613 - 744 West Hastings
Vancouver, BC
Canada V6C 1A5
T: 604.451.4555
F: 604.451.4558
CSAPsociety.bc.ca

Contaminated Sites Approved Professionals of British Columbia

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[1] https://csapsociety.bc.ca/wp-content/uploads/ATT-3_-CSAP-Professional-Judgement-May2nd.pdf

Environmental Excellence 25th 1998-2023

#148, 2257 Premier Way
Sherwood Park, AB T8H 2M8
tel: 780.496.9048
fax: 780.496.9049

Suite 202, 701 64 Avenue SE
Calgary, AB T2H 2C3
tel: 403.592.6180
fax: 403.283.2647

#102, 11312 98 Avenue
Grande Prairie, AB T8V 8H4
tel: 780.357.5500
fax: 780.357.5501

#105, 116 Research Drive
Saskatoon, SK S7N 3R3
tel: 306.518.2442

303 Vernon Street
Nelson, BC V1L 4E3
tel: 1.888.722.2563

Burnaby, BC

Fort St. John, BC

Victoria, BC

Ottawa, ON

Halifax, NS

toll free: 888.722.2563
mems.ca

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www.arcadis.com

A Review of Vapour Attenuation Factors and Chemical Partitioning Relationships with Focus on Shallow Contamination Scenario

Prepared for:
Contaminated Sites Approved Professionals (CSAP Society) of British Columbia

Prepared by:
Millennium EMS Solutions Ltd.
303 Vernon Street
Nelson, BC V1L 4E3

Hers Environmental Consulting Inc.
&
Arcadis Canada Inc.
100 - 1275 West Pender Street
Vancouver, BC V6E4 B1

May 2024
File #23-00456-00

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[1] Prepared by CSAP

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1.0 INTRODUCTION

Millennium EMS Solutions Ltd. (MEMS), in collaboration with Hers Environmental Consulting Inc. (HEC) and Arcadis Canada Inc. (Arcadis), was retained by the BC Contaminated Sites Approved Professionals (CSAP) Society in BC to prepare this report on "*A Review of Vapour Attenuation Factors and Chemical Partitioning Relationships with Focus on Shallow Contamination Scenario*". This is the second report prepared by MEMS, HEC and Arcadis as part of an overall project on the soil vapour intrusion pathway in British Columbia. The first report, "*A Review of Soil Vapour Issues for Soil Relocation in British Columbia*", was published in September 2023 (CSAP 2023). This report builds on the following previous guidance:

- CSAP "*Guidance for Assessment of Soil Vapour and Ambient Air – Update*" (September 2022), prepared by MEMS and HEC.
- CSAP "*Guidance on the Assessment of the Soil Vapour to Air Pathway*" (August 2020), prepared by ARIS Environmental Ltd. and Golder Associates Ltd.

Research on vapour attenuation factors and partitioning is warranted because of the importance of the vapour intrusion pathway, which is often the driver for remediation of contaminated sites in British Columbia. Further, questions on models and relationships used for estimation of attenuation factors and partitioning often arise. New, and potentially less conservative approaches and methods that more realistically account for site conditions are needed for this pathway. When there is shallow contamination or a scenario with groundwater in contact with the floor slab, there is currently uncertainty on available approaches and the applicability of attenuation factors and models. To address these issues, a review of existing approaches and data was conducted, and available data from sites in British Columbia were compiled and analyzed. The project objective was to recommend estimation approaches for attenuation factors, including the shallow groundwater scenario, and partitioning based on recent data and science that would better reflect potential field conditions. The users of this guidance are expected to have a functional understanding of vapour intrusion, including terminology and processes.

When conducting a generic standards-based vapour investigation in British Columbia, the requirements of the BC Ministry of Environment and Climate Change Strategy (BC ENV) in *Protocol 22* must be followed, and guidance in ENV Technical Guidance 4 should generally be followed. The recommendations in this report are therefore provided in the context of site-specific detailed risk assessment when provincial certification documents are sought.

This report is organized as follows:

1. Introduction – this section.
2. Background and Rationale for Research.
3. Conceptual Site Model Factors for Shallow Vapour Intrusion Scenario.
4. Jurisdictional Review.
5. Research on Vapour Attenuation Factors.
6. Review of Partitioning Models and Data.
7. Empirical Data Analysis.
8. Site-Specific Vapour Risk Assessment
9. Conclusions and Recommendation.

The principal co-investigators and co-authors of the guidance were Dr. Ian Hers of Hers Environmental Consulting, Inc., and Mr. Ian Mitchell of MEMS. Mr. Vijay Kallur of Arcadis provided peer review of the report. The work was conducted under the direction of a steering committee consisting of members of the CSAP Technical Review Committee (TRC) led by Mike Gill of SLR. The contributions of the steering committee and reviewers are gratefully acknowledged.

1.1 Glossary

AF	attenuation factor (ratio of the indoor air to soil vapour concentrations; dimensionless coefficient)
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
bgs	below ground surface
CCME	Canadian Council for Ministers of the Environment
CL	commercial land use (under CSR)
CSAP	Contaminated Sites Approved Professionals (Society of BC)
CSM	conceptual site model
CSR	Contaminated Sites Regulation (of BC)
DOD	Department of Defence (of US)
DTSC	Department of Toxic Substances Control (of California)
ENV	Ministry of Environment and Climate Change Strategy (of BC)
foc	fraction organic carbon
HVAC	heating, ventilation and air conditioning (system)
IL	industrial land use (under CSR)
ITRC	Interstate Technology and Regulatory Council

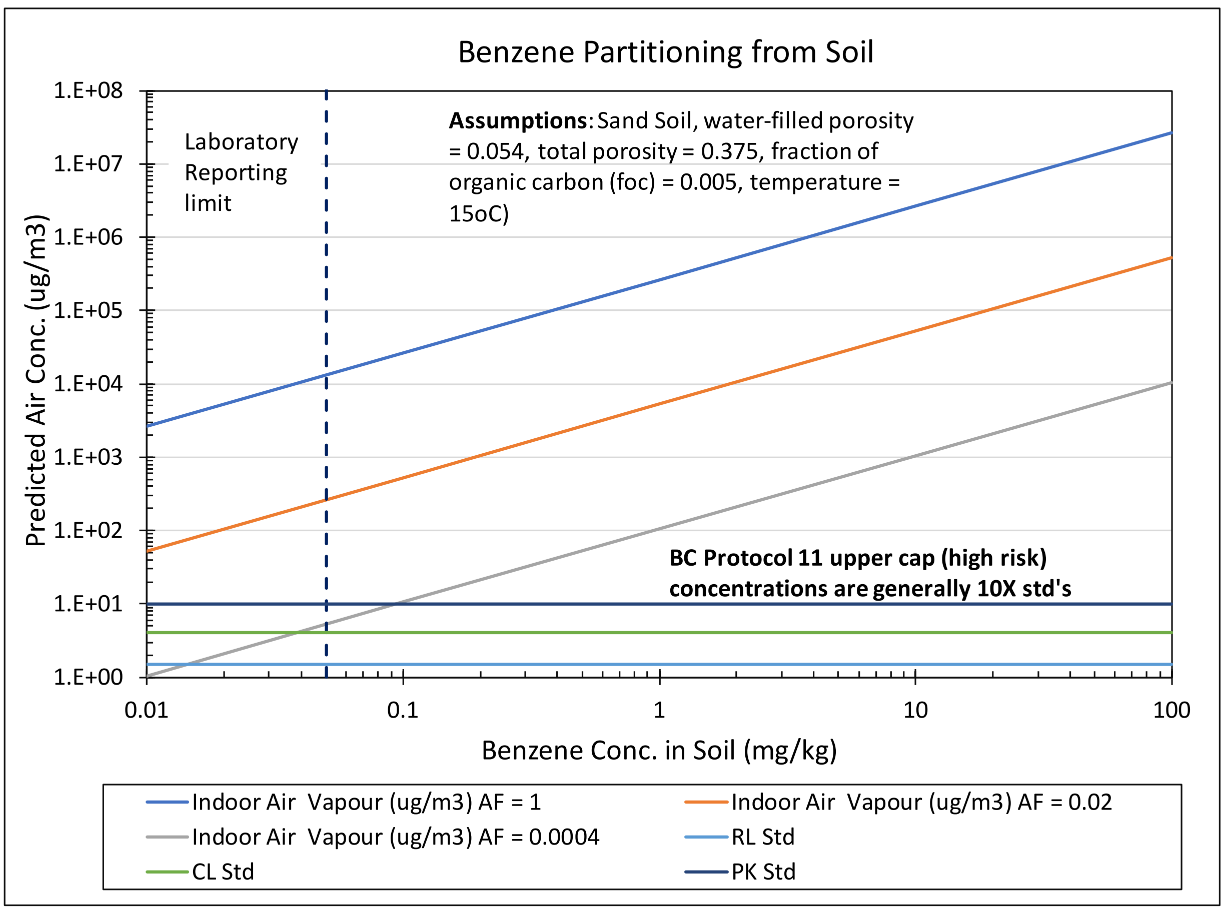
J&E	Johnson & Ettinger
LNAPL	light non-aqueous phase liquid
MLE	multiple lines of evidence
NAPL	non-aqueous phase liquid
PCE	tetrachloroethylene
PCOC	potential contaminant of concern
PHC	petroleum hydrocarbon
PID	photoionization detector
PK	parkade land use (under CSR)
PVI	petroleum vapour intrusion
RL	residential land use (under CSR)
RSC	Records of Site Condition (Ontario)
TCE	trichloroethylene
TMB	trimethylbenzene
TPH	total petroleum hydrocarbon
TRC	Technical Review Committee (of CSAP)
VAF	vapour attenuation factor
VC	vinyl chloride
VI	vapour intrusion
VOC	volatile organic compound
VPH	volatile petroleum hydrocarbon

2.0 BACKGROUND AND RATIONALE FOR RESEARCH

In British Columbia, under ENV *Protocol 22*, attenuation factors are used to estimate vapour concentrations in indoor air, which for shallow depths to soil vapour are empirical factors, and for deeper depths are model-derived factors. There have been questions by contaminated sites Approved Professionals in British Columbia on the applicability of the *Protocol 22* empirical attenuation factors when there is shallow contamination near to the building, and whether the empirical attenuation factor for commercial and industrial buildings is overly conservative (0.02, which is the same as the factor for low-density residential buildings).

The collection and analysis of soil vapour samples at sites, while preferred, is not always feasible or practical. Soil and groundwater concentration data may be used to estimate soil vapour concentrations following ENV Technical Guidance 4. However, there are questions on the applicability of conventional equilibrium partitioning models typically used to estimate soil vapour concentrations.

To illustrate the implications of soil-to-soil vapour partitioning, an example calculation for benzene using a three-phase linear equilibrium partitioning model (see Section 6.0 of this report for discussion on partitioning models) and a range of possible vapour attenuation factors is shown in Figure 1. Depending upon the attenuation factor, the predicted indoor air concentrations may exceed the BC Contaminated Sites Regulation (CSR) vapour standards, and a high-risk condition as defined in ENV *Protocols* 11 and 12, may be indicated for a relatively low soil concentration equal to or less than the typical laboratory reporting limit (0.05 mg/kg). There are select chlorinated solvent compounds where partitioning calculations show similar or even a higher potential to exceed standards at very low soil concentrations. The concern is that these situations are not realistic and conservative leading to significant costs for mitigation that may not be necessary.



(AF = attenuation factor) (RL = residential; CL = commercial, PK = parkade). Soil vapour concentrations predicted from three-phase equilibrium partitioning equation (Eq. 1 in CSAP 2023). Input parameters are provided in figure.

Figure 1 Example Soil Partitioning Calculations for Benzene

The current approach often results in the classification of sites as high risk or risk managed high risk and the implementation of soil vapour mitigation measures, particularly for shallow contamination scenarios. There are potential economic impacts (*e.g.*, expensive vapour mitigation systems that would not be necessary) and schedule impacts (*e.g.*, delays in completion of the projects) on remediation and redevelopment of sites because of these potentially over-estimated outcomes. While there is a need to protect human health from vapour intrusion, there is also value in understanding whether soil vapour intrusion mitigation is necessary based on vapour intrusion occurring, or having the potential to occur, under actual site conditions.

3.0 CONCEPTUAL SITE MODEL FACTORS FOR SHALLOW VAPOUR INTRUSION SCENARIO

The vapour intrusion conceptual site model is described in detail in numerous guidance including Health Canada (2023), CSAP (2022), CSAP (2020), CCME (2016), U.S. EPA (2015a) and ITRC (2014). The objective of the conceptual site model discussion within this document is to describe processes and factors that are important when there is shallow contamination near to or in contact with the building foundation. Consequently, a focus of the CSM discussion in this document is the influence of the building on vapour intrusion.

3.1 BC Building Code

Basic knowledge and requirements for building construction start with the BC Building Code, which was recently updated (March 8, 2024)[2]. The BC Building Code includes requirements related to protection from soil vapour ingress including an air (soil vapour) barrier. While these requirements reduce potential soil vapour ingress when required, they are not consistent with industry practice for mitigation or prevention of vapour intrusion of chemical VOCs into buildings from contaminated sites. A new requirement in the 2024 BC Building Code is that all new small (Part 9) residential buildings in BC must have a "roughed"[3] in radon mitigation system. If such a system were to become active under future conditions or requirements, it could also be effective for mitigation of chemical vapour intrusion.

3.2 Low-Density Residential Buildings

Knowledge of the type and details of the building foundation at a site is important, as vapour intrusion can occur through openings in the foundation in contact with soil, and to a lesser extent through bulk materials (*e.g.*, concrete, see information in CSAP 2022). Common foundation types for low-density residential buildings include: 1) a slab-on-grade with footings, and 2) a structurally

[2] https://www2.gov.bc.ca/gov/content/industry/construction-industry/building-codes-standards/bc-codes/2024-bc-codes#Access-the-codes
[3] A rough-in consists of a gas permeable layer, separated from the conditioned space, connected to a pipe that is ready for the installation of a fan.

supported lowest floor with air gap below, which if sufficiently large is a crawlspace. Typically, perimeter foundation walls are connected to spread or strip footings. A poured slab is placed in the interior of the building, and if below the exterior grade, enables construction of a basement. There may be an (sealed) edge crack along the foundation wall to floor slab interface. Typically, there is a perimeter land drain near the base of footings, and there may be interior drains that connect to the land drain. Sumps may be installed in basements in wet areas with a high water table. Coarse-grained structural fills are usually placed below slabs and footings for free draining of water. Additional information on low-density residential construction is provided in BC Housing "*Builder Guide to Site and Foundation Drainage Best Practices for Part 9 Buildings in British Columbia*" (2021)[4] .

3.3 High-Density Residential, Commercial or Industrial Buildings

There are a range of building foundations for high-density residential, commercial, or industrial buildings including shallow or deep foundations, strip or single footings, pier and beam foundations, raft foundations and piled foundations. Some soil vapour entry points for non-residential buildings are like those described for residential buildings, but the range and types of pathways is more varied and complex. Typically, there are numerous subsurface utilities that penetrate the subsurface building envelope including sewer, water, gas, electrical and telecommunications. In addition to sumps, there may be elevator pits that extend below the ground floor slab and that are closer to potentially impacted groundwater. Certain types of subsurface foundations could enhance upward migration of contaminants (piles, stone columns).

3.4 Mechanisms for Migration of VOCs through Foundations

Soil vapour entry points into the building include edge cracks, shrinkage cracks, cracks along the outside of utilities, drains, and sumps. If groundwater impacted by VOCs enters sewers or land drains, there is the potential for migration of volatile chemicals *via* the conduit airspace into the building. This pathway was addressed in detail in CSAP (2022). A more direct pathway is represented by a high-water table where impacted groundwater enters sumps, or seeps into the building through cracks or other openings. The transport of VOCs through concrete pores *via* either diffusion in water or air-filled pores can also occur. This wet basement scenario is of significant potential concern because VOCs in water directly volatilize into the airspace in the basement and direct contact with chemicals in water can occur.

3.5 Measures to Address High Water Tables

Buildings with basements that intersect the water table may either have drains to reduce water pressure on the building, or be "tanked" (with below grade waterproofing) and thus not require measures to reduce water pressure because groundwater is allowed to be in contact with a portion of

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[4] https://www.bchousing.org/publications/Builder-Guide-to-Site-and-Foundation-Drainage.pdf

the building foundation. There are prescribed requirements for damp-proofing or water-proofing in the BC Building Code and BC Housing "*Design Guidelines and Construction Standards*" (2019)[5]. There are several options for water-proofing including use of polyethylene, rubberized asphalt or elastomeric asphalt emulsion type barriers. While there are some general similarities with types of materials used in mitigation of chemical vapour intrusion, the design is specifically for prevention of water or water-vapour ingress and is not intended for VOCs from contaminated sites. There are also considerations relating to the design of an overall barrier system for mitigation of vapour intrusion (ITRC 2020). There are established specialist vapour intrusion mitigation contractors and VOC specific barriers (*e.g.*, geomembranes or multilayer systems) that are used in mitigation of chemical vapour intrusion, when warranted.

3.6 Heating, Ventilation and Air Conditioning (HVAC) Systems

The heating, ventilation, and air conditioning (HVAC) systems can play a major role in vapour intrusion and its mitigation in high-density residential, commercial, and industrial buildings. The HVAC system may also be important for certain types of low-density residential buildings with active ventilation. The HVAC system is designed to heat, cool, ventilate, filter, humidify, or dehumidify air in a room or building. It can also pressurize or depressurize space within the building relative to the subsurface or outdoor environment. A common HVAC system type is a central all-air system, whereby a central air handling unit supplies heated or cooled air to multiple spaces/rooms in a building *via* a duct network and where a portion of the return air is recycled to the air handling unit and the rest is discharged outdoors. Often these types of systems are designed to be balanced resulting in a neutral pressure or to create a slight positive pressure. Another relatively common HVAC system for spaces such as kitchens, laboratories or certain industrial processes is an exhaust only system where air is removed from the space and air naturally infiltrates to replace air that is removed. This type of system often creates negative pressures in the building airspace. An HVAC system "test and balance" report provides information on air flows and pressures. It is important to recognize there are other factors for building pressures including stack effect (warm air rising in building because of colder outdoor than indoor temperatures), which tends to be a function of building height, wind, and natural solar heating. While the stack effect during the heating season may increase pressure gradients within buildings (*i.e.*, negative in lower parts, positive in upper parts), multi-story buildings are designed with measures to minimize pressures and cross-floor leakage.

Because soil vapour advection (bulk flow of soil gas) tends to be the main process for vapour intrusion for a shallow contamination source, the HVAC system can consequently increase or decrease the potential for vapour intrusion. However, because HVAC system operation and

[5] https://www.bchousing.org/publications/BCH-Design-Guidelines-Construction-Standards.pdf

pressures can be variable both spatially within different parts of the building and over time based on daily or seasonal factors, the processes for vapour intrusion are also expected to be variable. A shallow contamination source near to the building may increase the variability in intrusion processes. The building HVAC system and natural factors can have significant implications for subslab soil vapour and indoor air sampling where at certain times sampling may reflect primarily indoor air that is unimpacted by soil vapour, while at other times sampling may reflect indoor air impacted by soil vapour.

HVAC and ventilation requirements are defined in the BC Building Code. A useful reference is by the Government of Canada is "*Draft guidance on improving indoor air quality in office buildings: Ventilation*"[6] . The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) provides training and learning resources for those who seek further knowledge on building HVAC systems[7]. As warranted, it is recommended that the advice of qualified persons in HVAC or mechanical engineering be sought.

4.0 JURISDICTIONAL REVIEW

A jurisdictional review was completed of select agencies and guidance in Canada and United States for existing regulations and guidance on vapour intrusion. The review generally addressed the following:

- Generic vapour attenuation factors.
- Specific generic vapour attenuation factors for commercial or industrial buildings, if available.
- Adjustments to factors or models based on biodegradation or partitioning, if available.
- Methods for addressing shallow groundwater and/or shallow contamination, if available.
- Methods for developing site-specific vapour attenuation factors, if available.

4.1 Review of Select Canadian Guidance

4.1.1 Canadian Council of Ministers of the Environment (CCME)

CCME (2014) in "*A Protocol for the Derivation of Soil Vapour Quality Guidelines for Protection of Human Exposures via Inhalation of Vapours*" present a protocol for derivation of soil vapour standards using the Johnson and Ettinger model. Precluding factors to the use of the model include a water table within 1 m of the building foundation or a source of vapours (*e.g.,* soil with elevated VOC concentrations) within 1 m of the foundation. In these cases, the soil vapour screening is conducted through sampling of shallow soil vapour (a short distance below the building foundation) or subslab soil

[6] https://www.canada.ca/en/health-canada/programs/consultation-draft-guidance-improving-indoor-air-quality-office-buildings/ventilation.html
[7] https://www.ashrae.org/technical-resources

vapour. Soil vapour-to-indoor air attenuation factors for samples collected < 1 m bgs are based on empirical data (observations or measurements) and are 0.03 for residential buildings and 0.01 for commercial buildings (Table 1). The empirical attenuation factors for residential and commercial buildings were derived through analysis of the U.S. EPA (2012) database. The number of data points (93) for the commercial building scenario was relatively small (note the U.S. EPA did not derive an attenuation factor for commercial buildings because of limited data).

CCME (2008) in the "*Canada-Wide Standard (CWS) for Petroleum Hydrocarbons (PHC) in Soil: Scientific Rationale*" describe how an adjustment factor of 10 times was applied to the equilibrium partitioning model to decrease the soil vapour concentration and increase the PHC fractions soil standards for the indoor vapour inhalation pathway. The attenuation factor was estimated using the Johnson and Ettinger model. The scientific rationale for the 10 times adjustment factor included that volatilization of sorbed phase contaminants may be rate limited, that non-equilibrium partitioning is observed particularly as soil contamination sources weather and that biodegradation is likely to occur. Additionally, CCME (2008) indicate "*a review of matched soil and soil vapour data for F1 in coarse soils undertaken for the PHC CWS revision found that predicted to observed concentration ratios for F1 were consistently greater than 100*". The PHC standards apply to soil contamination that is a minimum 0.3 m below the building foundation slab.

Table 1 Shallow Vertical Attenuation Factors from 2014 CCME Protocol

Sample Location	Sample Depth Below Foundation	Attenuation Factors – Indoor Exposure			
		Residential Building		Commercial Building	
		Soil Vapour to Indoor Air	Groundwater to Indoor Air	Soil Vapour to Indoor Air	Groundwater to Indoor Air
Subslab	-	0.03	-	0.01	-
Subsurface	> = 1.0	Estimated from Johnson and Ettinger model			

Note: CCME (2008) CWS-PHC soil standards for vapour inhalation pathway are calculated using Johnson and Ettinger model and apply to depths equal to or greater than 0.3 m

4.1.2 Health Canada

The Health Canada 2023 "*Supplemental Guidance for Soil Vapour Intrusion Assessment At Federal Contaminated Sites*" provides depth-dependent vertical attenuation factors for residential and commercial buildings. For distances of 1 m or greater between the vapour source and building, the Johnson and Ettinger model is used to derive vapour attenuation factors (Table 2). Biodegradation attenuation reduction factors of 10 or 100 may be applied to the attenuation factors under certain conditions. Because of seasonal fluctuations in groundwater levels, differences in the thickness of the capillary fringe and the potential presence of sumps in basements, the model-derived attenuation factors are not applicable if the contamination is within 1 m of the building. For distances less than 1 m, empirical attenuation factors of 0.03 for residential buildings and 0.01 for commercial buildings are adopted. When groundwater is in contact with the building, the empirical attenuation factors do not apply, and instead Health Canada recommends conducting indoor air sampling.

Table 2 Select Shallow Vertical Attenuation Factors from 2023 Health Canada Vapour Intrusion Guidance

Sample Location	Sample Depth (below Foundation)	Attenuation Factors – Indoor Exposure			
		Residential Building		Commercial Building	
		Soil Vapour to Indoor Air	Groundwater to Indoor Air	Soil Vapour to Indoor Air	Groundwater to Indoor Air
Subslab	-	0.03	-	0.01	-
Subsurface	1.0	0.0029	0.0021	0.00041	0.00022

Note: Readers should consult Health Canada guidance for additional depth-dependent attenuation factors and precluding conditions.

4.1.3 British Columbia

BC Ministry of Environment and Climate Change Strategy's (ENV) *Protocol* 22 provides depth-dependent vertical attenuation factors for multiple land uses. Attenuation adjustment divisors are used to modify the vertical attenuation factors to account for certain conditions consisting of a parkade (underground parking garage), biodegradation, and lateral vapour migration. For distances between the vapour source and receptor (building) equal to or greater than 1 m, the Johnson and Ettinger model was used to derive the vapour attenuation factors[8]. For distances less than 1 m, the vapour attenuation factors were empirically derived. Precluding conditions and footnotes in *Protocol* 22 must be considered when selecting applicable vapour attenuation factors, with the discussion herein focussed on shallow conditions.

A subset of the *Protocol* 22 attenuation factors of interest are extracted in Table 3. The use of vertical attenuation factors is not permitted if groundwater is in contact with the foundation slab at any time of the year, or if there is active pumping or drawdown of groundwater at the site, except for parkades built to the equivalent or better: 2012 or later BC Building Codes. For the parkade condition, a vapour

[8] The protocol used to derive the Johnson and Ettinger model attenuation factors is documented in Golder Associates Ltd. report "BC MOE TECHNICAL GUIDANCE VAPOUR INTRUSION COMPUTER MODEL", dated October 6, 2010 https://sabcs.ca/documents/

attenuation factor of 0.02 may be applied, and a 50X divisor may additionally be applied under a risk-based standards approach meeting the requirements in ENV Technical Guidance 4.

