in the source area manholes was 165 μg/m^3 (range 8–1500 μg/m^3). The VOC concentrations in the vapor phase typically decreased quickly with distance away from the source areas (see Fig. 3). A similar rapid decrease in vapor concentrations upstream of water table sewer sites was also observed (see Fig. 4; at these sites, the median source area concentration was 260 μg/m^3 (range 32–10,300 μg/m^3)). This relatively rapid attenuation may be explained by connections between sewer lines and ambient air, allowing both dilution of vapors with ambient air and escape of VOC vapors to the atmosphere.

For the final scenario, contaminated groundwater can enter a sewer line and flow downstream with the liquid flow in the sewer. At these study sites, vapor concentrations in manholes over the groundwater

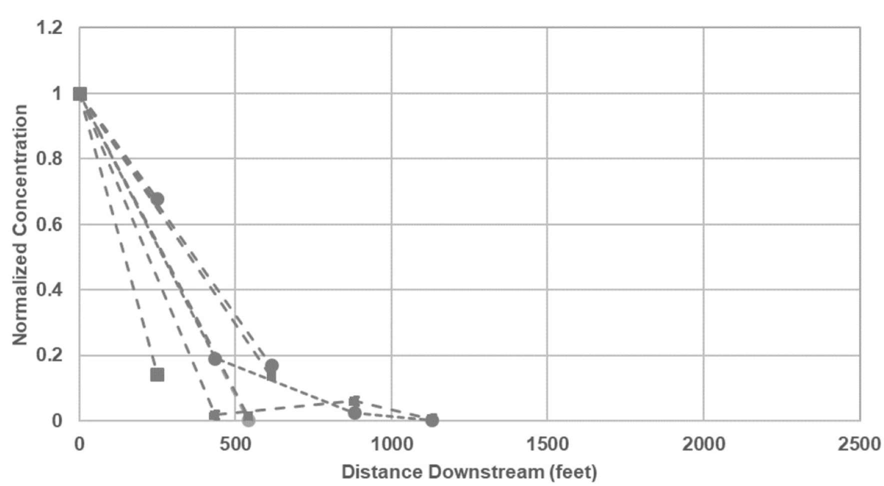

Fig. 3. Normalized concentration vs. distance downstream of source area (vadose zone sewer sites). Notes: 1) Manholes over plume source areas are plotted at 0 ft. Downstream manholes were outside of mapped groundwater plume boundaries. 2) Normalized concentrations were calculated as manhole concentrations divided by plume source area manhole concentration.

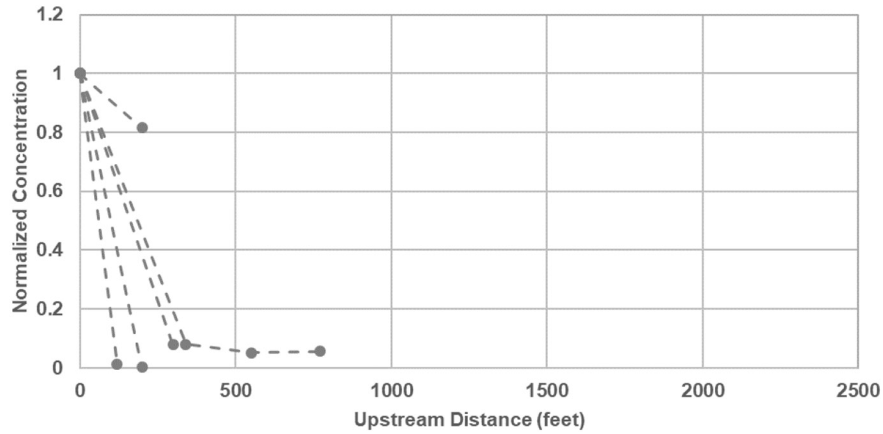

Fig. 4. Normalized concentration vs. distance to upstream manholes (water table sewer sites). Notes: 1) Manholes above mapped plume are plotted at 0 ft. Upstream manholes were outside of mapped plume boundaries. 2) Normalized concentrations were calculated as manhole concentrations divided by plume source area manhole concentration.

plumes ranged from 5 to 115,000 μg/m^3; median 1665 μg/m^3. The VOC vapor attenuation observed downstream of the plume footprint was highly variable but generally slower (i.e., less attenuation with distance) than for the first two scenarios (see Fig. 5). VOCs partitioning from the liquid phase into the vapor phase can result in vapor impacts for an extended distance downstream of the subsurface source area. In this case, the extent of downstream impacts will depend on a number of factors and will be difficult to predict. For example, in some instances, we observed that relative vapor concentrations were higher downstream. This increase could result from variability in the underlying groundwater concentrations within the sewer line or differences in dilution or ventilation along the line.