Table 3 Select Shallow Vertical Attenuation Factors from BC ENV *Protocol* 22

Sample Location	Sample Depth (below foundation)	Vertical Attenuation Factors – Indoor Exposure		
		Agricultural, Urban Park, Residential Use	Commercial, Industrial Use	Parkade Use
Subslab	-	0.02	0.02	0.02
Subsurface	< 1.0	0.02	0.02	0.02
Subsurface	1.0	0.0028	0.00037	0.0028

Note: Readers should consult Protocol 22 for additional attenuation factors for sample location types and depths, and applicable footnotes.

Protocol 22 does not specifically address vapour attenuation factors that should be applied when vapour contamination sources are within 1 m vertically (below) or laterally from current and future buildings.

CSAP (2009) provides the following recommendations for shallow vapour attenuation factors (excluding the case where groundwater is in contact with the building foundation) [9]:

- Contaminant Source Within 1 m of Grade or 1 m of an Existing Building Foundation: Provided representative soil vapour is collected, an attenuation factor of 0.02 is recommended.
- Contaminant Source Within 1 m of a Potential Future Building Foundation (but collected more than 1 m below current grade): Provided representative soil vapour is collected, an attenuation factor of 0.02 is recommended.

Recommendations for buildings with crawlspaces and earthen foundations are also provided in CSAP (2009). Lateral vapour migration is not addressed in CSAP (2009).

4.1.4 Alberta

Alberta has adopted the CCME (2014) protocol for soil vapour guidelines, but allows for modelled attenuation factors to be used at distances greater than 0.3 m from the building foundation and uses a default attenuation factor of 0.01 for distances less than 0.3 m. The attenuation factor of 0.01 can also

[9] CSAP (2009) included an important review of issues. Much of this guidance has been superseded by recent guidance including CSAP (2020) and CSAP (2022); however, attenuation factors were not addressed in these recent guidance documents. The CSAP (2009) guidance is therefore considered a reasonable starting point for evaluation of attenuation factors.

be applied in other circumstances where Tier 1 guidelines are precluded, including high vapour permeability soils or shallow groundwater/capillary fringe in contact with the building; alternatively, a site-specific risk assessment can be conducted (AEPA, 2022).

4.1.5 Ontario

The Ontario MOECC generic soil and ground water (Tier 1) standards for use under Part XV.1 of the Environmental Protection Act were derived incorporating the vapour intrusion pathway.[10] The Johnson and Ettinger model with a Soil Depletion Multiplier (SDM) was used to derive the S-IA soil standards (Ontario MOE 2011). Because of the complexity of the SDM it is not possible to determine an equivalent vapour attenuation factor. The soil standards apply to contamination that is 0.3 m or greater distance below the base of the building foundation (or at the base of an assumed 0.3 m thick gravel crush layer). A 10X bioattenuation factor is applied in the model to the commercial/industrial land use scenario only to aerobically-degrading substances below 1.5 m from the building foundation.

The Johnson and Ettinger model (without a depletion module) was used to derive the GW2 groundwater standards (Ontario MOE 2011). The modeling assumes a building-groundwater separation distance of 1.1 m. As biodegradation is considered operable at distances greater than 1 m, the groundwater-to-indoor air attenuation factor is divided by a 10X bioattenuation factor to account for biodegradation. For example, the calculated groundwater-to-indoor air vapour attenuation factor for benzene is 0.00078 for residential land use and coarse-grained soil where the soil vapour concentration is estimated using the Henry's law constant. For derivation of the benzene groundwater standard (44 ug/L), the above attenuation factor is divided by 10. The Ontario standards (Ontario MOE 2011) includes this precautionary note:

> *"Conditions can exist at a site for which the assumptions used to develop the generic criteria may not be valid. The Qualified Professional (QP) must ascertain that the site conditions are appropriate for use of the generic standards such that he/she can be comfortable with signing the certifications on the Records of Site Condition (RSC). Specifically, if the annual average of the capillary fringe of the water table is < 0.8 metres from the outer edge of the gravel crush (free draining layer) beneath the building foundation, then the 10 × biodegradation factor assumed in the GW2 pathway may be non-conservative."*

In Ontario, soil vapour standards may be derived using a Tier 2 approach. Additionally, the shallow contamination condition precluded under Tier 1 is addressed. For Tier 2, if the shallowest water table is expected to be within the 0.3 m thick gravel crush layer beneath a building slab, then the Johnson and Ettinger model may not be used to determine the attenuation factor. Instead, an empirically derived value of 0.02 is used for the residential setting and 0.004 for the commercial/industrial setting

[10] https://www.ontario.ca/page/soil-ground-water-and-sediment-standards-use-under-part-xv1-environmental-protection-act

citing a study by Dawson (2006). The study by Dawson (2006) was an early study of empirical attenuation factors that has been superseded.

Under a Tier 2 approach, there are multipliers to reduce vapour attenuation factors based on building type and construction. For example, the attenuation factors may be reduced by a factor of 100X for an underground parking garage structure. There are also reduction factors for vapour risk management measures. A site-specific risk assessment (Tier 3) may include vapour intrusion modeling, with some requirements for modeling included in Ontario Ministry of Environment and Climate Change (MOECC) "*(Draft) Technical Guidance for Soil Vapour Intrusion Assessment*" (Ontario MOECC 2021).

4.2 Review of Select U.S. Guidance

The U.S. EPA guidance on vapour intrusion published through the Office of Solid Waste and Emergency Response (OSWER) program is primarily intended for halogenated (chlorinated) compounds that do not generally aerobically biodegrade (U.S. EPA 2015a). Under the U.S. EPA Office of Underground Storage Tanks (OUST) program there is guidance that addresses petroleum hydrocarbon compounds that aerobically biodegrade (U.S. EPA 2015b).

The approach in U.S.EPA (2015a) for halogenated compounds was to establish screening vapour attenuation factors for different media as summarized in Table 4. The attenuation factors were based on an empirical database published in U.S. EPA (2012). The database consisted primarily of data for chlorinated solvent compounds and residential buildings with very little data for petroleum hydrocarbons and non-residential buildings.

The U.S. EPA (2015a) guidance indicates there is greater potential for indoor vapour intrusion when groundwater is in contact or near to the building. Consequently, if the depth to groundwater is less than five ft. (1.5 m) below the building foundation, U.S. EPA (2015a) recommends investigation of indoor air quality, as contaminated groundwater may contact the building foundation, either because the capillary fringe intersects the building foundation or groundwater level fluctuations result in groundwater contacting the foundation. When there is shallow contamination, features such as sumps, unlined crawlspaces, or earthen floors (in addition to utilities) have a greater influence on indoor vapour intrusion.

U.S. EPA (2015a) indicates that mathematical modeling of vapour intrusion is most appropriately used together with other lines of evidence. Three approaches for applying mathematical models are described:

1. Calibrating the model to the measured indoor air and/or subslab soil vapour concentrations.
2. Conducting an uncertainty analysis to understand the probability distribution of predictions.
3. Using a bounding case analysis, where parameters are chosen to represent "reasonable worst" conditions.

U.S. EPA (2015a) describe how site-specific soil textures can be used in modeling, but caution that moisture content determined from soil cores taken external to a building may over-estimate soil moisture underneath a building (citing Tillman and Weaver 2007).

Table 4 U.S. EPA (2015a) Recommended Vapour Attenuation Factors for Risk-based Screening of the Vapour Intrusion Pathway

Sampling Medium	Medium-specific Attenuation Factor for Residential Buildings
Groundwater, generic value, except for shallow water tables (less than five feet below foundation) or presence of preferential vapour migration route in vadose zone soils	1E-03 (0.001)
Groundwater, specific value for fine-grained vadose zone soils, when laterally extensive layers are present	5E-04 (0.0005)
Subslab soil gas, generic value	3E-02 (0.03)
"Near-source" exterior soil gas, generic value except for sources in the vadose zone (less than five feet below foundation) or presence of routes for preferential vapour migration in vadose zone soils	3E-02 (0.03)
Crawl space air, generic value	1E-00 (1.0)

For petroleum hydrocarbons, U.S. EPA (2015b) adopted a different approach where an empirical database was used to evaluate subsurface vapour attenuation as opposed to indoor air quality data. In part, this approach was adopted because of the often-significant vapour attenuation observed in subsurface petroleum hydrocarbon vapour concentrations and poor correlation observed between vapour source and indoor air concentrations.

The subsurface vapour concentration data were used to estimate vertical screening distances for petroleum hydrocarbon vapour concentrations to attenuate to below levels of concern where the distance is based on vapour migration in biologically active, oxygenated soil (Table 5). A similar evaluation of petroleum vapour intrusion was conducted by the Interstate Technology and Regulatory Council (ITRC) (Table 5). The guidance also includes lateral screening distances.

Table 5 Screening Distances for Petroleum Vapour Intrusion Recommended by U.S. EPA (2015b) and ITRC (2014)

Categories	U.S. EPA (2015b)	ITRC (2014)
Vertical screening distance		
Dissolved PHC - all sites	6 ft.	5 ft.
LNAPL – UST sites	15 ft.	15 ft.
LNAPL – Industrial sites	30 ft.	18 ft.
Lateral screening distance or inclusion zone	Site-specific	30 ft.

Twenty-two U.S. states have adopted a vertical screening distance approach for evaluation of petroleum vapour intrusion, with most states adopting either U.S. EPA or ITRC recommended distances (Eklund *et al*. 2024).

State guidance from eight states were reviewed (California, Minnesota, Massachusetts, Wisconsin, Michigan, Washington, New Jersey, Georgia) (see Appendix A for references and more in-depth reviews). Consistent with U.S. EPA (2015a), guidance reviewed recommends use of groundwater and/or soil vapour to estimate indoor vapour concentrations from vapour intrusion (as opposed to soil), or direct measurement of indoor air when appropriate. Henry's law partitioning is used to estimate source soil vapour concentrations from groundwater concentrations.

Several other aspects of the state guidance reviewed varied between jurisdictions. Key findings are:

1. Six states in part or in whole adopt U.S. EPA (2015a) vapour attenuation factors.
2. Two states calculated groundwater-to-indoor air attenuation factors using the Johnson and Ettinger model (Massachusetts and New Jersey). The generic calculated groundwater-to-indoor attenuation factors are close to or slightly lower than the U.S. EPA (2015a) factor of 0.001. For PHC compounds that aerobically biodegrade, the attenuation factor is reduced by a factor of 10 (New Jersey).
3. Two states (Wisconsin and Georgia) provide generic attenuation factors for commercial or industrial buildings that are lower than U.S. EPA recommended values by up to a factor of 10X depending on media. The Wisconsin commercial building scenario is defined as a "large" commercial building. The Georgia approach is described below.

4. Michigan has developed a model for estimation of acceptable soil and groundwater concentrations, for non-residential buildings meeting certain criteria (competent foundation, no direct pathways such as utilities or elevator pits) in contact with groundwater. For groundwater, intrusion is assumed to occur through two mechanisms: 1) diffusion in bulk concrete; and, 2) volatilization of contaminants in sump water/water in other openings (estimated using mass transfer coefficients). The diffusive component is estimated using a volatilization factor of 0.03 for subslab to indoor air attenuation and Henry's law partitioning between vapour and water. If the area of sumps is negligible, the overall attenuation factor is close to 0.03.
5. In several guidance documents, the collection of subslab or shallow soil vapour, if possible, and/or indoor air samples is recommended when the distance to the water table from the building foundation is less than 5 ft. New Jersey recommends collection of soil vapour below an impervious surface such as a paved area if soil vapour samples below the building cannot be obtained.
6. Michigan has developed a big building model (BBM) where with sufficient soil vapour or subslab vapour data, a weighted average estimation method may be used to estimate soil vapour concentrations for comparison to screening values for "big" buildings.
7. Modeling is generally a line of evidence that must be supported or validated by other data.

Georgia has developed a noteworthy hybrid approach to derivation of attenuation factors that warrants a more detailed description. In their guidance, generic U.S. EPA attenuation factors are adopted for residential land use; however, for a commercial building with a slab-at-grade foundation, a subslab soil vapour-to-indoor attenuation factor of 0.01 is used. Groundwater-to-indoor air attenuation factors may only be used when the distance from the building to water table is ≥ 5 ft. A modeling approach may be used to derive site-specific factors. For commercial buildings, within a narrow band that is about ½ order of magnitude less than the generic criteria, a site-specific attenuation factor may be derived without validation (*i.e.,* by monitoring data). Lower attenuation factors are allowed if validated by data. Conceptually, this multi-faceted approach accounts for the expected greater attenuation in vapour intrusion for commercial buildings but provides guiderails for derivation of site-specific attenuation factors.

4.3 Summary

The Canadian and U.S. jurisdictions have widely varying approaches to generic screening and attenuation factors. The Canadian jurisdictions reviewed in this document incorporate a hybrid approach where empirical attenuation factors are used to derive standards or estimate indoor air concentrations for shallow or subslab soil vapour samples and where the Johnson and Ettinger model is used to derive deeper vapour attenuation factors. The CCME and two provincial jurisdictions reviewed (Alberta and Ontario) provide standards for soil media, which was not a component of the U.S. guidance reviewed. Most U.S. jurisdictions just adopt empirical attenuation factors, but two jurisdictions reviewed (New Jersey and Massachusetts) use the Johnson and Ettinger model to calculate groundwater-to-indoor air pathway standards and Michigan has a shallow groundwater model for vapour intrusion. Jurisdictions including the U.S. EPA and numerous U.S. states have also adopted a vertical screening distance approach for petroleum vapour intrusion.

The residential subslab soil vapour-to-indoor air attenuation factors are relatively consistent among jurisdictions reviewed and range from 0.01 to 0.03. The commercial/industrial subslab soil vapour-to-indoor attenuation factors (AF) are sometimes equal to the residential factors, but in some cases are lower, as summarized below:

- CCME commercial subslab soil vapour AF: 0.01.
- Health Canada commercial subslab soil vapour AF: 0.01.
- Ontario commercial subslab soil vapour AF: 0.004.
- Georgia commercial subslab soil vapour AF: 0.01.
- Wisconsin industrial and large commercial shallow subslab soil vapour AF: 0.01.
- Wisconsin industrial and large commercial deep soil vapour AF: 0.001 (deep is defined as greater than 5 ft. between building and soil vapour source).

5.0 RESEARCH ON VAPOUR ATTENUATION FACTORS

Research studies on vapour attenuation factors primarily derived from empirical data are summarized below with more in-depth descriptions of each study provided in Appendix B. Several modeling studies that were performed in conjunction with reviews of empirical data are also summarized.

5.1 U.S. EPA (2012) Empirical Attenuation Factor Database

U.S. EPA (2012) report on a large empirical database of paired subsurface media (groundwater, soil vapour, subslab soil vapour) and indoor air concentrations for primarily chlorinated solvent chemicals and residential buildings. When data was filtered using factors considered most effective at minimizing the influence of background sources on indoor air concentrations, and only chlorinated solvent data were considered, the 95th percentile (other percentiles are given in Appendix B) attenuation factors were:

- groundwater-to-indoor air: 0.0012;
- (exterior[11]) soil vapour-to-indoor air: 0.25; and,
- subslab soil vapour-to-indoor air: 0.026.

The above 95th percentile empirical attenuation factors were subsequently used to guide selection of recommended attenuation factors in U.S. EPA (2015a).

There is uncertainty in the U.S. EPA data provenance and variability particularly when 95th percentile values are used (*e.g.*, Song *et al*. 2011; Brewer *et al*. 2014). Modeled attenuation factors using generally conservative input parameters are often an order of magnitude, or more, lower than empirical values (Brewer *et al*. 2014; Yao *et al*. 2018). However, models are an idealized representation of processes, and the reality is that there is considerable variability in vapour sources and quantity and quality of data collected at sites. Consequently, the distribution of U.S. EPA empirical attenuation factors may be mostly representative of the range of attenuation that could be measured at sites, but there remain concerns on whether the upper (95th) percentile values are biased by outliers that are not representative.

The U.S. EPA (2012) exterior soil vapour-to-indoor air attenuation factor is about one order of magnitude higher than the subslab soil vapour-to-indoor air attenuation factor. However, the 50th percentile values are relatively close as the exterior soil vapour-to-indoor air and subslab soil vapour-to-indoor air attenuation factors are 0.0038 and 0.0027, respectively. The higher variability in the exterior soil vapour-to-indoor air attenuation factors suggest possible bias caused by outliers and a smaller dataset. A possible source of variability is that measurement data and modeling simulations often show that shallow external soil vapour concentrations are lower than subslab soil vapour concentrations (Abreu *et al*. 2009; U.S. EPA 2012). The comparison of external and subslab soil vapour concentrations can be improved through collection of near-source external soil vapour data. The depths of the external soil vapour samples relative to sources are not well documented in the U.S.EPA database and collecting near-source data may not have been an emphasis when the data was collected (circa 1990's and 2000's).

[11] Exterior or external means soil vapour samples collected adjacent to, i.e., outside of the building footprint

5.2 Recent Studies

At and since the time of the U.S. EPA empirical database study, there have been several studies that provide information on vapour attenuation factors for different site types and buildings, summarized below and in Table 6, with details in Appendix B.

- Testing of residential homes above a chlorinated solvent plume indicated seasonal individual point-in-time groundwater-to-indoor air 1,1-dichloroethylene (DCE) attenuation factors ranged from 10^{-4} to 10^{-6} in five homes at the Redfield site in Colorado, USA (Folkes *et al*. 2010).
- Testing of a commercial building and a residential building yielded similar groundwater-to-indoor air attenuation factors ranging from 10^{-4} to 10^{-6} for a site in Massachusetts, USA, with fine-grained soils (Pennell *et al*. 2016). Soil vapour monitoring above the capillary fringe indicated about 1000X attenuation of chlorinated solvent concentrations across the capillary fringe compared to theoretical equilibrium partitioning predictions.
- Based on testing of chlorinated solvents in air and subslab soil vapour in 51 schools across France, the estimated 90th percentile subslab soil vapour-to-indoor air attenuation factor was 0.0075 for buildings less than 50 years old, and 0.037 for buildings greater than 50 years old (Derycke *et al*. 2018).
- A database of soil vapour (external soil vapour and subslab soil vapour) and indoor air chlorinated solvent concentration data compiled from sites in California for a mixture of residential, commercial, and industrial buildings yielded a soil vapour-to-indoor air attenuation factor of 0.0008 based on a reliability analysis (corresponding to < 5% false negatives) (Lahvis and Ettinger 2021).
- Based on testing of 76 industrial buildings at 22 DOD sites (including several northern U.S. sites), it was concluded that the upper range values of attenuation factors suitable for generic screening of industrial buildings were 0.001 for subslab soil vapour-to-indoor air and 0.0001 for groundwater-to-indoor air (Hallberg *et al*. 2021 and Levy *et al*. 2023)
- Based on testing of 77 industrial buildings at a site in mid-west USA, the calculated 95th percentile subslab soil vapour-to-indoor air attenuation factor for chlorinated solvents was approximately 0.00064 (Eklund *et al*. 2022).
- A database of soil vapour and indoor air chlorinated solvent concentration data compiled by the California Department of Toxic Substances Control (DTSC) from 52 sites and 213 residential (53%) and commercial/industrial (47%) buildings yielded a 95th percentile subslab soil vapour-to-indoor air attenuation factor of 0.005 and a 95th percentile soil vapour-to-indoor air attenuation factor of 0.0009 (Abassi 2023).

Table 6	**Summary of Empirical Vapour Attenuation Factors from Recent Research**			
Reference	**Building use, contaminant and location**	**Groundwater-to-indoor air AF**	**Soil vapour-to-indoor air AF**	**Subslab soil vapour-to-indoor air AF**
Folkes *et al*. (2010)	Residential buildings, 1,1-DCE, Co, USA	10-4 to 10-6		
Pennell *et al*. 2016	Commercial and residential, chlorinated solvents, MA, USA	10-4 to 10-6		
Derycke *et al*. 2018	Schools, chlorinated solvents, France			90th percentile, < 50 yrs old – 0.0075; > 50 yrs – 0.037
Lahvis and Ettinger 2021	Residential, commercial and industrial, chlorinated solvents, CA, USA		Based on reliability analysis corresponding to 5% false negatives = 0.0008	
Hallberg *et al*. 2021; Levy *et al*. 2023	Commercial and Industrial buildings, USA	Upper range* 0.0001		Upper range* 0.001
Eklund *et al*. 2022	Industrial buildings, chlorinated solvents, mid-west USA			95th percentile 0.00064
Abassi 2023	Residential, commercial and industrial, CA, USA		95th percentile 0.0009	95th percentile 0.005

Recent developments also include a machine learning technical framework applied to predict VI attenuation factors based on site-specific data in the U.S. EPA and CalEPA's VI databases, which through multivariate analysis of variance to identify effective covariates claims to potentially overcome the limitations of traditional VI models (Man *et al*. 2022). Using the machine learning (ML) models that were developed, the predicted attenuation factors are generally within one order of magnitude of the observations recorded in the databases. While big-data analysis using ML techniques have promise, further work is needed to better understand predictive capabilities of these methods.

There did not appear to be empirical studies or models in the research literature on estimation of vapour attenuation when there is a very shallow contamination source near to or in contact with the building (note the common recommendation is to sample indoor air in this circumstance). Ma *et al*. (2020) state "*compared to the conventional VI pathway and the VI preferential pathway, less research has been focused on the direct building contact/infiltration pathway*". The author (Ian Hers) has developed a contamination-building contact model for vapour intrusion, but the model has not yet been published.

5.3 Summary

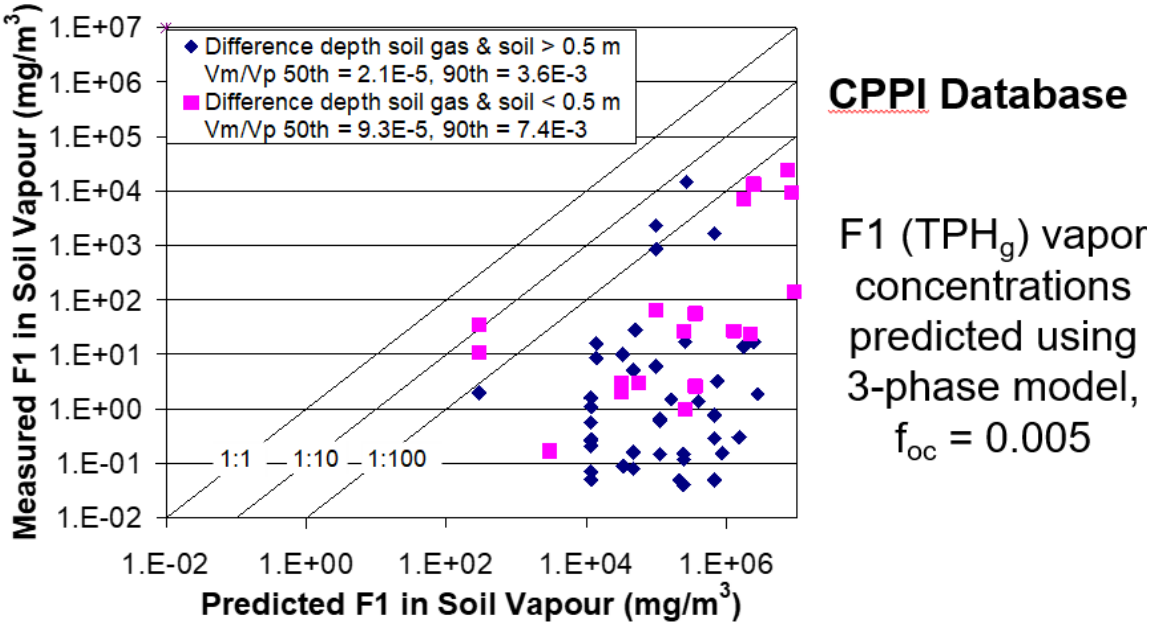
The recent studies are instructive and indicate a common trend of attenuation factors that are mostly lower than the U.S. EPA 95th percentile attenuation factors. Studies of commercial/industrial buildings or residential/commercial/industrial buildings indicate subslab soil vapour-to-indoor air attenuation factors of generally 0.001 or lower excepting one study where the 95th percentile attenuation factor was 0.005. There were less data for groundwater-to-indoor attenuation factors; however, the available data indicates soil texture can significantly affect attenuation above the water table. While the reported groundwater-to-indoor air attenuation factors for investigations of residential and commercial buildings were 0.0001 or lower, we caution in extrapolating these results to generic factors as sites with very coarse-grained soil (coarse sand or gravel) may not have been represented. Soil grain size and texture influence VOC transport across the capillary fringe. There were even less data for external soil vapour-to-indoor air attenuation factors (one CA study), where the reported factor for residential/commercial/industrial buildings was 0.0009.

For reference and comparison, the subslab soil vapour-to-indoor attenuation factor in BC ENV *Protocol* 22 is 0.02 for residential and commercial/industrial land uses. The soil vapour-to-indoor air attenuation factors in *Protocol* 22 for 1 m depth are 0.0028 for residential land use and 0.00037 for commercial/industrial land use with lower attenuation factors at greater depths.

The upper range empirical subslab soil vapour-to-indoor air attenuation factors for commercial/ industrial building types in recent studies are generally approximately one order-of-magnitude lower than the *Protocol* 22 subslab factor. The upper range empirical external soil vapour-to-indoor air attenuation factors for residential and commercial/industrial building types are either greater or lower than the *Protocol* 22 factors (at 1 m depth) depending on the study. The potential limitations in empirical external soil vapour-to-indoor air attenuation factor data were previously described in this report. Because the *Protocol* 22 attenuation factors at 1 m depth or greater are not conservative, it highlights the importance of collecting representative near-source soil vapour data when relying on external soil vapour data to evaluate the vapour intrusion pathway.

6.0 REVIEW OF PARTITIONING MODELS AND DATA

Theoretical aspects of partitioning models between soil and soil vapour were described in CSAP (2023). Hewitt (1998) through experimental data demonstrated that the common three-phase linear equilibrium model describes partitioning at a small scale in sealed vials and shows partitioning of non-polar compounds is controlled by organic carbon content. Two field studies comparing soil to soil vapour concentrations were summarized in CSAP (2023); one conducted at a site with PHC contamination (Figure 2) and another with TCE contamination. Both studies indicated theoretical predicted soil vapour concentrations from soil concentration data were between one and three orders of magnitude greater than measured vapour concentrations.



(F1 = CCME F1 (C6-10) fraction, Vm = measured vapour, Vp = predicted vapour, CPPI = Canadian Petroleum Products Institute)

(Golder 2007 – see additional discussion in CSAP 2023)

Figure 2 Co-located Measured and Predicted F1 Vapour Concentrations from Soil Concentrations

While direct sampling of soil vapour is preferred for assessment of vapour intrusion, in some cases, sampling of soil and/or groundwater may be required because it is not possible to obtain soil vapour samples. Because of the uncertainty in the prediction of soil vapour concentrations from soil and groundwater, follow-up analysis of partitioning is conducted in this report. A summary is provided below with additional details in Appendix C.

The common assumption for groundwater to soil vapour partitioning is equilibrium partitioning based on Henry's Law. Empirical studies indicate the estimated soil vapour concentrations from the dissolved groundwater concentrations (based on equilibrium partitioning) were two to three orders of magnitude higher than the measured near-source vapour concentrations above the capillary transition zone (*i.e.,* zone from the water table to where air-filled pores are continuous) (Appendix C). Because the rate of diffusion in high moisture content soils is slow, there tends to be greater concentration attenuation across the capillary transition zone for fine- than coarse-grained soil. Additional attenuation can occur through biodegradation processes. The studies reviewed were primary for sandy soil sites; the difference between measured and theoretical concentrations may be less in very coarse-grained soil (*e.g.*, gravel).

Empirical studies at UST sites with LNAPL sources at the water table were also reviewed (Appendix C). In these studies, the predicted soil vapour concentrations estimated from either groundwater concentrations or equilibrium partitioning from NAPL were two to seven times higher than the measured concentrations in soil vapour samples obtained near to the contamination source.

The common three-phase partitioning model assumes linear equilibrium partitioning between the absorbed phase in natural organic carbon in soil, the water phase, and the vapour phase. The potential factors affecting the partitioning relationship include:

- VOCs may adsorb to soil minerals as well as organic carbon;
- partitioning is affected by the type of organic carbon present; and
- VOCs may be adsorbed by anthropogenic carbon sources, including residual hydrocarbons in soil, and organic compound residues may form in occluded soil pores (U.S. EPA 1993; Shih and Wu 2005).

U.S. EPA (1993) stated that non-equilibrium soil adsorption may be significant and increase over time due to weathering. This is because the more soluble or easily desorbed fraction is initially preferentially removed resulting in the non-equilibrium sorbed fraction becoming dominant over time. There may also be rate limitations in the VOC desorption and water diffusion processes that result in non-equilibrium concentrations in the vapour phase.

The review found limited research on newer soil to soil vapour partitioning models summarized below (with details in Appendix C).

- Chen *et al*. (2004) introduced a dual equilibrium desorption (DED) model by combining a traditional linear model and a nonlinear Langmuirian expression considered by the authors to predict concentrations of common hydrophobic chemicals more accurately. The DED model includes several empirical parameters that are difficult to estimate.
- Zhang *et al*. (2022) described a multiphase model for partitioning that includes partitioning between adsorbed soil (mineral) and absorbed (organic carbon) and vapour phases, and water and vapour phases. The model is considered to predict soil vapour concentrations more accurately than the conventional three-phase linear partitioning model, which is considered by the authors to overpredict soil vapour concentrations. A noteworthy finding was that soil vapour to adsorbed mineral phase partitioning was important at relatively higher soil moisture contents up to 20% relative saturation. At relative saturations greater than 20% absorption into organic carbon was the primary mechanism. The practical implication is that

soil vapour concentrations may be lower than predicted using conventional models in lower to moderate moisture content soils because of adsorption on mineral surfaces.

In summary, the implications of the partitioning studies include that groundwater-to-indoor air attenuation factors are expected to be lower than soil vapour-to-indoor air attenuation factors because of attenuation across the capillary transition zone. For fine-grained soil, there can be several orders of magnitude attenuation in concentrations across the capillary transition zone resulting in measured soil vapour concentrations that are much lower than predicted by an equilibrium partitioning model. However, within or close to LNAPL impacted zones, measured soil vapour concentrations may be close to theoretical predicted concentrations.

Empirical studies comparing co-located soil and soil vapour concentrations indicate theoretical concentrations often significantly over-predict measured concentrations. Conventional equilibrium partitioning models are lacking in predictive capacity but operationally it is challenging to develop a practical theoretical model that more accurately quantifies partitioning. Adjustment of partitioning models using an empirical factor or divisor is another possible approach that is evaluated in the following sections of this report. An implication for practitioners is to whenever possible avoid the use of soil media for assessing vapour intrusion consistent with recommendations in ENV Technical Guidance 4.

7.0 EMPIRICAL DATA ANALYSIS

Two phases of empirical data collection and analysis were conducted in summer 2023 to support evaluation of vapour sampling requirements for soil relocation in British Columbia (CSAP 2023) and in winter 2024 (this report).

7.1 First Phase

The objectives of the first phase study included to better understand partitioning relationships based on field data and to determine whether correlations could be developed to inform when soil vapour sampling for soil relocation is required (see CSAP 2023 for regulatory background).

The data collection process generally involved Approved Professionals in British Columbia providing Site ID(s) of sites with soil vapour data that have received regulatory certificates. Site investigation reports were obtained from ENV based on the Site IDs. Relevant data was manually extracted from reports. The Site ID and location was removed in all information extracted for analysis and published.

The relations between soil, groundwater and soil vapour concentrations were evaluated for seven BC sites with publicly available data (no indoor air data were available). All data were for *in-situ* samples. Petroleum hydrocarbons (PHC) were present at three sites, chlorinated solvents were present at two sites, and two sites were impacted by mixtures of PHCs and chlorinated solvents. The sites with PHCs were relatively small service station sites with underground storage tanks (USTs), dispensing areas and related facilities (*e.g.,* repair garages, oil-water separators). In general, the site geology was relatively complex with fill underlain by layered soil deposits.

Data filtering was conducted to assemble co-located pairs of soil-soil vapour and groundwater-soil vapour data. All data pairs with greater than 5 m lateral separation distance were filtered out. Data were screened out where both media concentrations were less than the detection limit but were retained where one media type was non-detect and the other was detected.

The filtered database consisted of 171 groundwater-soil vapour or soil-soil vapour data-pairs from seven sites (Appendix D, Sites #1 to #7). The vertical separation distance for soil-soil vapour pairs varied from as little as almost perfectly co-located (within 0.05 m) to approximately 4 m. When all data was considered, 58% of samples were within 1 m vertically while 42% of samples were greater than 1 m apart. With respect to temporal comparisons, much of the paired data was concurrent within one year. While ideally a more stringent criteria would have been followed to screen out non co-located and non-concurrent data, a less stringent approach was followed because of limited data.

Soil vapour concentrations were estimated for select substances from groundwater concentrations and the Henry's Law constant, and from soil concentrations using the three-phase partitioning model. Particularly the estimates from soil concentrations are considered highly approximate and uncertain because of unknown soil properties (*e.g.,* fraction of organic carbon).

Key results are summarized below:

1. There is a high degree of variability in media concentrations and data-pair comparisons. A high-level observation is that the data analysis support site characterization using soil vapour concentration data.
2. In most cases, the soil vapour concentrations were greater than the detection limit (but often just above), and either or both the soil and groundwater concentrations were below the detection limit, although for one site, there were detectable soil concentrations and non-detect soil vapour concentrations at some sampling locations. A possible reason is vapour attenuation over the distance between the soil and soil vapour sample, which in some cases was several meters.
3. Limited or no correlation was observed between soil and soil vapour concentrations, while a better but still weak qualitative correlation was noted between groundwater and soil vapour concentrations based on visual inspection of data.

4. Estimated soil vapour concentrations from the theoretical three-phase linear equilibrium partitioning model and soil concentrations were overpredicted at all but one site with chlorinated solvent contamination. For PHCs, the predicted soil vapour concentrations were one to two orders of magnitude (or more) greater than the measured vapour concentrations at all sites.
5. Estimated soil vapour concentrations from groundwater partitioning more closely matched measured concentrations, although in some cases groundwater also overpredicted the soil vapour concentrations.

The data analysis did not support correlations to refine soil vapour sampling requirements for soil relocation but the comparison of predicted and measured soil vapour concentrations for PHCs in soil was considered useful (see CSAP 2023 for additional discussion).

7.2 Second Phase

The objectives of the second phase study included to better understand partitioning relationships and vapour attenuation factors based on field data. A secondary objective was to evaluate vapour attenuation in the unimpacted vadose zone through soil vapour profiles, where such data was available. A similar data collection process was followed as for the first phase. A Data Request sent by CSAP to Approved Professionals is provided in Appendix E.

Publicly available investigation and remediation reports for 21 BC sites were obtained and reviewed. Based on suitability, 14 sites were retained for detailed evaluation, and available soil, groundwater, and soil vapour data were compiled in a database. Indoor air data were available for three sites, each with one building. Petroleum hydrocarbons (PHC) were present at six sites, chlorinated solvents were present at seven sites, and one site was impacted by a mixture of PHC and chlorinated solvents. The sites with PHCs were service station sites like the Phase 1 study. Sites with chlorinated solvent contamination were either dry cleaners or manufacturing sites. In general, the site geology was relatively complex with fill underlain by layered soil deposits.

Data filtering was conducted to assemble co-located pairs of soil-soil vapour and groundwater-soil vapour data (Appendix F). The maximum lateral distance between retained data pairs was 13 m, although the distance for almost all data was less than 5 m (see meta-data table in Appendix F). Data were screened out where both media concentrations were less than the detection limit but were retained where one media type was non-detect and the other was detected.

The filtered database consisted of 63 groundwater-soil vapour or soil-soil vapour data-pairs from ten sites (Sites #8, 10-12, 14-19, Appendix F). Meta-data on data-pair comparisons, site summaries and figures for individual sites are provided in Appendix F. The vertical separation for soil-soil vapour pairs varied from as little as almost perfectly co-located (within 0.1 m) to approximately 1.2 m vertical separation for soil-soil vapour pairs and 2 m vertical separation for groundwater-soil vapour pairs. When all data was considered, 81% of the samples were within 1 m vertically while 19% of the samples were greater than 1 meter apart. With respect to temporal comparisons, much of the paired data was concurrent within one year. While ideally a more stringent criteria would have been followed to screen out non co-located and non-concurrent data, a less stringent approach was followed because of limited data.

The results of the partitioning analysis are presented in Figures 3 and 4. For groundwater analyses, the concentrations were predicted using the Henry's law constant assuming equilibrium partitioning and were corrected for an assumed temperature of 15°C. For soil analyses, the concentrations were predicted using the three-phase equilibrium partitioning model described in the Stage 1 report. Physical-chemical parameters are provided in Table 7.

Table 7 Physical-chemical Parameters used in Partitioning Analysis

Substance	Dimensionless Henry's law constant, H' (at 25°C)	Ref.	Dimensionless Henry's law constant, H' (estimated at 15°C)	Soil-organic carbon partitioning coefficient, koc (L/kg)	Ref.
Benzene	0.227	1	0.141	146	1
Xylenes	0.271	1	0.143	383	1
Trichloroethylene (TCE)	0.403	1	0.245	60.7	1
Tetrachloroethylene (PCE)	0.724	1	0.407	94.9	1
1,2,4-Trimethylbenzene	0.252	2	0.130	657	3
Vinyl chloride	1.14	1	0.903	21.7	1

References: 1 BC ENV Protocol 13; 2 MacKay et. al (2006). Handbook of Physical-Chemical Properties and Environmental Fate for Organic Chemicals, 2nd ed. CRC Press: Boca Raton, FL; 3 https://pubchem.ncbi.nlm.nih.gov/compound/1_2_4-Trimethylbenzene

The key findings of the analysis include:

- Weak correlations between groundwater and soil vapour, and soil and soil vapour concentrations were observed. There was too much scatter in the data for meaningful statistical parameters to be estimated.
- There were many sampling locations where soil concentrations where non-detect, and where there were measurable soil vapour concentrations (72% of data points). There were fewer

locations where soil vapour concentrations were non-detect, and where there were measurable soil concentrations (4% of data points). Similar trends were observed for groundwater.

- There was a relatively high degree of variability in soil, soil vapour, and groundwater concentrations at sites. This reinforces the recommendation that where possible soil vapour measurement data should be obtained.
- For both groundwater and soil vapour, there were different trends when measured and predicted concentrations were compared for PHC vapours (benzene, xylenes, 1,4-trimethylbenzene (TMB)) and chlorinated solvent vapours (PCE, TCE). In general, the measured PHC vapour concentrations were lower than the predicted concentrations from groundwater or soil, while measured chlorinated solvent vapour concentrations were closer to the predicted concentrations. It is likely that greater biodegradation for PHC vapours is the main reason, although there may be other differences including desorption or volatilization kinetics, or differences in source chemical distribution.
- For soil-soil vapour partitioning, the measured PHC vapour concentrations were at least one order of magnitude lower than the predicted concentrations, except for two data points where the difference was slightly less than one order of magnitude (Figure 4). For the two exceptional data points, benzene was non-detect in soil, but measured in soil vapour at relatively low concentrations (up to 325 ug/m^3). These vapour concentrations may represent isolated zones of chemicals.
- The partitioning relationship for soil to soil vapour is highly sensitive to fraction organic carbon, and to a lesser extent chemical-specific properties. The partitioning relationship for groundwater to soil vapour is sensitive to chemical-specific properties (Henry's law constant). When considering the implications of the partitioning analysis, these assumptions should be considered.

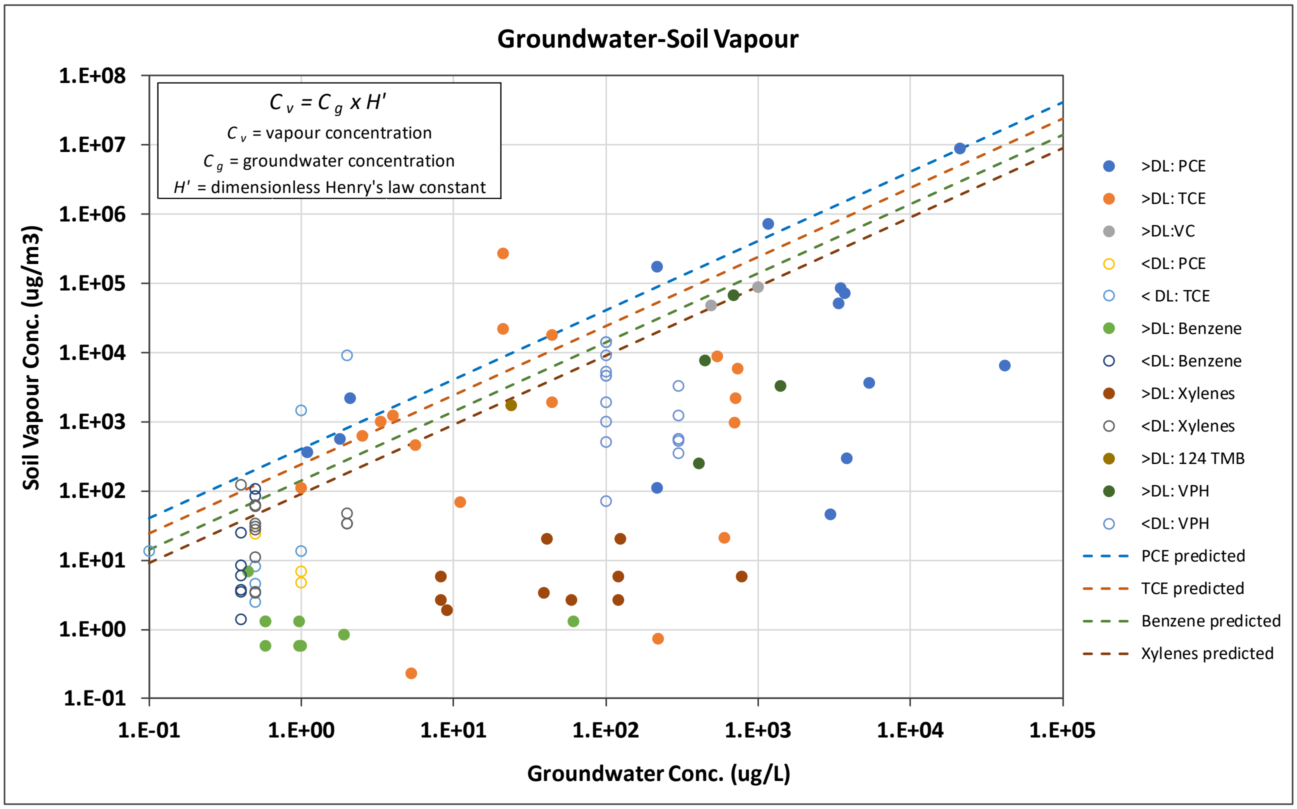


Figure 3 Relationship between Groundwater and Soil Vapour Concentration Data (Phase 1 and 2 of this study)

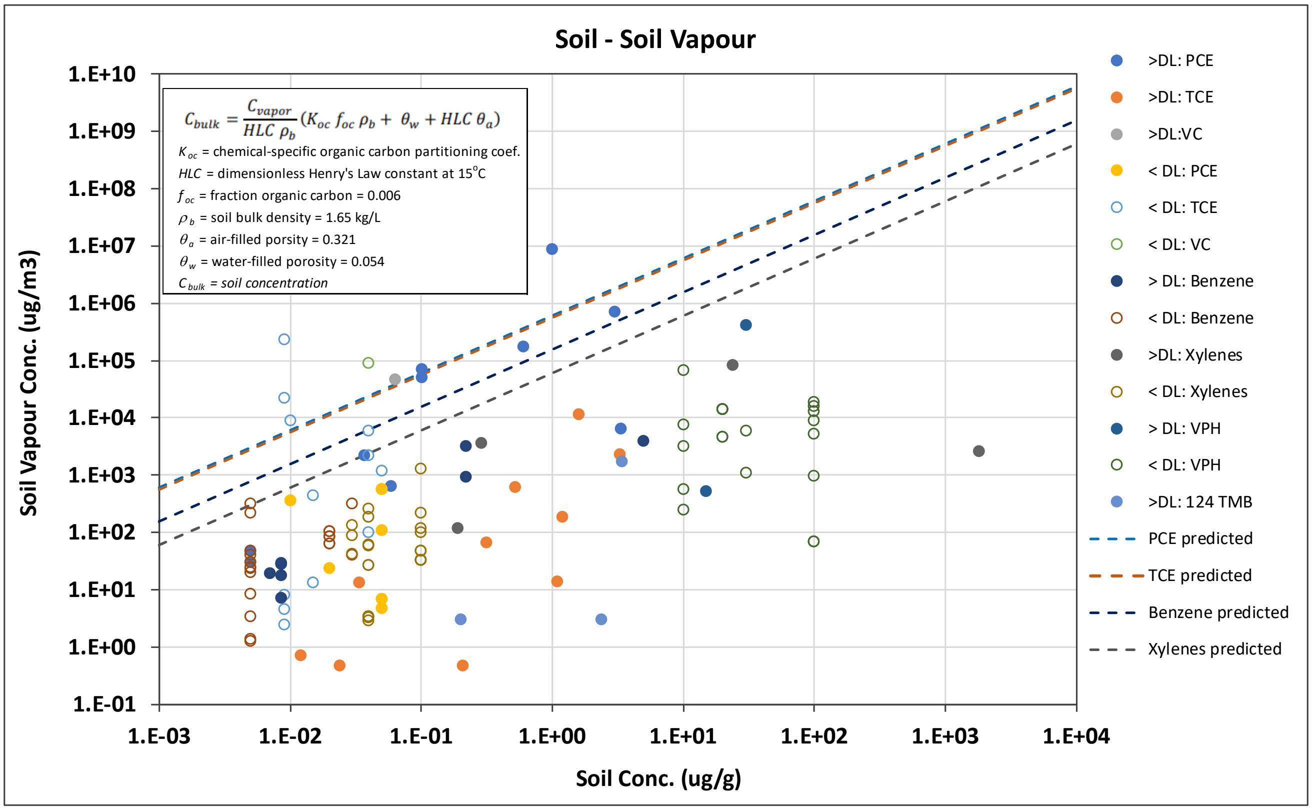


Figure 4 **Relationship between Soil and Soil Vapour Concentration Data (Phase 1 and 2 of this study)**[12]

There were three sites with indoor air chemistry data. The results of data comparisons are summarized in Appendix F, with a synopsis below.

- Site #9: Subslab and indoor air concentration data are reported for a commercial building with slab at grade construction. A shallow groundwater TCE plume migrated below the building. Building footprint area was approximately 1,400 m^2. The attenuated TCE subslab concentration exceeded the vapour standard at one location, and consequently an indoor air sample at that location was analyzed (one sample, one event). The subslab and indoor TCE concentrations were 510 and 0.0083 ug/m^3, respectively, resulting in a vapour attenuation factor of 1.6E-05.
- Site #20: Soil vapour and indoor air data are reported for a site undergoing development as a high-density residential development with underground parking garage. The site investigation indicated elevated PHC vapour concentrations in an area with residual PHC

[12] VPH prediction not included because uncertainty in physical-chemical properties and estimation; TMB prediction not included because of limited data

contamination in soil. Predicted indoor air concentrations in the future parking garage exceeded the CSR parkade vapour (air) standards. Partial remediation of contamination was completed, and a risk assessment was conducted. To address vapour intrusion, risk management through construction of a barrier was proposed. Indoor air samples were obtained during construction for analysis from the lowest parkade floor before and after sealing and tanking of the building was completed (understood to be before completion of the ventilation system). A polyolefin water-barrier designed for tanked buildings was installed. The maximum indoor air concentrations of benzene before and after tanking/sealing were 91 ug/m^3 (2 events, 7 locations) and 0.4 ug/m^3 (1 event, 3 locations). In contrast, a significant decline in xylenes vapour concentrations was not observed, but all reported post-tanking concentrations, including xylenes, were below the parkade standard. The post-tanking/sealing vapour attenuation factors for benzene and xylenes were 2E-05 and 6E-3, respectively. The reason for the difference in benzene and xylenes attenuation factors is not known.

- Site #21: Subslab soil vapour and indoor air concentration data are reported for an industrial building with partial basement / slab at grade foundation where TCE was used. Building footprint area was approximately 1,400 m^2. Average TCE concentrations in subslab vapour were 494 ug/m^3 for one event (n=3), while average indoor air TCE concentrations were 2.6 and 3.9 ug/m^3 for two events (n=7). There were several sumps in the building floor, and indoor vapour intrusion may have been affected by these sumps. The corresponding subslab vapour attenuation factors were 0.005 and 0.008. A new slab-at-grade commercial building with a subslab depressurization system was constructed at the location of the historical industrial building. The post-construction TCE vapour concentrations in three subslab vapour ports, for three events, ranged from <0.5 to 288 ug/m^3. Because the predicted attenuated TCE concentrations (using an attenuation factor of 0.02) in indoor air were less than the standard, no indoor air monitoring was conducted.

The indoor air analyses highlight the complexity of analysis and diverse approaches to characterize indoor air concentrations. The analysis demonstrates the types and quantity of data obtained. Generally, limited data were available on the building and HVAC properties.

8.0 SITE-SPECIFIC VAPOUR RISK ASSESSMENT

Site-specific risk assessment in British Columbia must follow site ENV *Protocol* 1 for Detailed Risk Assessment, which states:

> *"Worst case conditions for current and potential future breathing zone air for human health must be evaluated when vapour contamination is present at the site. Evaluation of the vapour pathway must be completed in accordance with ENV Protocol 22, "Application of Vapour Attenuation Factors to*

> *Characterize Vapour Contamination" Version 1.0. In addition, Technical Guidance 4, "Vapour Investigation and Remediation" Version 2 must be followed."*

Specific instructions for conducting a site-specific vapour assessment are not provided in ENV *Protocol* 1. The reference to *Protocol* 22 and Technical Guidance 4 in *Protocol* 1 is interpreted as the general framework for vapour investigation that must be met when conducting a detailed risk assessment. Technical Guidance 4 states:

> *"note that alternative vapour assessment approaches are acceptable under risk assessment provided they are supported by written defensible scientific rationale."*

For ease of terminology, this section of the report refers to site-specific assessment or site-specific modeling, which means a site-specific detailed risk assessment.