For conventional VI investigations, focus areas for building-specific evaluation of VI are typically designated as areas above the footprint of subsurface impacts plus a buffer, commonly taken as 100 ft (USEPA, 2015). The evaluation of VOC attenuation within sewer lines suggests that this footprint plus buffer approach is likely appropriate at lower risk sewer preferential pathway sites. In other words, for lower risk preferential pathway sites, indoor air testing of residences above and within 100 ft of the groundwater plume is likely to cover those structures at higher risk for vapor intrusion impacts. However, at sites where contaminated groundwater enters the sewer (i.e., sites at higher risk for sewer VI), the preferential pathway may result in impacts to buildings located away from the subsurface VOC source (i.e., beyond the screening distance commonly used to identify at-risk buildings; Fig. 2).

3.4. VOC attenuation from sewer lines into buildings

Tracer chemicals were used to characterize the relationship between VOC concentrations in sewer lines and VOC concentrations in buildings attached to those sewer lines. PFTs were used, as described in the Methods section, to avoid the possible confounding effects of either conventional VI or indoor sources of VOCs. The tracer attenuation was measured for two buildings where sewer VI had been previously documented and 13 buildings without prior evidence of a sewer preferential pathway (Table 5).

For the buildings with prior evidence of a preferential pathway, there was 40- to 50-fold attenuation in at least one of the connections tested in each of these buildings. In contrast, most of the other buildings with no known or suspected pathways had high levels of attenuation. Ten of 13 buildings without prior evidence of a sewer preferential pathway exhibited 100-fold or greater attenuation.

Although the field investigation program did not focus on identifying the specific mechanisms of vapor migration for sewers into buildings, a review of published literature and other public reports documents a diverse range of vapor entry mechanisms (Table 6).

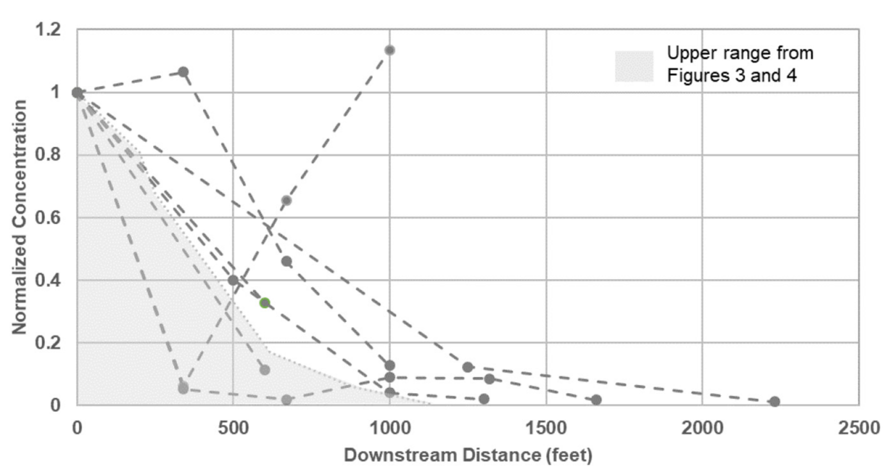

Fig. 5. Normalized concentration vs. distance downstream of source area (water table sewer sites). Notes: 1) Manholes above plume source areas are plotted at 0 ft. 2) Normalized concentrations calculated as manhole concentrations divided by plume source area manhole concentration.

Similarly, for sites where sewer vapor intrusion has been identified, published literature and other public reports document a diverse range of effective mitigation measures (Table 7).