A generic standards-based investigation of vapours must follow the specific requirements and factors in *Protocol* 22 and should follow Technical Guidance 4.

8.1 What Information is Available from the Jurisdictional Review?

Several examples on use of modeling to calculate site-specific attenuation factors were identified in the jurisdictional review. CCME (2014) in Appendix E describes how the Johnson and Ettinger (1991) model can be used to derive site-specific guidelines. Default input parameters are provided. Precluding conditions, to the use of a modeling approach, include the following:

- source-building distances less than 1 m;
- preferential pathways of significance (as defined);
- buildings taller than 4 floors (because of possible enhanced stack effect); and,
- methanogenic conditions causing pressure-driven soil vapour flow and safety risk.

The preferential pathway and pressure-driven soil vapour flow conditions are considered important and appropriate. The criteria that buildings taller than four floors should be precluded appears to lack supporting data or rationale. The source-building distance condition is addressed in subsequent sections.

The Ontario MOECC "*(Draft) Technical Guidance for Soil Vapour Intrusion Assessment*" (January 4, 2021) provides recommendations on conducting site-specific modeling assessment using the Johnson and Ettinger model including selection of input parameters. Health Canada (2023) provides detailed rationale on Johnson and Ettinger model inputs used to derive vapour attenuation factors.

The U.S. jurisdictions reviewed generally do not allow site-specific modeling of vapour attenuation factors without calibration or validation of the modeling results with some exceptions as highlighted below. There are few guidance or details on how to conduct site-specific modeling.

- New Jersey Department of Environmental Protection (DEP) (2016) provides Johnson and Ettinger spreadsheets that are constrained so that the only inputs that may be adjusted are the soil type and distance between building and vapour source (https://www.nj.gov/dep/srp/guidance/vaporintrusion/njje_instructions.pdf).
- California Department of Toxic Substances Control (Ca DTSC) (2023) describe how the Johnson and Ettinger model may be used for a future building scenario (*i.e.,* when subslab soil vapour sampling is not feasible) in consultation with the regulatory agency oversight. The model must be configured such that the attenuation factor between the subslab soil vapour concentration and indoor air concentration is 0.03, which is equivalent to the empirical attenuation factor adopted by CA DTSC. To achieve a subslab attenuation factor of 0.03, a very high Qsoil / Qbuild ratio (where Qsoil is the soil vapour advection rate into the building and Qbuild is the building ventilation rate) needs to be selected, which generally is unrealistic for all building types, and particularly so for larger commercial or industrial buildings. Site-specific soil properties may be used.
- Georgia Environmental Protection Division (EPD) (2021) require a constrained modeling approach where modeled attenuation factors may be used in site-specific risk assessment within certain attenuation factor ranges.
- Pennsylvania DEP (2004) provide guidance on selection on Johnson and Ettinger model parameters.[13]

8.2 When Can Site-Specific Modeling be Used?

Site-specific modeling as a minimum can be used as a supporting line of evidence when evaluating, for example, indoor air concentration data potentially affected by indoor background chemical sources or to gain a better understanding key processes and factors affecting vapour intrusion. In this context, modeling can be a valuable tool.

A key question is whether site-specific modeling can or should also be used to derive risk-based standards for subsurface media concentrations in regulatory certificates in British Columbia in absence of supporting or confirmatory indoor air data. Technical Guidance 4 indicates "*use of*

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[13] https://files.dep.state.pa.us/environmentalcleanupbrownfields/LandRecyclingProgram/LandRecyclingProgramPortalFiles/CSSAB/2015/Appendix%20Y%20DRAFT%2004-07-15.pdf).

site-specific vapour attenuation factors is only permitted under risk assessment" but neither Technical Guidance 4 nor *Protocol* 1 provide specific requirements.

A site-specific modeling approach to derive risk-based standards with constraints on modeling (see Section 8.5) may be appropriate under certain conditions for high-density residential (*e.g.*, underground parking garage scenario), commercial, and industrial land use and buildings. Site-specific modeling is generally not considered appropriate for low-density residential land use. This is because of the uncertainty in intrusion processes and future conditions of residential buildings. In addition, the current attenuation factors in *Protocol* 22 for low-density residential land use are not considered conservative, except under possibly limited cases (*e.g.*, a competent and extensive clay barrier or fresh-water lens).

8.3 What Models are Available?

The Johnson and Ettinger model is the primary model used in estimation of generic and site-specific attenuation factors. The U.S. EPA 2017 Johnson and Ettinger spreadsheet model is not recommended because of known potential issues, which were identified by CA DTSC and others. The DTSC web page (accessed March 15, 2024), indicates:

> *"DTSC is modifying the USEPA's September 2017 Version 6.0 of the J&E Model for use on California sites. The DTSC-modified Microsoft EXCEL spreadsheet of the J&E Model will be released by DTSC in 2024."*

Early versions of the U.S. EPA spreadsheet model may be a suitable alternative (*e.g.*, 2004 version), although not currently available on the U.S. EPA vapour intrusion webpage. There are proprietary commercially available vapour intrusion models including those by ARIS Environmental Ltd.[14] and GSI Environmental Inc. (Tier 2 Toolkit model).[15]

The BioVapor model is a steady-state 1-D analytical model that incorporates the same compartmental model processes as the Johnson and Ettinger model but additionally includes aerobic biodegradation.[16] The U.S. EPA PVIScreen model is similar but allows for probabilistic type analysis.[17] These models are formulated to provide the user with an improved understanding of the potential effect of vadose zone biodegradation on soil vapour intrusion.

There are several research analytical models of vapour intrusion, for example, Verginelli *et al*. (2016) describe an analytical method for estimating the oxygenated zone beneath foundations in a petroleum

[14] https://arisenv.ca/e-tools/
[15] https://www.gsienv.com/product-category/rbca-tool-kit/
[16] https://www.api.org/oil-and-natural-gas/environment/clean-water/ground-water/vapor-intrusion/biovapor
[17] https://www.epa.gov/land-research/pviscreen#:~:text=EPA's%20PVIScreen%20addresses%20this%20limitation,leaking%20underground%20storage%20tank%20sites.

vapour intrusion model while Yao *et al*. (2017) describe a two-dimensional analytical model incorporating vertical heterogeneity. There are also several examples of numerical models for evaluation of vapour intrusion (*e.g.*, see review in Verginelli and Yao 2021). To our knowledge, these models are not commercially available.

8.4 How Can Input Parameters for the Johnson and Ettinger Model be Estimated?

Estimation of Johnson and Ettinger model input parameters is based on combination of measurement data, models, and correlation methods. Professional judgment also plays a role. The soil science for estimating soil physical properties and building science for estimating building parameters is complex. Modeling studies should recognize the uncertainty in predictions (typically order of magnitude estimates) and include a sensitivity analysis to identify input parameters with a greater influence on the results. Typically, an upper range value of the vapour attenuation factor should be used in site-specific risk assessment. Modelers should be aware of, and incorporate, as warranted knowledge on site-specific modeling in Johnson and Ettinger (1991), Hers *et al*. (2003), U.S. EPA (2004), Johnson (2005), Tillman and Weaver (2005), Golder (2010), Yao *et al.* (2011), CCME (2014), Ontario MOECC (2021) and Health Canada (2023). Information on ventilation rates and pressures in underground parking garages are provided in SABCS / Golder (2011). See Appendix G for information on estimation of Johnson and Ettinger model inputs.

8.5 What Constraints on Site-Specific Modeling are Considered Warranted?

Site-specific modeling approaches are associated with a relatively high degree of uncertainty. Consequently, guiderails on application of modeled vertical vapour attenuation factors in derivation of risk-based standards are considered warranted consistent with the research on attenuation factors and jurisdictional review. The proposed guiderails are based on comparison to vapour attenuation factors in ENV *Protocol* 22 where the site-specific attenuation factors should not be more than ½ an order of magnitude lower than the *Protocol* 22 attenuation factors unless the model is validated or calibrated with site-specific data (*e.g.*, measured concentrations along the vapour migration pathway and/or in indoor air). With site-specific validation or calibration of the model following a statistically robust method, a lower attenuation factor may be justified.

The ½ an order of magnitude criteria is considered as a reasonable but narrow "window" for adjusting the attenuation factor that is based on empirical data studies and professional judgment of the authors (note that there currently are no bounds on calculation of an attenuation factor in ENV protocols or guidance for detailed risk assessment). The rationale for this constraint is that empirical data studies do not support large reductions in attenuation factors relative to current attenuation factors in *Protocol* 22 (except for subslab vapour-to-indoor attenuation factors for commercial and industrial land use). Because of the complexity of the vapour intrusion pathway, available models are generally order of magnitude predictors of indoor air concentrations and several input parameters are challenging to estimate. Consequently, a cautious approach to site-specific modeling is considered warranted.

8.6 What Options are Available for Shallow Contamination or Groundwater Scenarios?

The shallow contamination or groundwater scenarios (including saturated conditions where soil vapour measurement is not possible) are evaluated with respect to minimum depth criteria for application in context of *Protocol* 22 attenuation factors and site-specific modeling. Additionally, attenuation factors for these scenarios are recommended.

8.6.1 Minimum Depth Criteria for Application of *Protocol* 22 Attenuation Factors

ENV *Protocol* 22 does not specifically address whether vertical attenuation factors apply when there is a shallow vapour contamination source or groundwater within 1 m of the building foundation, except to state no attenuation may be applied when groundwater is in contact with the building, excepting parkades built to the 2012 or later BC Building Code. CSAP (2009) describe this scenario and considers that attenuation factors apply to shallow vapour contamination within 1 m of the building except when groundwater is in contact with the building. CSAP (2009) does not provide a criterion for the minimum distance groundwater should be below the foundation for attenuation factors to apply.

For an existing building scenario and shallow contamination scenario, an approach where representative subslab soil vapour samples are obtained and *Protocol 22* subslab vapour attenuation factors are applied is considered reasonable, except when:

- there is NAPL present in soil (residual or continuous phase) within 0.3 m of the lowest part of the building foundation slab or adjacent to the foundation wall, or
- the highest seasonal groundwater level or water table is within 0.3 m below the lowest part of the building slab, excepting parkades, as previously defined.

This application of vapour attenuation factors is generally consistent with CSAP (2009) and the minimum distance criterion of 0.3 m is consistent with the minimum distance requirements for application of generic guidelines for the vapour pathway in Alberta and Ontario. A minimum distance of 0.3 m is also expected to be consistent with water level control achieved by functioning drains installed near base of foundation footings. Site-specific data on the contamination extent, seasonal groundwater levels and building drains should be obtained (*i.e.*, sites should be well characterized). The additional caveat (to CSAP 2009) of no-NAPL present is important. The presence of petroleum hydrocarbon NAPL can be evaluated using indicators in ENV *Protocol* 16 and ITRC (2014). For high-density residential, commercial, and industrial buildings, there often will be an imported fill layer below the foundation that is around 0.3 m thick, and consequently, soil contamination is unlikely to be in contact with the foundation. For a future building scenario, representative soil vapour samples should generally be obtained from the vapour source area (see Section 8.9).

8.6.2 Site-specific Modeling of Shallow Contamination Scenario (< 0.3 m)

When groundwater is in contact with or within 0.3 m of the building foundation, there is greater potential for groundwater intrusion into buildings and direct volatilization from or contact with water. There is also currently limited knowledge and published models for the direct contact pathway. Therefore, site-specific modeling of attenuation factors under this condition is generally not advisable unless supporting or confirmatory measurement data is obtained, except as already allowed for in *Protocol* 22 for underground parking structures built to the 2012 or later BC Building Code. However, with further model development and validation, development of vapour attenuation factors for commercial and industrial buildings in contact with dilute groundwater plumes may be reasonable. Such models should consider transport through bulk foundation materials and openings, sumps, drains, *etc.*, and VOC mass transfer models and kinetic or rate parameters for volatilization, and should be validated by measurement data to the extent possible.

When NAPL is in contact with or near to the building foundation, appropriate actions should be taken including indoor air monitoring and risk management measures (modeling is not considered appropriate).

8.6.3 Shallow Attenuation Factors

For a residential land use scenario, a subslab soil vapour-to-indoor air attenuation factor of 0.02 is recommended. For a commercial or industrial building scenario, recent empirical data indicates representative (*i.e.*, for prediction) subslab soil vapour-to-indoor air or shallow soil vapour-to-indoor air attenuation factors are 0.005 or lower. Several jurisdictions (CCME, Health Canada, Ontario, Alberta, several US states) have adopted generic subslab soil vapour-to-indoor air attenuation factors of 0.004-0.01 for commercial and industrial buildings (see Section 4.0 of this report). An empirical attenuation factor of 0.01 is considered conservative and applicable to the expected range of high-density residential, commercial, and industrial buildings for use in site-specific assessment. Lower empirical attenuation factors may be appropriate, for example, for larger buildings with higher ventilation rates. Site-specific modeling can be used in conjunction with empirical data analysis to potentially support adoption of a lower attenuation factor. Note the *Protocol 22* parkade attenuation adjustment factor should not be applied to a site-specific vapour attenuation factor.

8.7 What Other Empirical Approaches are Available?

Goldstein and Goldberg (2023) based on their analysis of the California vapour intrusion database describe an approach to estimate a site-specific empirical attenuation factor. To start with, they identify a baseline empirical vapour factor of 0.003 that is considered to generally apply as an approximate mid-range factor. They then apply scaling factors based on subslab soil vapour strength (concentration), sewer source strength (concentration), building type, building floor condition, HVAC type, foundation type, and other factors. With application of either positive or negative factors, the attenuation factor can potentially increase or decrease by up to around an order of magnitude upward or downward from 0.003.

Unfortunately, while the recent empirical data analysis is useful in identifying general ranges of vapour attenuation factors, it is less instructive in identifying specific site factors that influence the attenuation factor. Therefore, while there is likely a reasonable conceptual basis for many of the factors in Goldstein and Goldberg (2023), further quantitative analysis and validation is considered warranted before such approaches can be reliably adopted.

Evaluations of published empirical attenuation factors and potentially frameworks such as described in Goldstein and Goldberg (2023) may be useful when conducting site-specific assessments. Such evaluations can be used to refine the conceptual site model, estimate initial screening attenuation factor ranges or help constrain modeling results.

8.8 Which Media Should be Used in Site-Specific Assessment?

We recommend collection of soil vapour samples where and when possible, to evaluate the vapour intrusion pathway, except under conditions described below.

When groundwater is in contact with part of the building foundation, *e.g.*, a tanked underground parking garage (and requirements for use of attenuation factors in ENV *Protocol* 22 are followed), caution must be followed when considering the representativeness of different media. Because of the possible significant attenuation in VOC concentrations across the capillary transition zone, use of measured soil vapour concentrations alone may not be appropriate for this scenario depending on the site conditions. Instead, both soil vapour concentrations, and groundwater concentrations and equilibrium partitioning estimates performed using the Henry's law constant are recommended as a multiple lines of evidence approach. We note there is little available research on partitioning and models for use in estimation of vapour intrusion for the direct contact pathway.

While soil vapour measurements are otherwise strongly preferred, we note that there may be instances when from a site characterization and economic standpoint, it could be desirable to use available soil and groundwater concentration data and partitioning relationships, for example, when VOC concentrations in soil or groundwater are at low or non-detect concentrations. We note that ENV Technical Guidance 4 allows for use of soil and groundwater concentration measurements. The use of soil and groundwater concentration measurements should be consistent with the conceptual site model, including the following considerations:

1. Soil or groundwater concentration data should not be used when there is a mobile or residual NAPL source (see Table 3-4 in ITRC (2014) for indicators of the presence of petroleum NAPL). In this circumstance, soil vapour sampling in or close to the NAPL source should be performed.
2. Generally, both groundwater-to-soil vapour partitioning and soil-to-soil vapour partitioning calculations should be performed using representative concentration data. The soil vapour concentration resulting in the highest predicted indoor air concentration should generally be used (in some cases with sufficient data a statistical approach may be implemented).
3. It may be appropriate to use groundwater as the sole media for evaluation of soil vapour if there is a dissolved plume only and soil concentrations are non-detect. It may be appropriate to use soil as the sole media if there is a deeper-water table and no dissolved plume. We note Technical Guidance 4 indicates to "collect soil and groundwater samples" for use in partitioning relationships. Therefore, consider seeking input from ENV on which media data to use.

8.9 What Partitioning Models are Available?

Conventional partitioning models for equilibrium partitioning between absorbed (into soil organic carbon), water and vapour phases (three-phase model), between the water and vapour phases (Henry's law constant partitioning) and volatilization from the NAPL phase based on Raoult's law partitioning are well understood and documented in the literature with examples available in CCME (2014) and Health Canada (2023). It is recommended that the Henry's law constant be corrected for the site temperature following accepted methods (*e.g.,* Health Canada 2023). There do not appear to be operationally practical modifications to equilibrium-based models or biphasic models that can be confidently used in standards-based assessments following ENV Technical Guidance 4.

The jurisdictional review indicates that the CCME in the development of the Canada-Wide Standards for Petroleum Hydrocarbons incorporated a soil-to-soil vapour partitioning adjustment factor of 10 times to decrease the predicted soil vapour concentration in the derivation of the PHC fractions soil standards. The scientific rationale for the CCME 10 times adjustment factor is described in Section 4.0 of this report. The empirical data analysis conducted for this study also supports a 10 times adjustment factor for petroleum hydrocarbon compounds such as BTEX for a lower concentration (non-NAPL) scenario. Because the 10 times adjustment likely reflects an aerobic biodegradation component, in addition to non-equilibrium partitioning, the adjustment only applies to aerobically-degrading substances. The recommended criteria for determining whether petroleum NAPL is present was previously described in this report (Sections 6.0 and 8.6). When similar conditions exist in a site-specific assessment, it may be appropriate to incorporate a 10 times adjustment factor to the equilibrium soil-to-soil vapour partitioning model.

8.10 How can Lateral Vapour Attenuation be Incorporated?

8.10.1 Application of *Protocol* 22 Attenuation Factors

The applicability of vertical attenuation factors in *Protocol* 22 to lateral contamination sources is a question asked by practitioners. Conceptually, vapours from a vadose zone source that is laterally offset from a subsurface building wall will migrate in multiple directions (upward, downward, and radially) compared to a source below a building where vapours will mostly migrate vertically upward toward the building. The potential for vapour intrusion through the walls and base of a building are expected to be similar (for vapours that migrate to the building). Consequently, greater attenuation will tend to occur for a source that is laterally adjacent to a building compared to vertically below a building. The Johnson and Ettinger (1991) model, while formulated as a one-dimensional model, for a dirt floor scenario, simplifies to the following term:

$$D_{eff} \times A_b / (L_T \times Q_b)$$

Where:

D_{eff} = the effective diffusion coefficient.

L_T = is the distance between the building and vapour source.

Q_b = is the building ventilation rate.

The A_b term is defined in Johnson and Ettinger (1991) as the "*cross-sectional area through which vapours pass*", which can be approximated by the subsurface area of the walls and base of the foundation (note the area includes the walls). Therefore, while the conceptual basis for the Johnson and Ettinger model is one-dimensional transport (from a source that typically is below building), applying the model in one-dimension to a lateral source does not appear to violate the model assumptions. Therefore, use of *Protocol* 22 attenuation factors for a lateral source is considered valid.

8.10.2 Site-Specific Modeling of Lateral Attenuation

Under a site-specific modeling approach, consideration could be given to two possible lateral modeling methods: 1) adjust the source vapour concentration to represent a lateral source (Figure 5), and 2) adjust the Johnson and Ettinger model inputs to represent a lateral source. Either method may be used (but not both).

The maximum soil vapour concentration is commonly used in risk assessment. If there is rationale to adjust the soil vapour concentration, a statistical estimation method may be used to estimate the average concentration along or near to the walls and base of the foundation. Statistical estimation methods may include a weighted average area estimation method or a contouring method. A conservative approach should be followed because of the often-spatial uncertainty associated with soil vapour data.

The Johnson and Ettinger model assumes a laterally uniform source and vapour migration through the subsurface walls and base of the building. Two possible adjustments may be considered to input values: 1) modification of Qsoil or Qsoil/Qbuild terms or 2) modification of the area of the subsurface building foundation term, Ab, both intended to account for contaminant soil gas advection or migration that is only occurring over a portion of the subsurface building envelope. For the first adjustment, see Hers et al. (2003) and Johnson (2005) for possible ways to adjust these terms based on building footprint area or crack length. The second adjustment requires that the volume of the building input in the model remain as the entire volume of building subject to vapour mixing, an adjustment that may not be available in some formulations of the model. The modification of the Johnson and Ettinger model should be conducted by knowledgeable modelers.

The required conditions for adjusting these parameters for a lateral vadose zone source are as follows:

1. The vapour source should be well characterized. Soil vapour data below and on all sides of the building are required. The method can also potentially be used when the lower part of the building is in contact with groundwater through a combination of groundwater and soil vapour data.
2. The enclosed building compartment in which vapours migrate into should be open and connected space that is well mixed.
3. When evaluating the area subject to vapour migration for a laterally adjacent source, consider that vapours may move around the sides of and below the building. A conservative approach should be followed.
4. The above approaches should not be used if there is the potential for vapour intrusion through preferential pathways.

The above approaches are most well suited to large buildings with open well-ventilated space such as an underground parking garage.

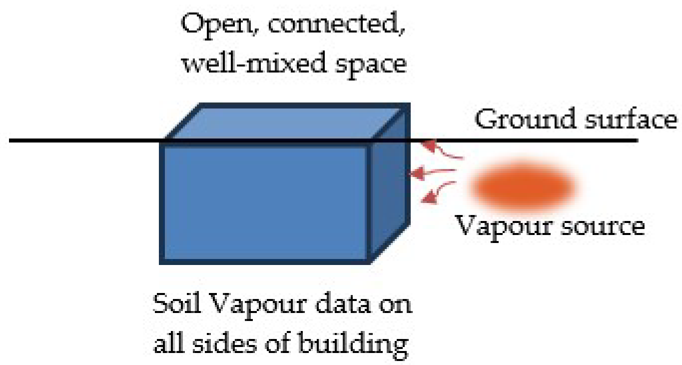

Figure 5 **Conceptual Model for Lateral Vapour Migration Adjustment of Vapour Source or Cross-sectional Area to Vapour Migration in Johnson and Ettinger model**

Lowell and Eklund (2004) describe an analytical model for lateral vapour attenuation that is based on two-dimensional diffusive transport. Nomographs allow the vapour attenuation to be estimated for varying lateral and vertical distances to a building. The source assumptions should align with model assumptions, *i.e.*, a sharp boundary vapour contamination source.

8.11 Can Similar Approaches to those Described for Lateral Migration be Used for Below-Building Vapour Sources?

Yes, provided that the same criteria listed above for lateral migration adjustment are met. For below-building vapour sources, the above approaches are most well suited to a large "big-box" type building with open, connected, well-mixed indoor space.

8.12 Can Mass Flux or Discharge be Incorporated in Site-Specific Assessments?

Possibly, yes. When there is a dissolved groundwater plume originating from an upgradient source that is migrating below a building, the mass available for volatilization and possible intrusion is constrained by the mass discharge in flowing groundwater. In some cases, *e.g.*, for a slow-moving groundwater plume with low mass discharge, the vapour attenuation factor may incorporate a mass discharge to the building that is unrealistically high. This model only applies to longer-term time-averaged fluxes or discharges and does not address short-term variability. It requires appropriate characterization of the groundwater mass discharge. A mass discharge check or model is included in the Health Canada (2023) guidance and the GSI Tier 2 Toolkit.

8.13 Can Source Depletion be Incorporated in Site-Specific Assessments?

Likely no, as there are few instances when incorporating source depletion is practical or appropriate without detailed analysis and regulatory input.

Johnson and Ettinger (1991) conceptually described how based on a physical mass-balance model and "peeling of the onion" approach, the contaminant depletion zone starting closest to building increases with time, and vapour transport distance correspondingly also increases. Following this approach, the time for the entire thickness of contamination to deplete can be calculated.

The GSI Tier 2 Toolkit includes an option to include source depletion based on multiple processes (diffusion, biodegradation, leaching) but the model is based on a bare-ground condition. Zhang *et al*. (2019) presented a source depletion model based on the Johnson and Ettinger model framework and compared results to the GSI Tier 2 toolkit.

Based on a mass balance approach, the time for the contamination source to be entirely depleted can be calculated, and if less than the exposure period, the dose can be averaged over the exposure period. While computationally feasible, source depletion is rarely considered in vapour intrusion modeling because of the uncertainty in source mass and incompatibility with risk assessment conventions and toxicological principles where dose averaging may only be acceptable under limited conditions and for certain chemicals.

9.0 CONCLUSIONS AND RECOMMENDATIONS

A comprehensive review of vapour intrusion attenuation and chemical partitioning relationships with focus on the shallow contamination scenario has been completed. Research on vapour attenuation factors and partitioning is warranted because the vapour intrusion pathway is often the driver for remediation of sites in British Columbia. New, and potentially less conservative approaches and methods are needed for this pathway, including when there is shallow contamination. A conceptual site model for vapour intrusion was developed that focusses on the building, and near- and within building processes for vapour intrusion to complement already available conceptual models that address subsurface processes. A jurisdictional and literature review were completed, and a database study was conducted where new data from sites in British Columbia were compiled and analyzed.

The key findings of the **jurisdictional review** include:

- Canadian regulatory regulations or guidance reviewed implement a generic or semi-site specific approach where empirical shallow or subslab soil vapour-to-indoor attenuation factors are used to estimate indoor vapour concentrations when there is a shallow vapour source or vapour measurement, and the Johnson and Ettinger model is used to derive vapour attenuation factors for a deeper source. The threshold distance for the two approaches varies between 0.3 and 1 m depending on jurisdiction and in some cases media.

- Canadian regulatory empirical subslab soil vapour-to-indoor attenuation factors recommended in the guidance reviewed are:
  - Residential buildings: 0.01 to 0.03.
  - Commercial and industrial buildings: 0.004 to 0.02.
- Most U.S state agencies reviewed adopt a generic empirical attenuation factor approach where vapour attenuation factors recommended by U.S. EPA (2015a) are in part or in whole adopted. The generic U.S. EPA attenuation factors are as follows:
  - Subslab soil vapour-to-indoor air of 0.03.
  - External soil vapour-to-indoor air of 0.03.
  - Groundwater-to-indoor air of 0.0005 to 0.001 depending on soil texture.
- Several states recommend a lower empirical subslab-to-indoor air attenuation factor of 0.01 for commercial and industrial buildings.
- In US guidance, site-specific modeling is generally a line of evidence that must be supported or validated by other data, although several state guidance reviewed include constrained modeling approaches that can be followed, for example, to adjust attenuation factors based on soil type, or for a future building scenario when subslab soil vapour data can not be obtained.
- In US guidance, several jurisdictions reviewed (U.S.EPA, State of Washington, California, New Jersey, Georgia) indicate that when the depth to groundwater or contamination is less than five feet a conventional investigation approach may be inadequate and subslab soil vapour or indoor air sampling (or other strategies) should be considered.
- Aside from Michigan, none of the jurisdictions (other than BC) reviewed have factors or models to estimate attenuation for when contamination or groundwater is in direct contact with the building.

The key findings of the review of research on **vapour attenuation factors** were:

- The U.S. EPA (2012) database is the most comprehensive evaluation of vapour attenuation factors for low-density residential buildings and halogenated (primarily chlorinated) solvent chemicals, and the U.S. EPA (2015a) guidance attenuation factors are based on 95th percentile attenuation factors estimated from empirical data. Although a relatively large data set was used in the analysis and measures were taken to reduce the potential effect of indoor background sources on attenuation factors, potential limitations include variability in soil vapour concentration data and possibly non-representative outliers, which would tend to have the greatest effect on the spread or tails of the attenuation factor distribution (*e.g.*, the 95th percentile).

- Recent U.S. database studies of commercial/industrial buildings or residential/ commercial/ industrial buildings indicate representative shallow soil vapour or subslab soil vapour-to-indoor air attenuation factors of 0.005 or lower. The representative groundwater-to-indoor air attenuation factors for commercial/industrial buildings are 0.0001 although less data was available for groundwater compared to subslab or soil vapour data.

The key findings of the review of **partitioning models and data** are:

- Review of case studies indicates predicted soil vapour concentrations estimated from dissolved groundwater concentrations and Henry's law are often higher than measured soil vapour concentrations above the capillary transition zone, with the difference in measured and predicted concentrations generally being greater for fine-grained than coarse-grained soil. However, a consistent and significant difference was not observed either based on site condition or contaminant type with the implication that a generic empirical adjustment to Henry's law partitioning is likely not warranted.
- Empirical studies comparing co-located soil and soil vapour concentrations indicate the three-phase equilibrium partitioning model often significantly over-predicts measured concentrations (excepting when NAPL is present). Conventional equilibrium partitioning models are lacking but operationally it is challenging to develop a practical theoretical model that more accurately quantifies partitioning. Adjustment of soil partitioning models using an empirical factor is a possible feasible approach.

The key findings of the **empirical data analysis** of data collected for this project were:

- Media concentration data from 28 sites in British Columbia were obtained (7 sites in Phase 1 and 21 sites in Phase 2), data were filtered according to quality criteria, and analysis of paired soil-soil vapour and groundwater-soil vapour and comparisons to linear equilibrium partitioning models were performed. The filtered database consisted of 234 groundwater-soil vapour or soil-soil vapour data-pairs (171 pairs in Phase 1 and 63 pairs in Phase 2).
- Estimated soil vapour concentrations from the theoretical three-phase equilibrium partitioning model and soil concentrations were generally at least one order of magnitude greater than the measured vapour concentrations for PHCs.
- A closer match was obtained between measured and predicted groundwater concentrations.
- Measured indoor air data was available for only three sites, with too few data to derive meaningful trends. At two sites, with commercial or industrial buildings, the subslab vapour to indoor air attenuation factors were 1.6E-5 and 0.005 to 0.008, respectively.

The implications and recommendations of the research are provided in the context of a site-specific risk assessment approach in British Columbia:

- A site-specific modeling approach to derive risk-based standards without supporting or confirmatory data is generally not considered appropriate for low-density residential land use. This is because of the uncertainty in intrusion processes and future conditions of residential buildings. In these cases, indoor air sampling (in conjunction with soil vapour and/or slab sampling to rule out potential background indoor air impacts) is recommended. A site-specific modeling approach that is constrained may be appropriate for high-density residential (*e.g.,* underground parking garage scenario), commercial and industrial land use and buildings. More broadly site-specific modeling can be a valuable supporting line of evidence when evaluating CSM processes and factors.
- A site-specific modeling approach should only be conducted when there is a minimum distance of 0.3 m from the base of the building to seasonal high groundwater level or water table, excepting parkades as previously defined. Sufficient data should be collected to support this determination. When there is only soil contamination within 0.3 m of the foundation (but no residual or continuous phase NAPL or groundwater), subslab soil vapour data and empirical or modeled attenuation factors may be used.
- When site-specific modeling is used to derive a vertical attenuation factor in support of a risk-based standard, it is recommended that the modeling be constrained such that there is no more than ½ an order of magnitude reduction in the attenuation factor relative to attenuation factors in *Protocol* 22, unless the model is calibrated or validated with site-specific data.
- For a residential land use scenario, a subslab soil vapour-to-indoor air attenuation factor of 0.02 is recommended. For a commercial or industrial building scenario, an empirical attenuation factor of 0.01 is considered conservative and applicable to the expected range of high-density residential, commercial, and industrial buildings for use in site-specific assessment. Lower empirical attenuation factors (*e.g.,* on the order of 0.005) may be appropriate, for example, for larger buildings with higher ventilation rates. Note the *Protocol* 22 parkade attenuation adjustment factor should not be applied to a site-specific vapour attenuation factor.
- A 10X adjustment factor to reduce the predicted soil vapour concentration from the soil concentration using the conventional equilibrium three-phase partitioning model is considered appropriate for PHC compounds (*e.g.,* BTEX, trimethylbenzenes, VPH) when there is only soil contamination (no NAPL).
- For a vapour contamination source that is laterally adjacent to one-side of the building or only below a portion of the building, methods are provided to enable adjustment of either the

source vapour concentration or Johnson and Ettinger model terms. More complex two-dimensional models are also available for estimation of lateral vapour attenuation.

The findings of this study support the refinements in vapour investigation described for sites with shallow contamination. While conceptually some vapour attenuation will occur between a shallow subsurface contamination source and indoor air, several factors are considered to preclude attenuation factors for direct groundwater building contact pathway including complexity of processes, lack of validated models (excluding underground parkades), and heightened concern for possible direct exposure to contamination. With further research and development, use of direct contact models may become an option.

While development of methodology is beyond the scope of this report, there may be alternative approaches that could provide relief when groundwater is in contact with a building based on a background concentration approach. For example, consideration could be given to adjusting the vapour (indoor air) standard if the ambient (outdoor) concentration is greater than the standard and is associated with regional air quality impacts. Another approach could be to conduct site-specific background measurements of soil vapour concentrations in areas unaffected by contamination, and to use applicable site-specific attenuation factors to adjust the vapour (indoor air) standards. These methods are not currently available under the BC regulatory regime.

10.0 LIMITATIONS

This report was prepared by Millennium EMS Solutions Ltd., Hers Environmental Consulting Inc. and Arcadis Canada Inc. for Contaminated Sites Approved Professionals Society (CSAP Society) of British Columbia, and has been completed in accordance with specific terms of reference. This report does not necessarily represent the views or opinions of CSAP Society.

Vapour assessment involves a number of uncertainties and limitations. As a consequence, the use of the process presented herein to develop site management strategies may either be overly protective or may not necessarily provide complete protection to human receptors or prevent damage of property in all circumstances. The process presented herein was determined in accordance with generally accepted protocols. Given the assumptions indicated, the process presented herein is expected to provide a conservative estimate of the risks involved. The services performed in the preparation of this report were conducted in a manner consistent with the level of skill and care ordinarily exercised by professional engineers and scientists practising under similar conditions.

While preparing this report, some proprietary algorithms, methods, compilations, processes, designs, formulas, and/or techniques, may have been used and advanced technologies for simulation, information modeling, generative design, and the development of project documentation (the "Technical Tools") employed. The Technical Tools may be further used to create data sets and result in simulations or models (collectively, the "Datasets") that may be included in this report. Both the Technical Tools and the Datasets are by-products of the internal processes and shall belong solely to Millennium. No unauthorized use of the Technical Tools or Datasets is permitted.

The results and interpretations included in this report do not represent any specific site. Millennium, Hers and Arcadis accept no responsibility for foreseeable or unforeseeable damages, or direct or indirect damages, if any, suffered by any party as a result of decisions made or actions taken based on the use of this report, including but not limited to damages relating to delay of project commencement or completion, reduction of property value, and/or fear of, or actual, exposure to or release of toxic or hazardous substances.

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APPENDIX A: JURISDICTIONAL REVIEW OF VAPOUR ATTENUATION FACTORS IN USA

Appendix A – Jurisdictional Review of Vapour Attenuation Factors in USA

This appendix reviews select U.S. state guidance on vapour attenuation factors.

1.0 CALIFORNIA

California Department of Toxic Substances Control (CA DTSC) (2023) guidance recommends the use of empirically derived attenuation factors for groundwater (0.001) and soil vapour (0.03) published by U.S. EPA (2015a) for evaluation of residential and commercial use buildings. Soil gas samples are recommended as the primary line of evidence for evaluating VI risk when groundwater is contaminated. Soil gas data should be collected from sample depths immediately above the known or suspected highest concentrations of subsurface contamination. Soil gas concentrations collected just above the source of contamination are indicated to be better correlated with subslab soil gas concentrations. Groundwater shallower than five feet beneath a building is a site condition that may warrant indoor air sampling. In this scenario, collecting soil gas samples may not be possible, as soil gas samples may be impacted by the capillary fringe, or soil gas samples can be biased low from breakthrough of ambient air. The use of mathematical models to derive attenuation factors for screening is not recommended but may be an option as a line of evidence in a detailed assessment.

When subslab soil gas sampling is not feasible, use of the Johnson and Ettinger model may be appropriate in consultation with the regulatory oversight agency. The model must be configured such that the attenuation factor between the subslab soil gas concentration and indoor air concentration is 0.03, which is equivalent to the empirical attenuation factor adopted by CA DTSC. To achieve a subslab attenuation factor of 0.03, a very high Qsoil / Qbuild value needs to be selected (where Qsoil is the soil gas advection rate and Qbuild is the building ventilation rate), which generally is unrealistic for all building types, and particularly so for larger commercial or industrial buildings.

2.0 MINNESOTA

The potential VI risk is assessed by collecting subslab soil gas samples below a building. A subslab soil gas-to-indoor air attenuation factor of 0.03 is applied in site screening (Minnesota Pollution Control Agency (MPCA) 2020). The guidance framework decision whether to mitigate is based on *potential* VI risk and subslab soil gas data (indoor air testing is not part of this framework). Where the potential for VI is higher based on building conditions (*e.g.,* crawlspace, earthen floor), a deeper subslab soil gas sample (3 feet below building) may be collected. If there is a shallow groundwater table that precludes deeper soil gas sampling, this is one condition where paired indoor and outdoor air samples may be obtained to assess the potential VI concern.

3.0 MASSACHUSETTS

Massachusetts Department of Environmental Protection (MassDEP) has developed screening criteria for subslab soil gas results that can be used in a lines of evidence evaluation of vapour intrusion (MassDEP 2016). The subslab soil gas-to-indoor air attenuation factor to be used in such assessments is 0.074. For groundwater, the GW-2 standard for the vapour inhalation pathway was estimated using the Johnson and Ettinger model for a source-receptor separation distance of 0.3 m. The corresponding groundwater-to-indoor air attenuation factor is approximately 0.0008 (calculated by authors for benzene using stated input parameters).

4.0 WISCONSIN

Wisconsin DNR (2018) uses the default attenuation factors listed in Table A-1 to calculate vapour risk screening levels (VRSLs). The factors are grouped by land use and building size (residential/small commercial *vs*. industrial/large commercial). The distinction between small and large commercial is qualitative, for example, a former home used as a retail store is small commercial, while a storage warehouse is large commercial. The shallow contamination scenario is not specifically addressed in the context of generic attenuation factors.

Table A-1. Wisconsin Vapor Intrusion Factors (https://widnr.widen.net/s/xnmrpgkqqr)

MEDIA	RESIDENTIAL & SMALL COMMERCIAL	INDUSTRIAL & LARGE COMMERCIAL[(a)]
Crawl Space	1	1
Sub-Slab Vapor	0.03	0.01
Soil Gas [(b)]	0.03	0.01
Deep Soil Gas/Utility[(c)]	0.01	0.001
Groundwater[(d)]	0.001	0.0001

a. The size, foundation condition, ceiling height, interior partitioning, and HVAC of a building should be provided to support using the default industrial/large commercial attenuation factors.

b. Soil Gas: These factors will apply to most soil gas samples. These are samples collected outside the footprint of a building, typically within 5 feet of the depth of the building foundation and at least 3 to 4 feet below ground surface.

c. Deep Soil Gas: These factors apply to limited situations where soil gas can only be collected from deeper than 5 feet below the depth of the building's foundation or when utility is the only potential vapor migration pathway onto a property. Use of a deep soil gas attenuation factor may not be allowed for CVOC; however, the case for using this factor for CVOCs strengthened when geologic conditions can be shown to limit vapor migration (*e.g.*, dense clay till between vapor source and building).

d. Groundwater: Groundwater concentrations posing a potential vapor risk can be calculated from the Henry's Law constant for a contaminant, which defines partitioning into the vapor phase from groundwater at the water table. With two exceptions: 1) use sub-slab vapor attenuation factor if contaminated groundwater is located within a few feet of the depth of a building's foundation or 2) if PCE or TCE > NR 140 ES at the water table, then vapor sampling is almost always needed to rule out the vapor pathway in overlying buildings.

Development of a site-specific attenuation factor is not allowed for residential buildings but is possibly allowed for large residential buildings (*e.g.,* school), mixed use buildings or commercial buildings, and is allowed for industrial buildings. The preferred method for estimating a site-specific attenuation factor in an industrial building is a tracer test.

5.0 MICHIGAN

Michigan Department of Environment, Great Lakes, and Energy (EGLE) (2020) updated their soil gas volatilization to indoor air screening levels on September 4, 2020. https://content.govdelivery.com/accounts/MIDEQ/bulletins/29fb99a. A shallow soil gas-to-indoor air attenuation factor of 0.03 is used in the derivation. EGLE (2024) has developed a groundwater screening level calculated for groundwater in contact with a non-residential building that includes intrusion through two mechanisms: diffusion through bulk concrete and volatilization of contaminants from sump water or water in other openings (model is not intended for residential buildings). Diffusive transport through bulk concrete is estimated using an attenuation factor of 0.03, *i.e.,* the groundwater criteria is back-calculated from a soil vapour criteria estimated using an attenuation factor of 0.03 and Henry's law constant. The volatilization factor for sump water utilizes mass transfer coefficients, according to methodology in Marti *et al.* (2014). The model is not currently provided by EGLE, but calculations are performed for consultants by EGLE. Michigan has developed a big building model (BBM) where with sufficient soil gas or subslab gas data, a weighted average estimation method may be used to estimate soil gas concentrations for comparison to screening values for "big" buildings that meet method criteria.

6.0 WASHINGTON

Washington Department of Ecology (DOE) (2022) guidance describe a methodology for calculating groundwater and soil vapour screening levels where the U.S. EPA generic vapour attenuation factors of 0.001 and 0.03, respectively, were adopted. When there are laterally extensive layers of fine-grained vadose zone soil, DOE will consider an attenuation factor of 0.0005 on a case-by-case basis. For commercial and industrial buildings, DOE will consider site-specific derivation of attenuation factors. One approach cited in the guidance for empirically determining factors for commercial and industrial buildings is provided in a paper by Ettinger, *et al*., titled: *Empirical analysis of vapor intrusion attenuation factors for sub-slab and soil vapor: An updated assessment for California sites.* This paper was presented at the Air and Waste Management Association Vapor Intrusion, Remediation, and Site Closure Conference in Phoenix, Arizona, on December 6, 2018. While predictive modeling provides another line of evidence when evaluating the potential for VI, models should not be used as the sole method to support a "screen-out" determination. Further evaluation and/or mitigation is needed if the seasonal high-water table is very shallow, generally within five feet of the building's lowest floor.

This can include a) collection of soil gas data; b) collection of indoor air data; or c) implementing mitigation measures.

7.0 NEW JERSEY

New Jersey Department of Environmental Protection (NJDEP) (2022) indicate the Soil Gas Screening Level (SGSL) incorporate a soil gas-to-indoor air attenuation factor of 0.02. The depth of the soil gas sample should be a minimum of 5 feet below the surface and above the capillary fringe. If a shallow groundwater table prevents the collection of soil gas samples, an alternative is to collect soil gas samples from below existing large impervious surfaces (*e.g.,* garage floors, patios, parking lots, roads, and driveways) immediately adjacent to the building.

The Ground Water Screening Level (GWSL) tables are calculated using the Johnson and Ettinger model. For benzene, the groundwater-to-indoor air attenuation factor calculated by the model is 0.0017 (calculated by the authors). However, the default GWSL for petroleum-related compounds (*e.g.,* BTEX) is calculated with an additional attenuation factor of 0.1 to account for aerobic biodegradation. The minimum depth for application of the GWSL is not specified although the distance between the building and groundwater in the default model is 5 ft. The NJDEP also includes as an option distance-based screening for PHCs.

Site-specific attenuation factors may be calculated as a line of evidence using the NJDEP supplied Johnson and Ettinger spreadsheets. These assessments are subject to greater DEP scrutiny. Only certain parameters may be adjusted, for example, the distance between the building and groundwater and soil texture.

For determining monitoring and mitigation requirements, the NJDEP guidance provides recommendations following an exceedance ratio approach (*e.g.,* 10X). For example, where the soil gas results do not exceed the Department's SGSL, but groundwater quality exceeds the Department's GWSL by greater than 10X, the investigator should consider additional soil gas investigation (based on professional judgment) to confirm the initial findings.

8.0 GEORGIA

Georgia Environmental Protection Division (EPD) (2021) adopted the generic U.S. EPA groundwater-to-indoor attenuation factors of 0.001 applicable to coarse-grained soil, and 0.0005 for fine-grained soil. Use of generic attenuation factors must be supported by a water table > 5 ft. below the base of the foundation and no preferential pathways. There are two options to derive site-specific attenuation factors for commercial buildings:

1. Model-supported value for attenuation factor that must fall between < 0.0005 and >= 0.0002 and soil classification performed.
2. Model-supported value with no bounds if model results are validated.

The generic U.S. EPA soil gas-to-indoor and subslab soil gas-to-indoor air attenuation factors of 0.03 are adopted for residential land use. For commercial land use, a generic attenuation factor of 0.01 is provided for a slab-at-grade building foundation.

There are two options to derive site-specific soil gas and subslab soil gas-to-indoor air attenuation factors for commercial buildings:

1. Model-supported value for attenuation factor that must fall between < 0.01 and >= 0.006.
2. Model-supported value with no bounds if model results are validated.

Appendix B: Vapour Attenuation Factor Research

APPENDIX B – Vapour Attenuation Factor Research

This appendix reviews select research studies on vapour attenuation factors.

1.0 U.S. EPA (2012) DATABASE STUDY OF RESIDENTIAL BUILDINGS

U.S. EPA (2012) report on a large empirical database of paired subsurface media (groundwater, soil gas, subslab soil gas) to indoor air concentrations for primarily chlorinated solvents and residential buildings. When data was filtered using factors considered most effective at minimizing the influence of background sources on indoor air concentrations, the 95th percentile groundwater-to-indoor air, soil gas-to-indoor air and subslab soil gas-to-indoor air attenuation factors were 1.2E-03, 2.5E-01 and 2.6E-02, respectively (Table B-1). The way in which the background filter works is, for example, for subslab soil gas, all data with subslab concentrations lower than 50X the median of the 90th percentile background concentrations calculated from multiple literature studies was screened out. Higher multipliers than 50X did not result in a significant reduction in the 95th percentile concentration.

Table B-1. Empirical Soil Vapour Attenuation Factors from U.S. EPA (2012) Study

Table 19. Descriptive statistics summarizing attenuation factor distributions for groundwater, exterior soil gas, subslab soil gas, and crawlspace vapor after application of the database screens considered most effective at minimizing the influence of background sources on indoor air concentrations.

Statistic	Groundwater (GW > 1,000X Bkgd)	Exterior Soil Gas (SG > 50X Bkgd)	Subslab Soil Gas (SS > 50X Bkgd)	Crawlspace (IA > Bkgd)
Min	1.0E-07	5.0E-06	2.5E-05	5.7E-02
5%	3.6E-06	7.6E-05	3.2E-04	1.0E-01
25%	2.3E-05	6.0E-04	1.5E-03	2.2E-01
50%	7.4E-05	3.8E-03	2.7E-03	3.9E-01
75%	2.0E-04	2.7E-02	6.8E-03	6.9E-01
95%	1.2E-03	2.5E-01	2.6E-02	9.0E-01
Max	2.1E-02	1.3E+00	9.4E-01	9.2E-01
Mean	2.8E-04	5.0E-02	9.2E-03	4.6E-01
StdDev	1.0E-03	1.7E-01	5.0E-02	2.8E-01
95UCL	3.4E-04	7.8E-02	1.3E-02	5.3E-01
Count All	774	106	431	41
Count >RL	743	106	411	41
Count <RL	31	0	20	0
No. of sites	24	11	12	4

Note: The applied database screens are groundwater (vapor) concentrations > 1,000X "background," exterior soil gas > 50X "background," subslab soil gas > 50X "background," and for crawlspace, indoor air concentrations > 1X "background."

2.0 REVIEWS OF U.S.EPA EMPIRICAL ATTENUATION FACTOR DATABASE AND MODELED ATTENUATION FACTORS

Brewer *et al.* (2014) considered that of the potential sources of error in the U.S. EPA vapor intrusion database, spatial variability of VOC concentrations in subslab soil gas is likely the most significant. Consequently, instead of an empirical approach, a modeling approach based on outdoor temperature was proposed to derive subslab soil gas-to-indoor air attenuation factors for U.S. regions for residential buildings, which range from 0.0005 in tropical areas to 0.0032 for colder areas.

Song *et al.* (2011) reviewed an earlier version of the U.S. EPA database and had various criticisms of which many were addressed in U.S. EPA (2012). An intrinsic limitation noted was that many of the data points were from a smaller number of sites. Yao *et al.* (2018) considered that the variability of measurements in the U.S. EPA's VI database could be partially caused by inaccurate source characterization and/or by the potential presence of preferential pathways that could affect the attenuation factor for some buildings. Based on Yao *et al.* (2018) questions on the accuracy of the empirical groundwater-to-indoor air attenuation factor, a modeling study was completed to estimate groundwater-to-indoor air attenuation factors. A key input in the model was vertically varying soil moisture within the capillary fringe and overlying soil. Using what were considered conservative inputs for a non-degrading chemical, a groundwater-to-indoor air attenuation factor of 0.0001 was estimated.

2.1 Folkes *et al.* (2010) Study of Redfield, Colorado, USA Residential Homes

Seasonal individual point-in-time groundwater to indoor air 1,1-DCE attenuation factors ranged from 1E-04 to 1E-06 in five homes at the Redfield site in Colorado, USA (Folkes *et al.* 2010). The seasonal variability in individual homes was about one order of magnitude. Soils consist of silty, clay loess with sand lenses and depth to groundwater is 10 to 20 ft. There was a poor to fair correlation between groundwater and indoor air concentrations (R^2 = 0.02 to 0.58) although the correlation may have been affected by out of phase groundwater and indoor air concentration variation (*i.e.,* an increase or decrease in source concentrations would take time to influence concentrations at points along the vapour transport pathway).

2.2 Pennell *et al.* (2016) Study of Massachusetts, USA Residential and Commercial Buildings

Pennell *et al.* (2016) reported on a monitoring and modeling assessment of vapour intrusion into three buildings in Massachusetts, USA. Properties A and B were multi-family homes with basements (5.5 ft depth) and Property C was a slab-on-grade commercial property. Soils were loamy sand to sandy clay and the depth to the water table was approximately 7 ft. Quarterly monitoring of groundwater and indoor air concentrations indicated groundwater-to-indoor air attenuation factors at Properties A and C ranged from 10-4 to 10-6. Soil gas monitoring directly above the capillary fringe indicated about 1,000X attenuation across the capillary fringe, and hence this high-water content layer was a resistive layer to vapour transport. Modeling incorporating variable moisture layers including a capillary fringe indicated mid-point attenuation factors of 7E-06 for the Johnson and Ettinger model and 3.1E-06 for a numerical model compared to a measured attenuation factor of roughly 1E-05. These data suggest measured and modeled attenuation factors were within one order of magnitude. Monitoring of Property B indicated indoor air vapour intrusion occurred through the sewer pathway and thus was addressed separately in terms of attenuation analysis.