4. Discussion

VOCs are commonly detectable in vapor samples collected from background manhole locations (i.e., manholes >400 ft from a known VOC plume in groundwater). However, concentrations in background manholes are typically less than generic screening levels such as screening levels based on an attenuation factor of 0.03 (e.g., USEPA vapor intrusion screening levels (VISLs) for sub-slab soil gas to indoor air; see Table 1). This is true for most VOCs that drive VI investigations such as PCE or TCE. In contrast, VOC concentrations in sewer manholes within or close to known VOC plumes can be much higher. For example, at sites where PCE was the primary groundwater COC, PCE concentrations in sewer vapor were as high as 12,000 μg/m^3. About 10% of these manhole samples had PCE above the generic screening level (360 μg/m^3) while only 3% of background manholes had PCE above this level. The generic screening level for TCE is lower (16 μg/m^3). At sites where TCE was the primary groundwater COC, TCE concentrations in sewer manholes were as high as 1500 μg/m^3. Almost 70% of these manhole samples had concentrations greater than the screening level while only 10% of background manholes had TCE above this level. These data suggest that false positive results from sewer manholes will be relatively uncommon. The potential for false positive results, however, is greater with very low screening levels.

Sites with subsurface sources of VOCs in groundwater can be classified as higher risk (sewer line intersects VOC plume) or lower risk (sewer line in vadose zone above the VOC plume) for sewer VI. At lower risk sites, VOC vapors attenuate laterally away from the groundwater source area with an 80% or greater decrease in concentration typically observed over a distance of 500 ft. Our dataset suggests that a standard VI investigation approach would be appropriate at lower risk sites, assuming that this includes building indoor air testing. Sewer VI could then be evaluated if indicated by the building results. At higher risk sites, when contaminated groundwater infiltrates into a sewer line, vapor concentrations decrease more slowly and less predictably with distance in the downstream direction (i.e., in the direction of liquid flow). Because of these two factors, early sewer vapor testing during a VI site investigation is recommended for higher risk sites to determine if elevated VOCs are indeed present.

Although not a primary focus of this study, we have observed that VOC concentrations within sewer manholes can vary by 10× over a time period of days and 100× over a time period of months. Thus, the potential for VOC concentrations within sewer lines to vary over time should be considered when interpreting the sewer test results.

When elevated VOC vapors are present within a sewer line, these vapors may migrate into connected buildings resulting in VI impacts. The magnitude of vapor attenuation from the sewer into the buildings is often large (>1000× attenuation); however, building-specific plumbing faults can result in much lower vapor attenuation (<100×). Vapors have been found to migrate from sewers into buildings through a range of entry mechanisms including cracked pipes, faulty seals, and dry p-traps. Predicting the specific mechanism of vapor entry for individual buildings is likely to be difficult. However, at sites where sewer VI has been identified, there are a variety of effective sewer mitigation measures including rerouting the sewer line away from the groundwater plume, lining the sewer to prevent groundwater infiltration, depressurizing the sewer line to remove VOC vapors, or installing check valves within the sewer laterals to prevent migration of vapors into buildings.

Table 5
Sewer to building attenuation.

Sewer type	Building type	Range of attenuation [Note 1]
Buildings with known sewer preferential pathways (specific pathway in italics)		
Land drain (upstream)	*Residence (ASU VI research house)*	*40–70×*
Sanitary sewer (upstream)	*Residence (ASU VI research house)*	*40–60×*
Storm/sanitary sewer (upstream)	Residence (USEPA VI research duplex)	160–>1000×
Storm/sanitary sewer (downstream)	*Residence (USEPA VI research duplex)*	*50–100×*
Buildings without known or suspected sewer pathways		
Sanitary sewer	Residence (Houston duplex #1)	150–790×
Sanitary sewer	Residence (Houston duplex #2)	470–590×
Sanitary sewer (upstream)	Residence (San Rafael house #1)	90–110×
Sanitary sewer (upstream)	Residence (San Rafael house #2)	20–50×
Sanitary sewer (downstream)	Residence (San Rafael house #1)	>1000×
Sanitary sewer (downstream)	Residence (San Rafael house #2)	>1000×
Sanitary sewer	Residence (NASCC area 1 apartment)	>1000×
Sanitary sewer	Office/storage building (Moffett bldg 107)	>1000×
Sanitary sewer	Office/lab building (San Diego)	>1000×
Sanitary sewer	Hospital (NASCC area 2)	>1000×
Sanitary sewer	Office building (NASCC area 3)	>1000×
Sanitary sewer	Shop building (NASCC area 3)	>1000×
Sanitary sewer	Office building (NASCC area 4)	>1000×
Sanitary sewer	Office building (Burlingame)	550–>1000×
Sanitary sewer	Warehouse (Houston)	50–470×

Notes: 1) Several attenuation values were calculated for each building (sewer to kitchen, sewer to bathroom, etc.), with the range of values presented in the table. See Appendix A, Table A.3 for individual tracer results.