2.3 Derycke *et al.* (2018) Study of Schools in France

Derycke *et al.* (2018) analyzed paired subslab soil gas and indoor air samples for VOCs from 51 schools in France. After data filtering, including selecting halogenated VOCs for detailed analysis, there were 102 paired samples in the database. Principal component analysis on possible site factors affecting vapour intrusion indicated the age of building (with 50 years as the cut-off between old and new buildings) had the greatest influence on the vapour attenuation factor (Table B-2).

Table B-2. HVOC Subslab Soil Gas-to-Indoor Air Attenuation Factors for Database of Testing of Schools in France (from Derycke *et al.* 2018)

	Number	50th Percentile	90th Percentile
All ages	102	0.0004	0.0078
< 50 years	70	0.0003	0.0075
‘> 50 years	32	N/A	0.037

2.4 Hallberg *et al.* (2021) and Levy *et al.* (2023) Study of Department of Defense Non-residential Sites in USA

Hallberg *et al.* (2021) reported on the results of a large empirical database study of non-residential buildings at primarily Department of Defence (DoD) sites in the USA. The database represents testing conducting at 76 buildings at 22 sites. The building footprints ranged from 1,600 to 800,000 square feet. The database includes both commercial and industrial buildings built between 1905 and 2011, with most uses commonly found at DoD installations (*e.g.,* maintenance, offices, storage). Analysis of indoor air–subslab soil gas (SSSG) data pairs found that there is substantially more attenuation occurring from SSSG to indoor air in DoD commercial and industrial buildings relative to residential buildings, and that the DoD buildings’ attenuation factors (AFs) are one to three orders of magnitude lower than US EPA’s residential-based default of 0.03 (Figure B-1). The author concluded the results support the use of a generic SSSG-to-indoor air AF of 10–3 (0.001) to support VI assessment and development of SSSG screening levels at large commercial and industrial buildings as an alternative to the residential default AF. A companion study by Levy *et al.* (2023) concluded that the DoD data support the use of a generic groundwater AF of 10^{-4} (0.0001) for conducting VI assessment and developing groundwater screening levels at large commercial and industrial buildings.

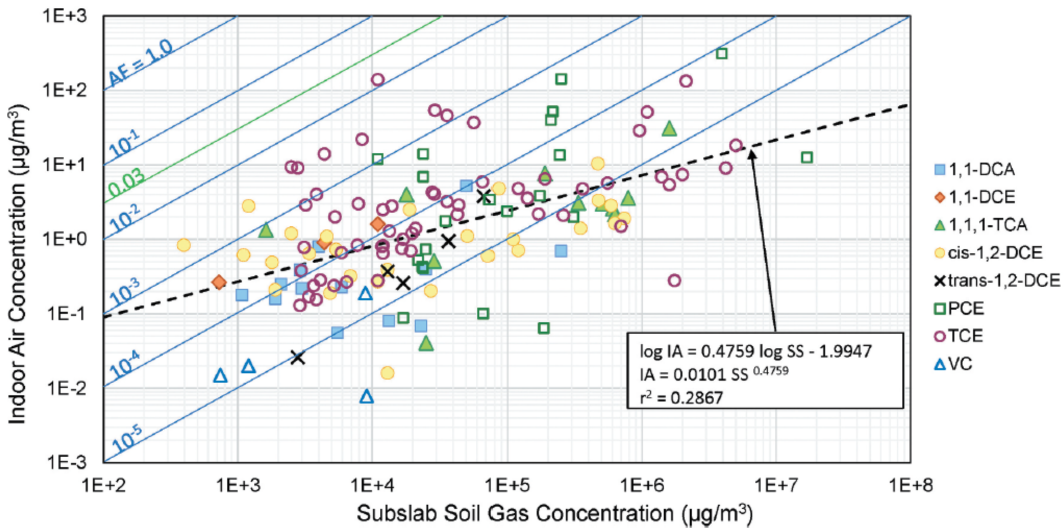


Figure 3. Plot of indoor air–SSSG data pairs for the VOCs included in the analysis. Each data point represents the average indoor air and SSSG concentrations for a building sampling zone for a given sampling event. Only pairs that passed the successive screening steps are included. Pairs with an indoor air concentration below detection limit are not shown. The blue oblique lines represent SSSG AF lines ranging from 10^{-5} to 1.0. The green line represents the EPA default AF of 0.03. Also shown is the linear best fit and associated equation with IA and SS representing the indoor air and SSSG concentrations, respectively.

Figure B-1. Plot of Indoor air – SSSG data pairs for VOCs in Hallberg *et al.* (2021) Study

2.5 Lahvis and Ettinger (2021) Study of California Attenuation Factors

Lahvis and Ettinger (2021) report on the analysis of a large vapour intrusion database of sites in California, USA comprised of residential, commercial, and industrial buildings. Beginning with a database of 8,415 paired indoor and subsurface vapour samples collected from 485 buildings at 36 sites, the data was filtered based on data quality criteria resulting in 788 soil vapour – indoor air pairs, with 82% of the data for trichloroethylene. Additional filtering was conducted based on TCE source strength compared to literature background indoor air TCE concentration to reduce the effect of background sources on indoor air concentrations (Figure B-2). The final TCE database used to derive the AF consisted of 643 soil vapor-indoor air pairs collected at 59 buildings from 12 sites. Approximately 72% and 28% of the data pairs were from residential and non-residential building types, respectively. Approximately 77% of the vapor data were exterior soil gas samples, with the remaining 23% subslab soil gas samples. Information on the depth of soil vapour samples was not reported. Using the final database and a reliability analysis (corresponding to < 5% false negatives), Lahvis and Ettinger (2021) derived a soil gas-to-indoor air attenuation factor of 0.0008. This attenuation factor is also likely representative of a subslab soil gas attenuation factor. Separate attenuation factors were not calculated for residential and non-residential building types because there was little difference in the results.

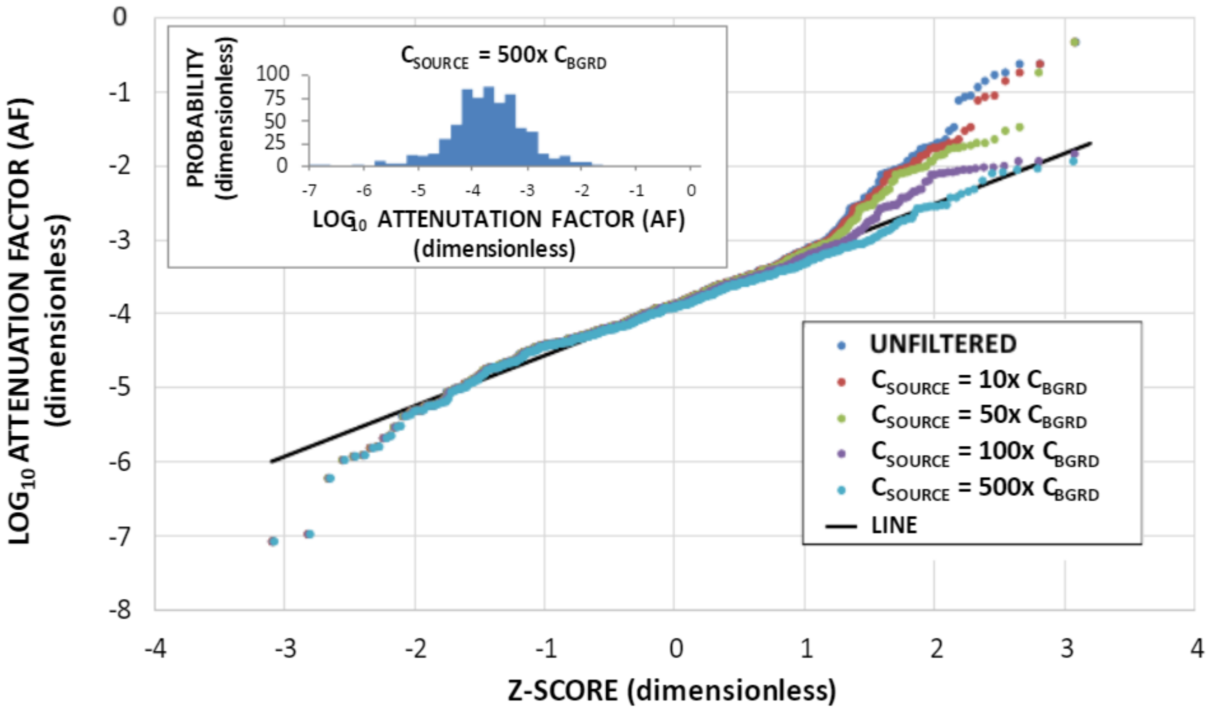


Figure B-2. Attenuation Factor Distributions for Varying Filtering Criteria from Lahvis and Ettinger (2021)

2.6 Eklund *et al.* (2023) Study of Mid-west, USA Industrial Facility Buildings

Eklund *et al.* (2023) reported on a large empirical study of attenuation of subsurface vapors occurring at a major facility in mid-west USA with multiple industrial buildings. Soil vapour data were collected at 718 unique locations across 77 buildings. Buildings investigated varied in age from recent construction to over 80 years old and building footprint areas varied from 3,000 to 120,000 square feet. The building uses included office space, research and development, laboratory space, warehouse, control room and maintenance shop. A total of 157 building-specific subslab soil gas attenuation factors were evaluated for chlorinated solvent compounds (primarily TCE and PCE) for subslab soil gas concentrations > 1,000 ug/m^3. The median and 95% upper confidence limit of the mean attenuation factors were 9.3E-05 and 2.7E-04, respectively (Figure B-3). The 95th percentile attenuation was approximately 6.4E-04. There is some evidence of lower attenuation under wintertime conditions. Eklund *et al.* (2022) conclude that the data suggests that the default U.S. EPA attenuation factor of 0.03 over-predicts indoor air impacts at this industrial facility by at least two orders of magnitude.

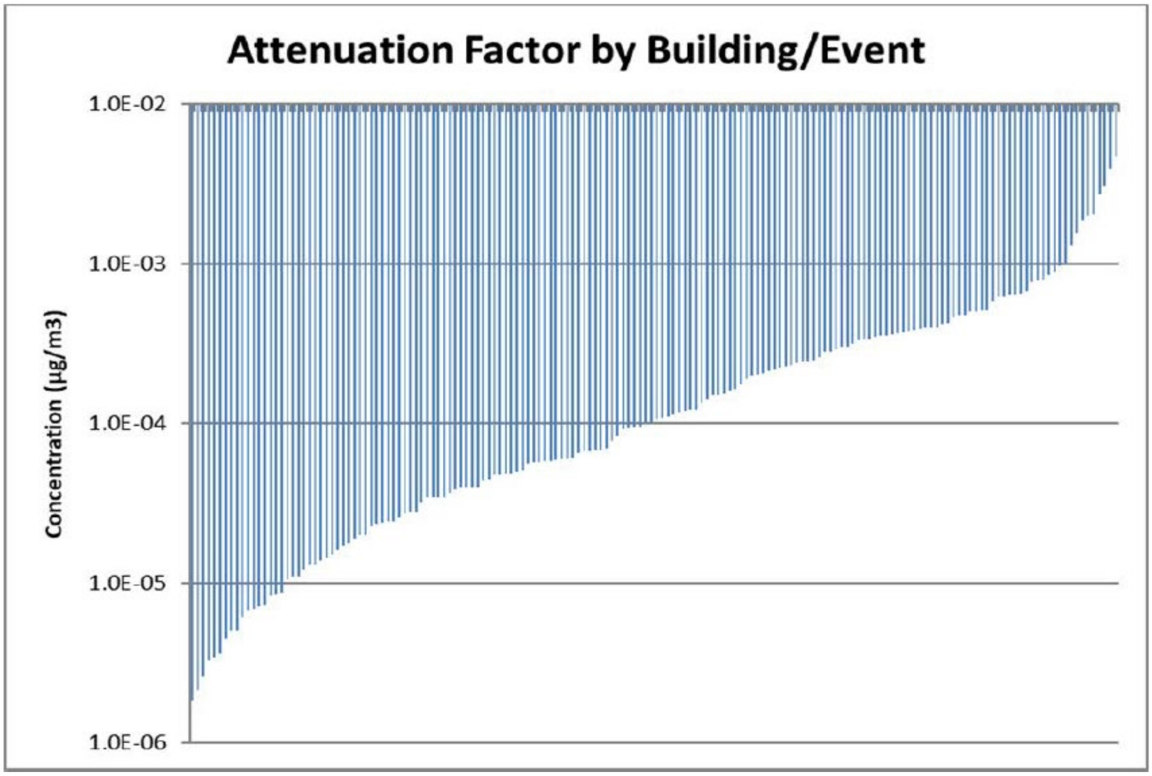


Figure B-3. Distribution of Attenuation Factors in Eklund *et al.* (2023) Study

2.7 Abassi (2023) CA DTSC Study of California Attenuation Factors

The California Department of Toxic Substances Control (DTSC) obtained empirical data from sites contaminated with chlorinated volatile organic compounds (Abassi 2023). The compiled vapor intrusion data includes 52 sites across California with 213 buildings, of which, 53% are residential, and 47% are commercial/industrial (non-residential). After filtering (based on criteria including maximum distance between samples of 50 ft and whether concurrent within 3 months) to 600 pairs from 32 sites across California, a subslab soil gas-to-indoor air attenuation factor (AF) distribution was calculated where the 95th percentile was 0.005. After filtering yielded 2,926 paired measurements from 39 sites across California, an external soil gas-to-indoor air AF distribution was calculated where the 95th percentile was 0.0009. The groundwater data were not analyzed due to the small size of the dataset.

APPENDIX C: REVIEW OF PARTITIONING MODELS AND DATA

Appendix C – Research on Partitioning Models

This appendix documents studies that provide insight into partitioning from soil contamination or NAPL sources to soil vapour and partitioning from groundwater to overlying soil vapour.

1.0 GROUNDWATER OR NAPL TO SOIL VAPOUR PARTITIONING FOR LNAPL SOURCES AT WATER TABLE

Three published case study studies at UST sites with groundwater and deep near-source soil vapour concentration data are summarized below. The partitioning relationships are complex because there could be partitioning from groundwater or residual NAPL above the capillary fringe.

- Based on a research study at the Stafford Site in New Jersey, USA (Sanders and Hers 2006), the ratio of predicted soil-gas BTEX concentrations from Henry's Law constant to measured concentrations at soil-gas probes within or close to the LNAPL smear zone and within approximately 1 ft of the water table was on average a factor of approximately seven.
- Based on a research study at the Beaufort Site in South Carolina, USA (Lahvis *et al.* 1999), the ratio of predicted soil-gas BTEX concentrations from Henry's Law constant to measured concentrations at soil-gas probes within or close to the LNAPL smear zone and within approximately 1 ft of the water table was on average a factor of approximately two.
- Based on analysis of data from the Hal's, Utah site reported in the empirical database presented in US EPA (2013), there were two soil-gas probes located within the LNAPL smear zone based on soil logs (VW-10 at a depth of 15 ft and VW-11 at a depth of 12 ft). The ratio of predicted deep benzene soil-gas concentrations based on Henry's law constant partitioning and an effective solubility based on an assumed mode fraction of 0.01 to measured soil-gas concentrations was approximately on average a factor six. The mole fraction was used because data from nearby groundwater wells (MW-9, MW-32, MW-33) was unsuitable.

2.0 GROUNDWATER TO SOIL VAPOUR PARTITIONING FOR DISSOLVED GROUNDWATER SOURCES

Studies with dissolved groundwater sources, and groundwater concentration and near-source (above capillary transition zone) soil vapour concentration data are summarized below:

- Rivett (1995) presented results of a field study at the Borden aquifer in sandy soils where vertical profiles of TCE groundwater and soil gas concentrations were obtained. For a groundwater DNAPL source, the measured soil gas concentrations immediately above the capillary transition zone were two to three orders of magnitude lower than predicted TCE vapor concentrations from shallow groundwater concentrations and Henry's Law constant. For a vadose zone DNAPL, the predicted and measured soil-gas concentrations were similar.

- McCarthy and Johnson (2003) reported on column experiments designed to investigate the transport of a dissolved trichloroethylene from shallow groundwater to the unsaturated zone. Columns were filled with Ottawa sand. Experimental data indicated that at moderate groundwater velocities (0.1 m/d), vertical mechanical dispersion was negligible and molecular diffusion was the dominant vertical transport mechanism. Under these conditions, TCE concentrations decreased nearly 3 orders of magnitude across the capillary fringe and soil gas concentrations remained low relative to those of underlying groundwater. While a drop in the water table caused an increase in soil gas concentrations, the effect was short-lived.
- Ronen *et al.* (2005) reported on high resolution monitoring of chlorinated solvent concentrations across the saturated to unsaturated interface zone measured using passive dialysis type probe in sandy soils. The results indicated that pore water concentrations in dialysis cells directly above the water table were comparable to concentrations at the water table indicating Henry's law partitioning to the gas phase surrounding the cells. With increasing distance above the water table, there was increasing attenuation of concentrations.
- Provoost *et al.* (2011) described column experiments that show toluene fugacity behaviour roughly in line with Henry's law for a column with just water, whereas the experiments which included soil material resulted in equilibrium soil concentrations that were around one order-of-magnitude lower than expected from a Henry Law-based estimation.
- Kurt and Spain (2013) through experimental column studies demonstrated that natural attenuation in the capillary fringe can prevent the migration of chlorobenzene and 1,2- and 1,4-dichlorobenzene vapors. Enumeration of bacteria capable of degrading chlorobenzenes suggested that most of the biodegradation took place within the first 10 cm above the saturated zone. There was a substantial biodegradation capacity for chlorinated aromatic compounds at the oxic/anoxic interface resulting from microbial activity and steep redox gradients.
- Yao *et al.* (2017) conducted soil column experiments and numerical simulations to investigate the transport of VOCs from groundwater to indoor air. The groundwater-to-indoor air attenuation factors varied just over an order of magnitude for the 12 soil textures evaluated with greater attenuation across the capillary transition zone for finer-grained soil textures. A noteworthy finding was that a higher shallow soil gas concentration does not necessarily indicate higher vapour intrusion potential as the concentration gradient and mass flux for this scenario may be lower.
- Several empirical data (U.S. EPA 2013; Lahvis *et al.* 2013) and modeling studies (Yao *et al.* 2019) studies provide evidence for significant attenuation of petroleum hydrocarbons across the capillary transition zone.

3.0 SOIL TO SOIL VAPOUR PARTITIONING FOR SOIL CONTAMINATION SOURCES

Studies that evaluate partitioning between soil (sorbed), water and soil vapour phases are summarized below:

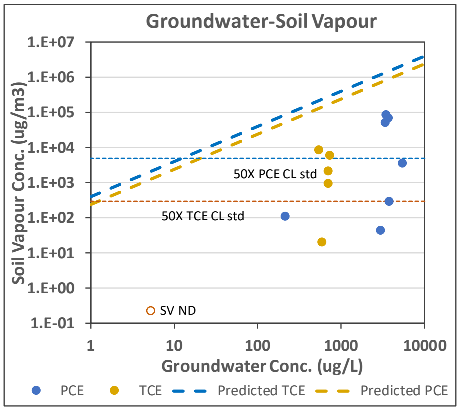
- Chen *et al.* (2004) from results of laboratory experiments found that common desorption models overpredicted the desorption of hydrophobic chemicals such as benzene and chlorinated solvents at low concentrations. Desorption is generally biphasic, with two soil-phase compartments. Correspondently, Chen *et al.* (2004) developed a dual-equilibrium desorption (DED) model by combining a traditional linear model and a nonlinear Langmuirian expression to account for the biphasic desorption. The DED model relates the amount of a chemical sorbed to the aqueous concentration based on input parameters that include octanol-water partition coefficient, solubility, and fraction organic carbon. The DED model involves several empirical parameters, such as the fraction of the second compartment that is saturated upon exposure (*i.e.*, parameter *f*), which cannot be directly measured in practice.
- Zhang *et al.* (2022) proposed a multiphase partitioning model between liquid phase, sorbed phase, and vapour phase in soil where there is both sorbed to vapour phase and liquid to vapour phase partitioning. The sorption models are absorption into organic carbon and adsorption on soil mineral surfaces according to the multi-layer Brunauer–Emmett–Teller (BET) model. The results indicated soil moisture is a controlling factor that affects partitioning, and that vapour to solid phase partitioning dominates benzene uptake when the relative saturation is under 20%. Above 20% relative saturation, partitioning into soil organic matter increasingly becomes important. The possible assumption that the benzene vapour concentration will be high in dry soils may not occur because vapour-solid mineral phase partitioning may dominate.
- Man *et al.* (2022) described a machine learning modeling approach to evaluate 2,225 soil-soil vapour data pairs collected from seven contaminated sites. The authors concluded that compared to the classic dual equilibrium desorption model, the random forest model can provide more accurate predictions of soil vapour concentrations by 1-2 orders of magnitude. While organic carbon-water partition coefficient is an important explanatory covariate affecting soil vapour concentrations, sorbed soil solid-vapour partitioning was observed to occur at up to 15% water content (by mass).

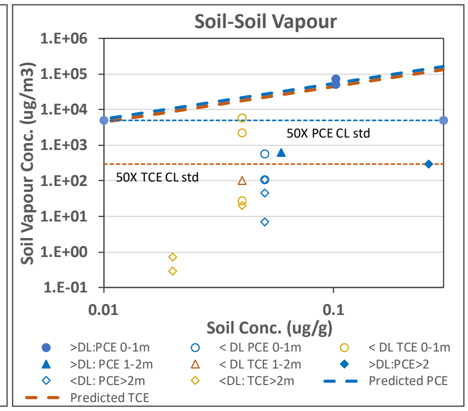
APPENDIX D: PHASE 1 COMPARISONS OF MEDIA CONCENTRATIONS

Appendix D – Phase One Comparisons of Media Concentrations

Site #1 a

Site Location: North Vancouver, BC
Soil type: granular fill up to 0.5 m thick underlain by till consisting of silty sand and some gravel
Depth to Groundwater: Approx 1-1.5 m prior to construction, < 0.5 m after construction
Source of contamination: Offsite dry cleaner
Comments: water table near top of well screen
Interpretation: Groundwater fair predictor of vapour, elevated soil vapour associated with detectable ground water concentrations. Soil poor predictor of vapour, many instances of elevated soil vapour associatd with non-detect concentrations in soil, but only 2 samples with attenuated soil vapour concentrations (AF=0.02) above CSR standard with non-detect soil concentrations





When conc. < DL (detection limit), DL is plotted
1 to 2 rounds of soil vapour data were available
Data pairs were concurrent within 0.5 month
CL = commercial land use

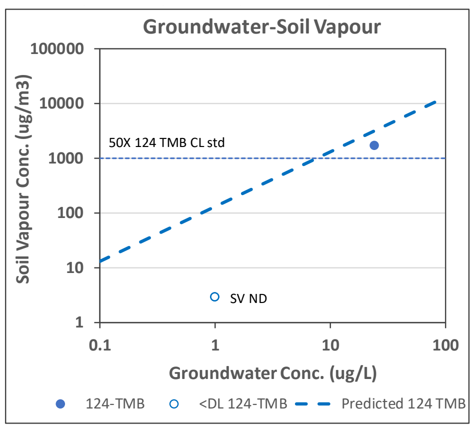
Soil vapour samples obtained from 0.2 to 1.2 m depth
Depth to top of well screen 1.1 to 1.5 m depth
Separation distance ranged from 0 to 1.3 m

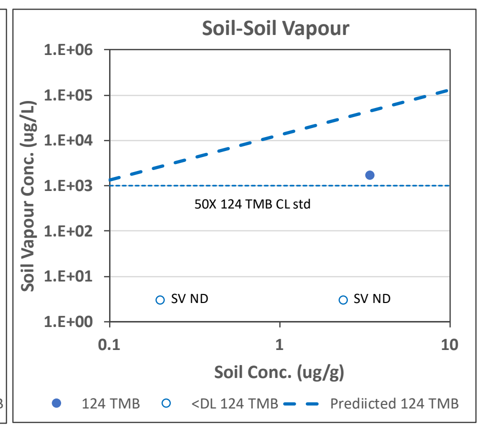
Soil vapour samples obtained from 0.2 to 1.2 m depth
Soil samples obtained from 0.38 to 5.2 m depth
Separation distance ranged from -0.75 to 4 m

Note: purpose of comparisons based on AF = 0.02 were to evaluate attenuation factors for soil relocation. Please see Stage 1 project report for details.

Site #2 b

Site Location: Vancouver, BC
Soil type: granular fill up to 1.5 m thick underlain by sand and silt til
Depth to Groundwater: Approx 1.1-3.3 m bgs
Source of contamination: Former onsite service station; vapour source considered to be a combination of soil and groundwater impacts
Interpretation: Measured vapour less than predicted, possible indication of biodegradation based on separation distance. No instances of measured attenuated vapour above CSR CL standard when non-detect in soil or groundwater using AF = 0.02.





When conc. < DL, DL is plotted
1 to 2 rounds of soil vapour data were available
Data pairs were concurrent within
1 day to 4 month

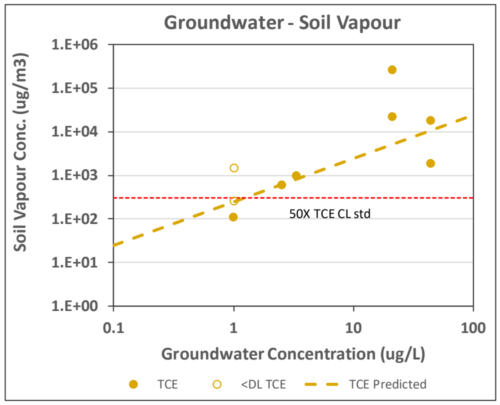
Soil vapour samples obtained from 0.75 to 1.3 m depth
Top of well screen depth from 1.7 to 3 m depth
Separation distance ranged from 0.4 to 2.1 m

Soil vapour samples obtained from 0.75 to 1.3 m depth
Soil samples obtained from 1.95 to 2.05 m depth
Separation distance ranged from 0.75 to 1.3 m

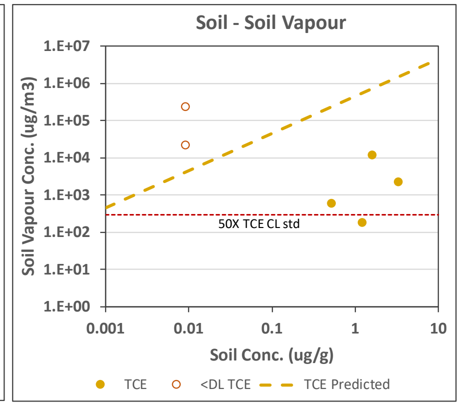
Site #3 c

Site Location: Victoria, BC
Soil type: sand and silt fill 0.5 to 1.5 m underlain by silt, underlain by clay
Depth to groundwater: 1.3-2.3 m
Source of contamination: Appears to be relatively localized source on site and dissolved plume emanating from source areas
Most measurements appear to be from non-source areas
Interpretation: Groundwater fair predictor of soil vapour, while soil is poor predictor. Elevated soil vapour concentrations of TCE were generally associated with detectable concentrations in soil and groundwater

when conc. < DL, DL is plotted
Data pairs were concurrent within
3 days to 2 years



Soil vapour samples obtained from 0.5 to 1 m depth
Depth to top of well screen 1.1 to 1.5 m depth
Separation distance ranged from 0 to 1.3 m

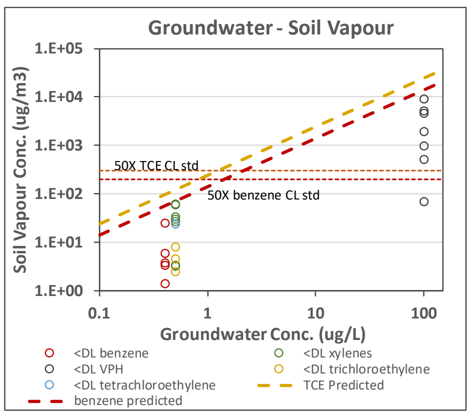


Soil vapour samples obtained from 0.5 to 1 m depth
Soil samples obtained from 1.6 to 4.6 m depth
Separation distance ranged from 0.7 to 4.05 m

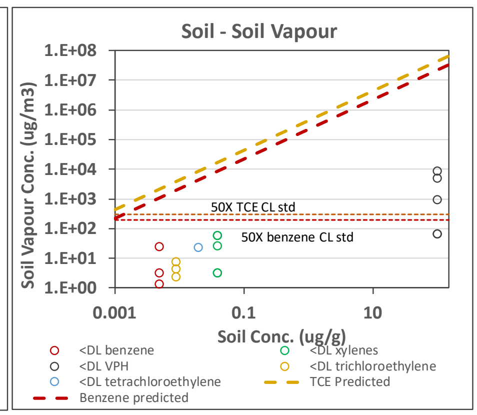
Site #4 d

Site Location: Coquitlam, BC
Soil type: Sand & gravel to ~ 1 m bgs, sand from 1-3 m bgs
Depth to Groundwater: Generally < 1 m
Source of contamination: Former Onsite service station and vehicle repair
Interpretation: All but one groundwater sample (with PCE at DL) and all soil sample concentrations were non-detect, however, all attenuated vapour conc. were less than CL standard using AF = 0.02.

When conc. < DL, DL is plotted
Data pairs were concurrent within
< 1 month to 13 months
1 to 2 rounds vapour data available



Soil vapour samples obtained from 0.4 to 0.6 m depth
Depth to top of well screen 0.5 to 1 m depth
Separation distance ranged from -0.1 to 0.4 m



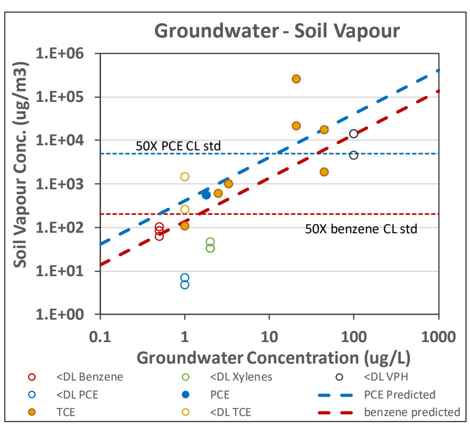
Soil vapour samples obtained from 0.4 to 0.6 m depth
Soil samples obtained from 0.65 to 1.35 m depth
Separation distance ranged from 0.2 to 0.95 m

Site #5 e

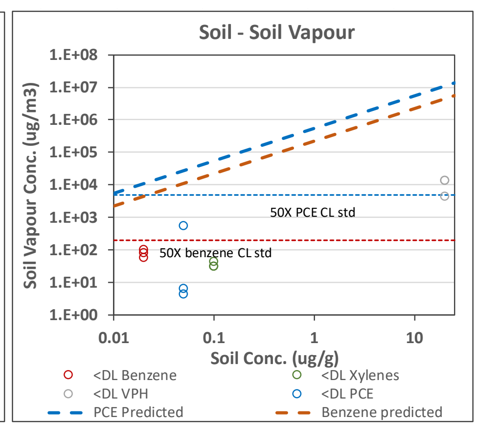
Site Location: Burnaby, BC

Soil type: sandy silt to silty sand
Depth to Groundwater: approx 0.7-2 bgs m in May, 2.5-3.4 m in August
Source of contamination: onsite former service station, PID rdgs suggest shallow contamination in some areas
Interpretation: almost all groundwater and all soil sample concentrations ND, however, all attenuated vapour concentrations < CL std using AF = 0.02

When conc. < DL, DL is plotted
Data pairs were concurrent within
3 days to 2 years



Soil vapour samples obtained from 1 to 1.1 m depth
Top of well screen depth from 1.8 to 2 m depth
Separation distance ranged from 0.7 to 1 m

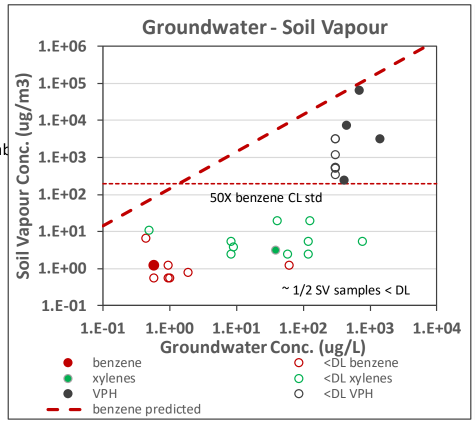


Soil vapour samples obtained from 1 to 1.1 m depth
Soil samples obtained from 0.84 to 2.75 m depth
Separation distance ranged from -0.26 to 1.74 m

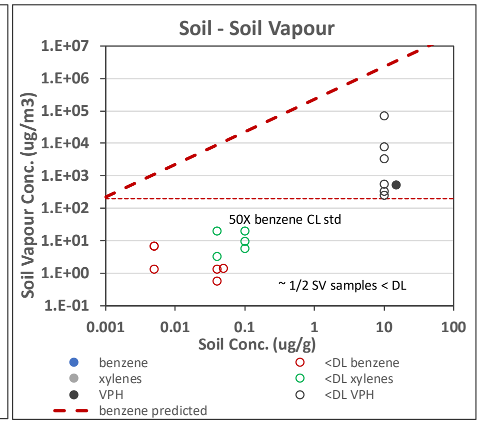
Site #6 f

Site Location: New Westminster, BC
Soil type: 0.5-2 m fill, underlain by 1-9 m low k silt to silty sand, underlain by high k sand & gravel
Depth to Groundwater: 1.8 to 38 m bgs, highly variab variable seasonally, with perched water tables in silt to silty sand
Source of contamination: Former service station at several locations, there were higher soil concentrations at deeper depths (e.g., 6-9 m)
Interpretation: Possible weak correlation between groundwater and soil vapour, there were no attenuated (AF=0.02) vapour concentrations that exceeded CL std for non-detect soil or groundwater concentrations.

When conc. < DL, DL is plotted
Data pairs were concurrent within generally 15 months, except 6 years in one case



Soil vapour samples obtained from 2.3 to 5.9 m depth
Top of well screen depth from 0.6 to 19.8 m depth
Separation distance ranged from -0.53 to 16.8 m

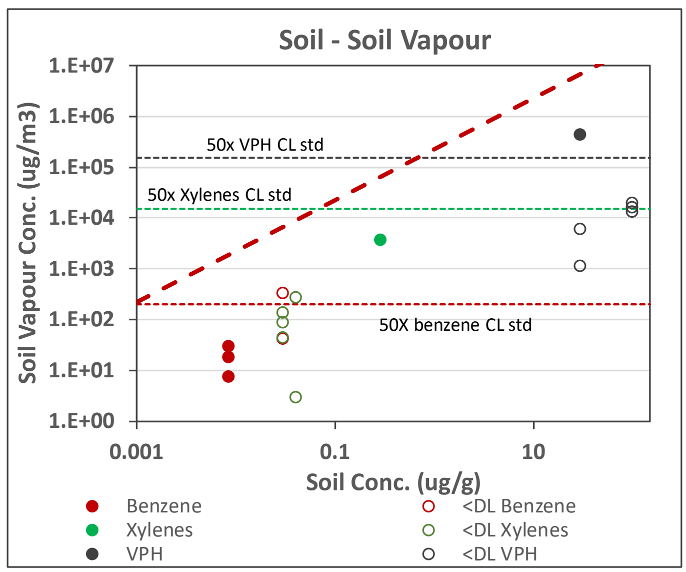


Soil vapour samples obtained from 2.3 to 5.9 m depth
Soil samples obtained from 2.8 to 6.3 m depth
Separation distance ranged from 0.1 to 3.4 m

Site #7 g

Site Location: Nanaimo, BC
Soil type: Fill to 0.2-1 m depth, underlain by dense silt till to 5 m bgs, uderlain by sand
Depth to Groundwater: 8-9 m bgs in dry season, as little as 4 m in wet season, water table is generally in sand layer
Source of contamination: Former service station, vapour hotspot was oil-water separator
Interpretation: Fair correlation between soil and soil vapour soil overpredicts concentration by at least 10X all attenuated vapour concentrations < CL std using AF = 0.02

Avg vapour calculation for some results because two rounds obtained within ~ 1 month
when conc. < DL, DL is plotted
Data pairs were concurrent within 20 months



Soil vapour samples obtained from 0.73 to 3.2 m depth
Soil samples obtained from 0.84 to 2.75 m depth
Separation distance ranged from -1.28 to 0.43 m

The physical-chemical parameters used in the partitioning analysis are provided below.

Table D-1. Physical-chemical Parameters used in Partitioning Analysis

Substance	Dimensionless Henry's law constant, H' (at 25°C)	Ref.	Dimensionless Henry's law constant, H' (estimated at 15°C)	Soil-organic carbon partitioning coefficient, koc (kg/L)	Ref.
Benzene	0.227	1	0.141	79.4	2
Xylenes	0.271	1	0.143	410	2
Trichloroethylene (TCE)	0.403	1	0.245	117	2
Tetrachloroethylene (PCE)	0.724	1	0.407	275	2
1,2,4-Trimethylbenzene	0.252	2	0.130	1910	2
Vinyl chloride	1.14	1	0.903	16.7	2

References:

1 BC ENV Protocol 13; 2 MacKay et. al (2006). Handbook of Physical-Chemical Properties and Environmental Fate for Organic Chemicals, 2nd ed. CRC Press: Boca Raton, FL. Estimated value from multiple values as documented in Health Canada PQRA model

APPENDIX E: DATA REQUEST

Appendix E – Request for Data

Request for Data *October 6, 2023*

1.0 RESEARCH PROJECT ON VAPOUR ATTENUATION FACTORS AND PARTITIONING MODELS FOR SHALLOW CONTAMINATION SCENARIOS

The Contaminated Sites Approved Professional (CSAP) Society recently awarded a research project to Millennium EMS Solutions, Arcadis Canada and Hers Environmental Consulting (HEC) to investigate vapour attenuation factors and partitioning models for shallow contamination scenarios.

Problem Statement: There can be significant challenges for investigation and risk management of sites impacted by volatile hydrocarbons and volatile organic compound (VOC) in British Columbia where vapour intrusion into buildings is a relevant pathway. This is particularly the case when contamination is relatively shallow. The applicable vapour attenuation factor in *BC ENV Protocol 22* for vapour sources < 1 m from a building is 0.02 for all building uses/types (except parkades under a risk-based approach). Because of the wide range of potential building types, the attenuation factor is also expected to vary. Depending on the substance being investigated, a high-risk condition can in some cases be indicated even when concentrations are low, which has cost and schedule implications for investigation, remediation, and site development. When it is not possible to investigate vapour intrusion using soil vapour data from field testing, the use of soil and/or groundwater data and theoretical partitioning models generally results in high estimates of soil vapour concentrations which do not reflect the actual conditions.

While the focus of the study is shallow attenuation conditions for a range of substances, a secondary objective is to better understand how volatile hydrocarbons and volatile organic compound (VOC) partitioning and biodegradation affect concentration attenuation.

Methods: The primary approach that will be followed as part of this study is to assess empirical data on vapour attenuation and intrusion in the subsurface and buildings from available sources. Existing empirical data sets in published literature will be summarized and new available data will be assembled, screened, and collated following accepted methods. We plan to cast a "wide net" for collection of the empirical data so that this study is optimized, and different components of the overall vapour intrusion pathway can be examined, including data on partitioning, on attenuation in soil, and migration into buildings.

How You Can Help: The research we are conducting will be broadly beneficial including to Contaminated Sites Approved Professionals, environmental professionals, regulatory agencies and industry. The project researchers are seeking assistance in identifying data sets for this study. There are potentially two general types of data of interest:

1. Investigations with subsurface and indoor air measurements of volatile hydrocarbon and VOC concentrations.
2. Investigations with subsurface investigations where different media / location measurements enable assessment of partitioning and attenuation (e.g., nearby or co-located samples of soil, groundwater and/or soil vapour, nested vapour wells).

There are multiple ways in which data can be provided:

1. If reports have been submitted to ENV and are publicly available, please provide the site ID and we will request reports from ENV and do the analysis.
2. Provide report pdf (and tables in Excel if possible), and we will conduct the analysis.
3. Provide data tables, with following parameters: site location (optional), sample location ID, media (soil, groundwater, soil vapour, indoor air, outdoor air), measurement method, date, sampling location (coordinates or shown on figure, sampling depth), chemical, concentration, unit, laboratory reporting limit. Ancillary data such as soil type, cover (building foundation, asphalt, bare ground), building type (footprint size, height, HVAC, etc.), depth to groundwater, utility information, etc. are also sought. If desired, both the client names and the site locations can be anonymous.

Your assistance is sincerely appreciated. If acceptable to you, we would like to acknowledge those individuals / firms that provide data in the CSAP quarterly newsletter and professional development meeting.

Please do not hesitate to reach out to Dr. Ian Hers, HEC (ian@hersenviro.com), if you have any questions.

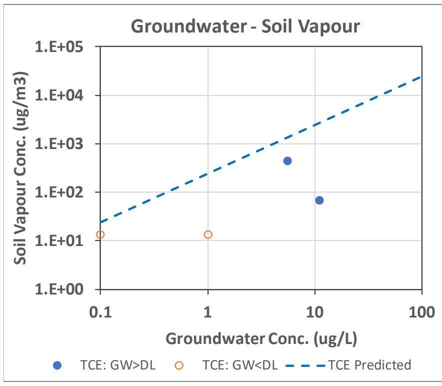
Thank you!

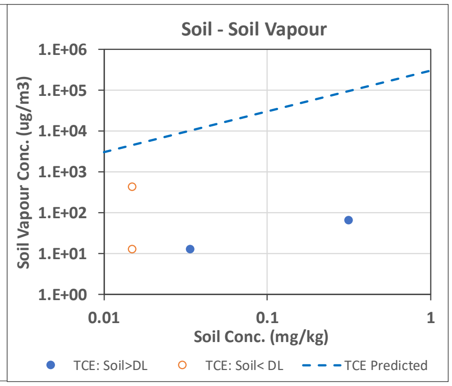
APPENDIX F: PHASE 2 COMPARISONS OF MEDIA CONCENTRATIONS

Appendix F - Phase 2 Comparisons of Media Concentrations

Site #8

Site Location: Port Moody
Contamination Type: Chlorinated solvent (primarily TCE), isolated PHC zone
Site Type: Former manufacturing plant
Soil type: Silty and/or clayey sand, sandy gravel
Depth to Groundwater: mean depth ~ 1.4 m bgs during wet season groundwater is shallower
Available Data: Soil, groundwater, soil vapour (external)
Compiled Data: Groundwater, soil vapour & soil
Synopsis: Low levels of TCE in soil, groundwater & soil vapour; measured soil vapour at least 1/2 to 1 OM less than predicted vapour from soil and groundwater concentration data.

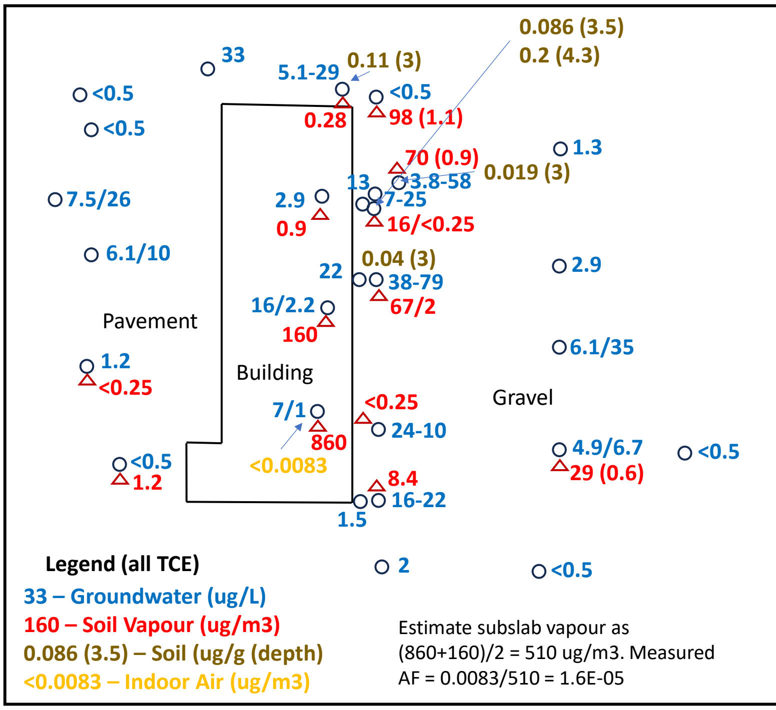




When conc. < DL, DL is plotted
Data pairs were concurrent within 2-3 yrs
All soil vapour conc. were > DL
Vertically soil vapour within 0.5 m of soil samples
Vertically soil vapour within 1 m of water table
Laterally groundwater and soil vapour were 3-4 m apart
Laterally soil and soil vapour were 2-9 m apart
OM = order of magnitude
DL = detection limit

Site #9

Site Location: Port Moody
Contamination Type: Chlorinated solvents (primariliy TCE)
Site Type: Former manufacturing
Soil type: Silt and sand with trace-some gravel
Depth to Groundwater: 0.3-2.4 m , flow is generally toward the northwest
Available Data: Soil, groundwater, soil vapour (external, subslab), indoor air (one sample / event). Vapour samples obtained using thermal absorbant tubes.
Synopsis: Extensive TCE contamination in groundwater and soil vapour. Subslab vapour concentrations were higher than shallow soil vapour concentrations external to commercial building with slab at grade foundation. Below building, attenuated subslab vapour concentration exceeded CSR TCE standard at one location. Consequently, at one location, an indoor air sample was obtained for TCE analysis. Measured indoor air conc multiplied by 10X to account for variability. 10X measured ambient was << vapour standard. Measured attenuation factor using unadjusted indoor air concentration was 1.6E-05. No information on building foundation and building HVAC system. In risk assessment, it is stated that concrete foundation is a barrier to vapour intrusion.
Compiled Data: Soil vapour and groundwater chemistry data obtained from many locations. Soil chemistry obtained from a few locations. Useful data to evaluate partitioning relationships.
Building information: commercial, slab at grade



TCE GW-Vapour Partitioning Henry's law	
ug/L	ug/m3
1	245
10	2450
20	4900
30	7350

TCE Soil -Vapour Partitioning (foc = 0.006, sand soil)	
ug/g	ug/m3
0.01	3120
0.1	31200

Key Learnings

1. Measured vapour lower than predicted from Henry's Law by at least ~ 1 order of magnitude.

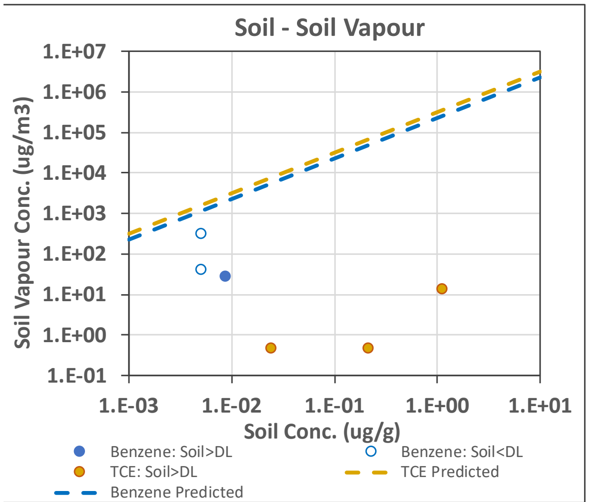
2. Subslab vapour concentrations (mostly 0.3 m deep) higher than external vapour (mostly 0.6-1.1 m deep).

3. Subslab vapour-to-indoor air AF = 1.6E-05 is significantly less than P22 AF = 0.02, but limited data.

Figure F-1. Detailed Analysis of Media Concentrations.