Table 6
Examples of mechanisms of vapor entry from sewer/utility tunnel preferential pathways into buildings.

Example site	Observation	References
Research House, Utah	TCE-impacted groundwater enters the land drain system. Vapors migrate up the lateral to a French drain system tied into the sub-slab gravel fill beneath the house. Vapors enter the house primarily through an expansion joint at the edge of the building slab.	Guo et al. (2015)
DoD Facility Building, California	cVOC-containing groundwater enters an underground utility (telephone) pipe. Associated vapors migrate into the building via an uncapped pipe that daylights in the phone closet.	McHugh et al. (2012)
PCE Plume, Denmark	Multiple residences evaluated. Leakage through plumbing connections identified as primary mechanism for VOC migration from sewer to buildings.	Riis et al. (2010)
PCE Plume, Massachusetts	VOC entry into the building via a faulty toilet wax seal.	Pennell et al. (2013)
TCE Plume, Indianapolis, Indiana	High TCE concentrations detected in sub-slab samples collected from residences located outside the footprint of the plume but connected to the downstream sewer with TCE in sewer liquids and vapor. Evidence suggests leakage of TCE vapors from sewer lateral into soil gas below building foundations.	ERM (2017)
Various Sites, Denmark	Leakage through plumbing connections identified as primary mechanism for VOC migration from sewer to buildings. In one specific case, the sewer vent stack for a multi-story apartment building was vented into the attic rather than above the roof resulting in high cVOC concentrations in the upper level of the building.	Nielsen and Hvidberg (2017)
DoD Facility	cVOC migration from sanitary sewer line into industrial building through i) uncapped pipe and ii) lines with dry or damaged p-traps.	Holton and Simms (2018)

Table 7
Examples of sewer mitigation methods used to control vapor intrusion.

Site	Mitigation method	References
Dry Cleaner Site, Denmark	Depressurization of sewer line	Nielsen et al. (2014)
Petroleum Solvent LNAPL, United Kingdom	Replaced collapsed portion of sanitary sewer line and installed an interior liner to prevent infiltration of LNAPL	Macklin et al. (2014)
TCE Plume, Indianapolis, Indiana	Relocated sewer line so that it did not intersect the contaminated groundwater plume	ERM (2017)
Various Sites, Denmark	Paper summarizes several approaches for sewer line mitigation: – Repairing or lining sewer line to prevent infiltration of liquids or vapors – Sealing or repairing leaky/damaged water traps inside of building – Passive ventilation of manholes – Depressurization of sewer system	Nielsen and Hvidberg (2017)
Tranguch Gasoline Site, Pennsylvania	Installed check valves (backflow preventers) in each of 292 sewer lateral lines connecting residences to the sanitary sewer line containing elevated petroleum vapor concentrations. For VI mitigation, the check valve must control both liquid and vapor flow (e.g., checkmate inline check valve).	Jarvela et al. (2004)
DoD Facility	Sewer line ventilation	Holton and Simms (2018)
TCE Plume, California	Repaired sewer line	Viteri et al. (2018)
Navy Facility, New Jersey	Installed liner (cured in-place pipe (CIPP)) inside sewer line to prevent infiltration of contaminated groundwater	Turco (1996)

5. Conclusions

This study involved collection of data from >30 sites across the United States. Based on this dataset, we have identified risk factors for sewers as preferential pathways for vapor intrusion. In general, sites with higher risk for sewer vapor intrusion are those with direct interaction between the subsurface VOC source (e.g., groundwater) and the sewer line itself. This information can be used to help design environmental site investigation programs. For example, for higher risk sites, it may be beneficial to investigate whether elevated concentrations are present in sewer vapors early in the site assessment process.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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