Site #10

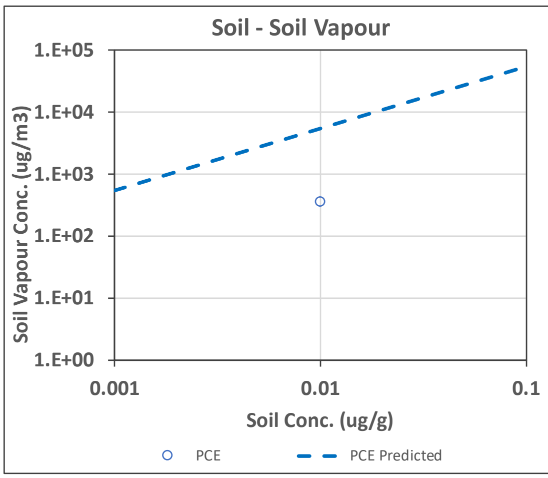
Site Location: Nanaimo
Contamination Type: PHCs, TCE
Site Type: Former machine shop, paint shop
Soil type: Sands to 4.2 m depth, underlain by gravelly sands
Depth to Groundwater: 3.9 to 10.7 m
Available Data: Soil, groundwater, soil vapour (external) during wet season groundwater is shallower
Compiled Data: Soil vapour & soil chemistry data from 3 locations. Groundwater only available from deeper wells; not representative of what could be partitioning to vapour.
Synopsis: Lower concentrations of PHCs in shallow vapour, with higher PHC concentrations in deeper vapour. Variable detections of PHCs in soil, some locations soil was ND but vapour detected. TCE not detected in soil vapour but was detected in shallow soil samples at low levels (up to 0.024 ug/g). Measured benzene vapour 1/2 OM less than predicted using DL

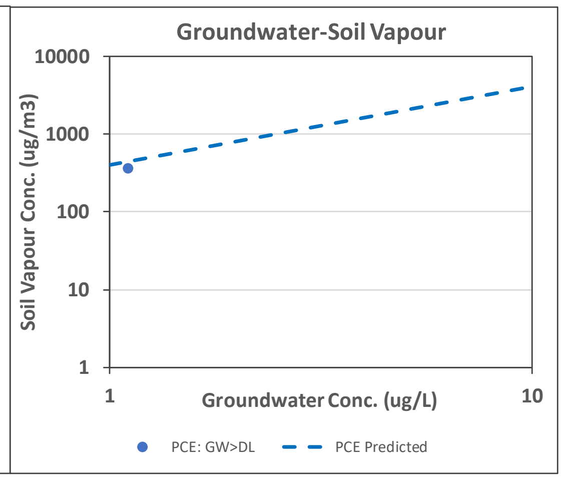


When conc. < DL, DL is plotted
Data pairs were concurrent within 2 years
Vertically soil vapour within 0.2 m of soil samples
Laterally soil and soil vapour 7-13 m apart

Site #11

Site Location: Sechelt
Contamination Type: Minor chlorinated solvent impacts (note PHCs were primary contamination of concern but were mostly ND)
Site Type:Former service station
Soil type: Sands to 4.2 m depth, underlain by gravelly sands
Depth to Groundwater: About 4 m
Available Data: Soil, groundwater, soil vapour (external, below asphalt pavement); relatively limited data
Synopsis: Detectable but relatively low PCE concentrations in soil vapour and groundwater, non-detect PCE concentrations in soil; measured vapour from soil at least 1 OM less than predicted; measured vapour from groundwater similar to predicted. PHC concentrations in all media generally ND and therefore not useful
Compiled Data: Soil vapour, groundwater and soil chemistry data from one location.
Building information: N/A
Comment: Summa canisters used

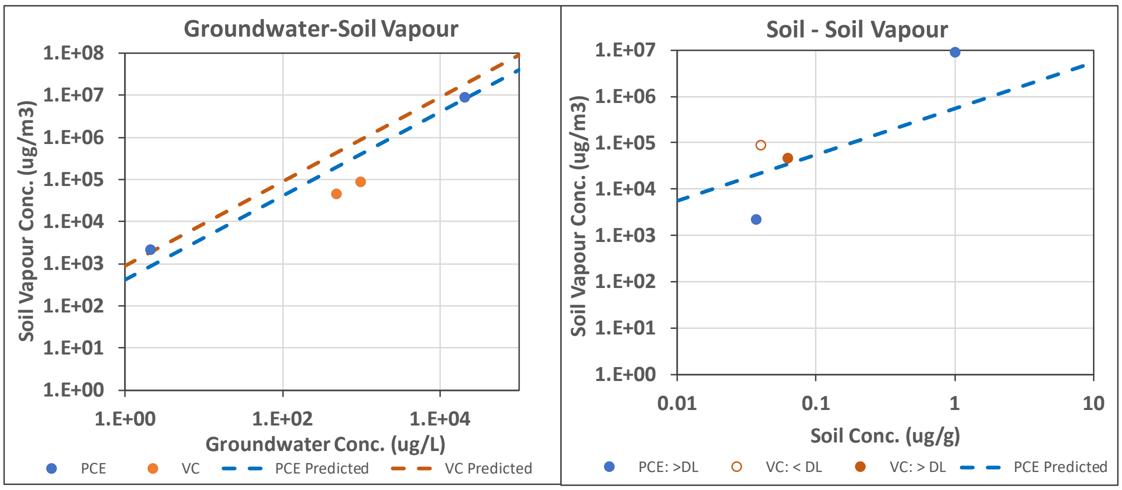




When conc. < DL, DL is plotted
Data pairs were concurrent within 1 week
Vertically soil vapour within 0.4 m of soil samples
Vertically soil vapour about 2 m from water table
Laterally soil and soil vapour were 0 m apart

Site #12

Site Location: Richmond
Contamination Type: Chlorinated solvents
Site Type: Former dry cleaner
Soil type: Sand fill to 0.8 m bgs (max); underlain by fine-grained sand to 4.6 m bgs, underlain by fine-grained sand with trace silt to 9.1 m bgs
Depth to Groundwater: 0.7-1.4 m
Available Data: Soil, groundwater, soil vapour (external, below asphalt pavement)
Synopsis: Elevated chlorinated solvent vapour concentrations in shallow soil vapour (0.6 m); PCE, TCE, cis-12-DCE and VC all detected at varying concentrations suggesting sequential degradation; elevated concentrations of chlorinated solvents in soil, groundwater and soil vapour; good candidate site to assess partitioning relationships
Compiled Data: Chlorinated solvent chemistry data in soil, groundwater, soil vapour at two locations.
Building information: N/A



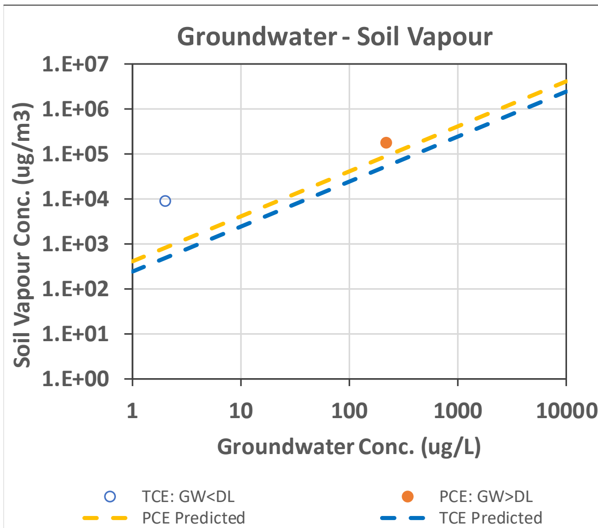
When conc. < DL, DL is plotted
Data pairs were concurrent within 1 week
Vertically soil vapour within 0.1 m of soil samples
Vertically soil vapour about 1 m from water table
Data pairs were laterally 1 m apart
PCE = perchloroethylene; TCE = trichloroethylene, DCE = dichloroethylene, VC = vinyl chloride

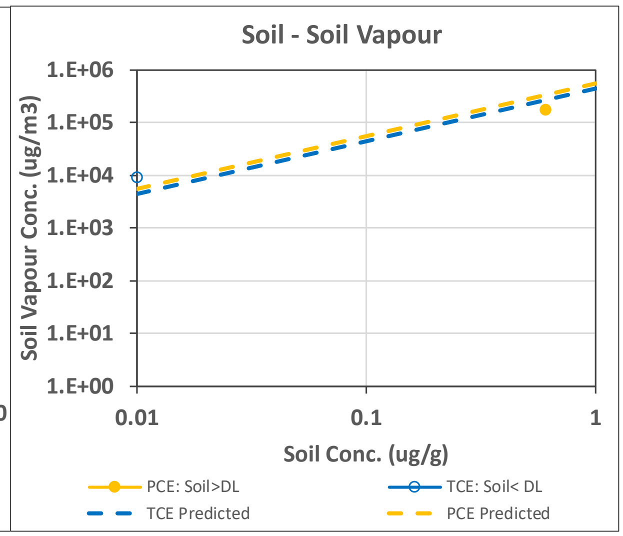
Site #13

Site Location: Campbell R.
Contamination Type: PHC
Site Type: Former bulk plant
Soil type: Sand with gravel from 0-2 m bgs; sand with silt to 10.7 m bgs.
Depth to Groundwater: Between 2.8 and 8 m, shallow groundwater flow to east-northeast
Available Data: Soil, groundwater, soil vapour (external)
Synopsis: Localized soil vapour contamination with pre-remediation VPH concentrations that were as high as 380,000 ug/m3 at SVP16-03 (1.1-1.2 m depth), BTEX vapour concentrations were much lower. At wells and boreholes nearest to vapour exceedance, soil and groundwater concentrations of VPH were non-detect. For example, VPH in soil at SVP16-03 at 0.6-1.2, 1.8-2.4 m were ND (<10 ug/g). Some boreholes were hydrovac'ed to 2 m. It is not clear whether SVP16-03 was hyrovac'ed. There were minor detections of PHC in other areas. VPH in vapour at SVP16-03 was remediated through excavation. Post-remediation vapour concentrations met standard.
Compiled Data: VPH concentrations in soil, groundwater, soil vapour at one location.
Building information: N/A
Insufficient data for figure

Site #14

Site Location: Colwood, BC
Contamination Type: Chlorinated solvents
Site Type: Former dry cleaner
Soil type: Sand and gravel fill from surface to 0.9-1.8 m bgs, silt with some sand to 0.6-2.1 m depth
Depth to Groundwater: 1.5-3.4 m bgs, groundwater flow to west to southwest
Available Data: Soil, groundwater, soil vapour (external, below asphalt pavement)
Compiled Data: Chlorinated solvent chemistry data in soil, groundwater, soil vapour at one location.
Synopsis: Elevated chlorinated solvent vapour concentrations in soil vapour (1.2-1.8m); PCE and TCE either >DL or <DL in soil and groundwater. Measured concentrations were slightly less than to greater than predicted concentrations.
Building information: N/A

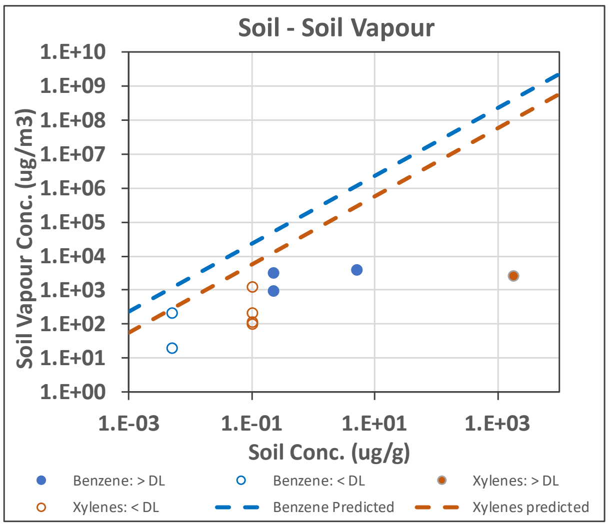




All soil vapour concentrations were > DL
Data pairs were concurrent within
one week and within 1 m vertically for soil
Groundwater-soil vapour data pairs were laterally 0 m apart
Soil-soil vapour data pairs were laterally 5 m apart

Site #15

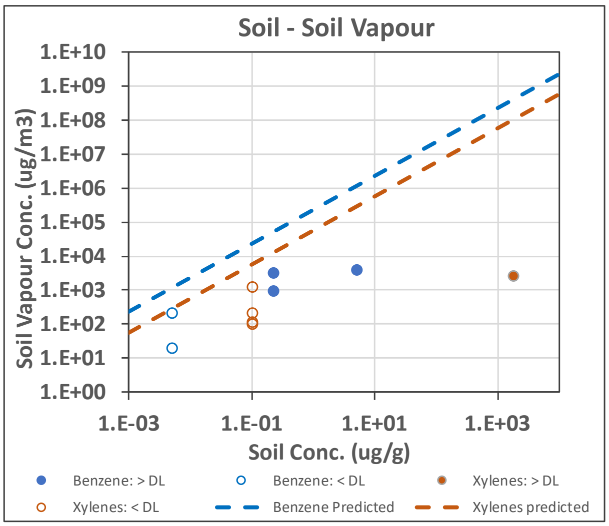
Site Location: North Vancouver, BC
Contamination Type: Chlorinated solvents
Site Type: Former service station
Soil type: sand to 3m, silt from 3-6 m, underlain by sand
Depth to Groundwater: 17-23 m bgs
Available Data: Soil, soil vapour (external, below asphalt pavement) (groundwater too deep to be useful)
Compiled Data: Chlorinated solvent chemistry data in soil and soil vapour at two locations.
Synopsis: Relatively low PHC vapour concentrations; benzene ND at one location where benzene vapour concentration was 220 ug/m3. Predicted vapour concentrations were at least 0.5 OM greater than measured. Difference in measured and predicted increases for higher concentrations.
Building information: N/A
Comment: Because of age of soil data (2006) may not had methanol preservation
Data retained because overall trends similar to other sites



When conc. < DL, DL is plotted
Soil data is from 2006, vapour is from 2015.
Soil analysis may not have used methanol preservation.
Soil and soil vapour samples vertically separated by 0.6 m
Lateral separation distance between data pairs was 3 m

Site #15

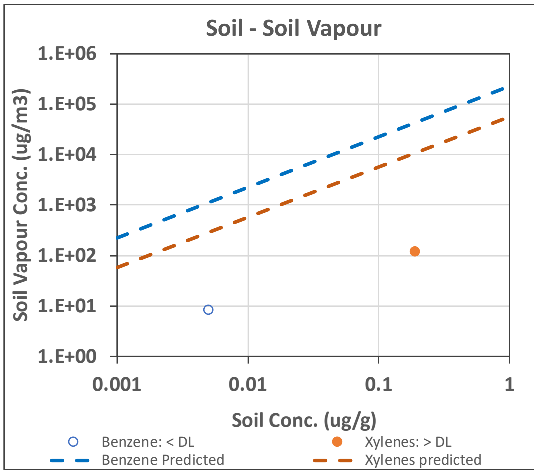
Site Location: North Vancouver, BC
Contamination Type: Chlorinated solvents
Site Type: Former service station
Soil type: sand to 3m, silt from 3-6 m, underlain by sand
Depth to Groundwater: 17-23 m bgs
Available Data: Soil, soil vapour (external, below asphalt pavement) (groundwater too deep to be useful)
Compiled Data: Chlorinated solvent chemistry data in soil and soil vapour at two locations.
Synopsis: Relatively low PHC vapour concentrations; benzene ND at one location where benzene vapour concentration was 220 ug/m3. Predicted vapour concentrations were at least 0.5 OM greater than measured. Difference in measured and predicted increases for higher concentrations.
Building information: N/A
Comment: Because of age of soil data (2006) may not had methanol preservation
Data retained because overall trends similar to other sites

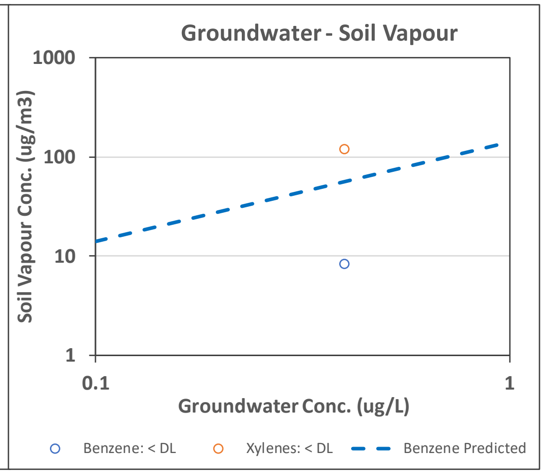


When conc. < DL, DL is plotted
Soil data is from 2006, vapour is from 2015.
Soil analysis may not have used methanol preservation.
Soil and soil vapour samples vertically separated by 0.6 m
Lateral separation distance between data pairs was 3 m

Site #16

Site Location: Victoria, BC
Contamination Type: PHCs
Site Type: Former service station
Soil type: Silt and clay fill underlain by native silt and clay
Depth to Groundwater: 0.7-2.3 m
Available Data: Soil, groundwater, soil vapour (external, below asphalt pavement)
Synopsis: Low vapour concentrations and low to ND soil and groundwater concentrations. Measured vapour is at least OM less than predicted.
Compiled Data: PHC data in soil, groundwater, soil vapour at one location.
Building information: N/A

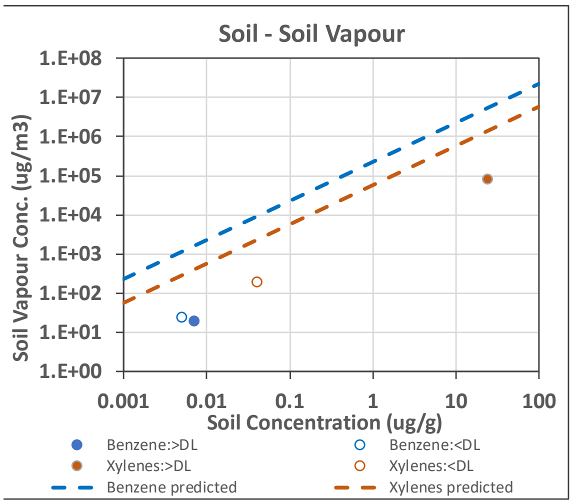




When conc. < DL, DL is plotted
Data pairs were concurrent within 1 year
Vertically, soil and soil vapour measurements were within 1.2 m
Soil vapour measurements were within 0.5 m of water table
Laterally separation distance between groundwater and soil vapour was 0 m
Laterally separation distance between soil and soil vapour was 1 m

Site #17

Site Location: Tumbler Ridge, BC
Contamination Type: PHCs
Site Type: Former service station
Soil type: Sand and gravel
Depth to Groundwater: 27-30 m
Available Data: Soil, groundwater, soil vapour (external, below asphalt pavement)
Synopsis: Low vapour concentrations and low to ND soil and groundwater concentrations. Measured vapour is at least 1 OM less than predictec
Compiled Data: PHC data in soil, groundwater, soil vapour at one location.
Building information: N/A
Comment:

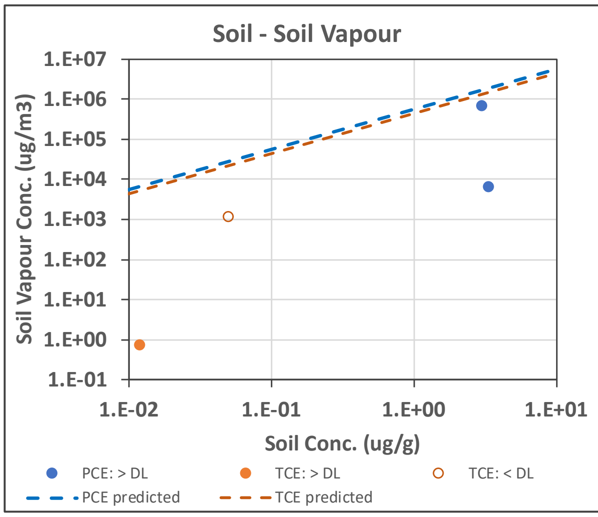


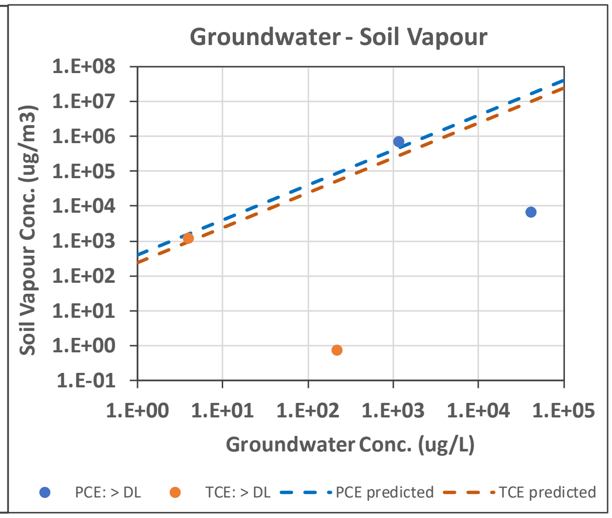
When conc. < DL, DL is plotted
Data pairs were concurrent within 1 week to 7 months
Vertically, soil and soil vapour measurements were within 0.3 m
Laterally separation distance between soil and soil vapour measurements was 0 m

Site #18

Site Location: Colwood, BC
Contamination Type: Primarily TCE, PCE; minor PHCs
Site Type: Former dry cleaner, service station
Soil type: Sand and gravel
Depth to Groundwater: 2-3m
Available Data: Soil, groundwater, soil vapour (external, below asphalt pavement), indoor air (parkade)
Synopsis: Low to moderate PCE and TCE vapour concentrations, which were below standard for parkade use, except at one location adjacent to the foundation wall of the underground parking garage, where PCE was 3930 ug/m3. The attenuated concentration using 0.02 was above PK standard. Instead of following a risk-based standards approach, indoor air samples were analyzed, where PCE was < 10 ug/m3 and below standard, facilitating a numeric standards COC. With regard to partitioning, measured vapour was close to predicted from soil at one location, and 1 to 2 OM less at other locations. Similar results were obtained for groundwater, where at one location a very close match between predicted and measured concentrations were obtained, while at another, measured concentrations were much lower than predicted.

Compiled Data: PCE and TCE data in soil vapour and indoor air, and soil, groundwater and soil vapour at two locations. Estimation of attenuation factors was not considered appropriate because of limited data and raised detection limit in indoor air.
Building information: Underground parking garage.

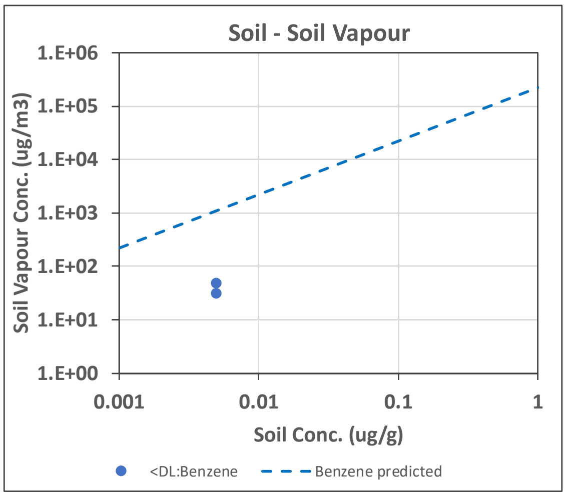




When conc. < DL, DL is plotted
Soil and soil vapour data collected about 5 years apart, groundwater and soil vapour ranged from within 1 week to 1.5 years apart
Vertically, soil and soil vapour samples separated by up to 1.2 m
Vertically, soil vapour samples were about 1.5-2 m above water table.
Laterally, soil and groundwater samples were separated from soil vapour by 4 to 6 m

Site #19

Site Location: View Royal, BC
Contamination Type: minor PHCs
Site Type: Former firehall (tanks)
Soil type: Sand and gravel fill to 1.5 m bgs, hard clay from 1.5-4.5, underlain by silt to 7.5 m
Depth to Groundwater: Around 3 m?
Available Data: Soil, groundwater, soil vapour (external, below asphalt pavement), subslab vapour
Synopsis: Low vapour concentrations met standard. However, soil vapour was obtained at 1.1 m depth, and not considered representive of future parkade (aound 3 m). Thus subslab samples were obtained once the builing was constructed, which were < std without attenuation. Comparisons of soil and soil vapour indicated measured benzene vapour was at least OM less than predicted for soil at detection limit.
Compiled Data: PHC data in soil, and soil vapour at two locations
Building information: N/A



When conc. < DL, DL is plotted
Data pairs were concurrent within 1 week to 3 months
Vertically, soil and soil vapour samples separated by up to 1.1 m
Laterally, soil and soil vapour samples separated by 0 m

Site #20

Site Location: Vancouver, BC
Contamination Type: PHC, minor PCE
Site Type: Service station
Soil type: Sand and gravel fill, underlain by sand with interbedded sandy silt to silty sand
Depth to Groundwater: 2.3 to 3.3 m
Available Data: Soil, groundwater, soil vapour (external, below asphalt pavement), indoor air (parkade)

Synopsis: Moderate BTEX vapour concentrations, high groundwater BTEX concentrations in some areas (>1 mg/L) indicating likely NAPL. Predicted indoor parkade concentrations > standard. Partial remediation performed through excavation. HHERA conducted, and risk management through barrier proposed. Polyolefin barrier designed for water-barrier for tanked buildings installed. Indoor air samples were obtained after first floor of parkade was mostly completed but apparently before barrier installation completed. Benzene concentrations in air exceeded the PK standard. After completion of the water-proofing, an additional monitoring event (one event was found in report, although more may have been planned) was conducted. Benzene concentrations were significantly lower than before water-proofing, and were below the PK standard. Xylenes indoor air concentrations did not change before and after water-proofing, although they were below standard. It was concluded based on indoor air monitoring that standards were met. Post-tanking vapour attenuation factors were calculated from the ratio of the post-tanking indoor air concentration to the shallow soil vapour concentrations in the AEC. The attenuation factors were approximately 2E-5 for benzene and 6E-3 for xylenes. The reason for the large difference in attenuation factors is not known but may be related to indoor air sources of xylenes.

Compiled Data: Benzene and xylenes in soil vapour and indoor air. The data collated was in the northeast area of the building where elevated source concentrations were measured.

Building information: Underground parking garage

Table 1. Shallow Soil Vapour and Indoor Air Concentrations in PHC-AEC

			Shallow Soil Gas (ug/m3)		
Pre-tanking/sealing			**Benzene**	**Xylenes**	**Comments**
2 locations	SV15-10	19/15/2015	14000	7200	
1 event n = 2	SV16-14	25/7/2016	11000	18000	benzene value <, assumed to equal value
	Average		**12500**	**12600**	benzene value <, assumed to equal value
	Geomean		**12410**	**11384**	
			Indoor Air (ug/m3)		
Pre-tanking/sealing			**Benzene**	**Xylenes**	**Comments**
3-4 locations	AA17-2	26-Aug-17	18	26	
2 events	AA17-3	26-Aug-17	40	79	
n=7	AA17-4	26-Aug-17	32	47	
	AA17-5	18-Sep-17	30	130	
	AA18-2	10-Mar-18	91	130	
	AA18-3	10-Mar-18	6.7	15	
	AA18-4	10-Mar-18	8.8	19	
	Average		**32**	**64**	
	Geomean		**23**	**46**	
			Indoor Air (ug/m3)		
Post-tanking/sealing			**Benzene**	**Xylenes**	**Comments**
3 locations	AA18-2	16-Jun-18	0.18	99	
1 event	AA18-3	16-Jun-18	0.41	120	
	AA18-4	16-Jun-18	0.16	27	Note 0.16 value ND
	Average		**0.25**	**82**	
	Geomean		**0.23**	**68**	
			Attenuation Factors		**Comments**
Pre-Tanking	Calc. using average		2.6E-03	5.1E-03	
	Calc. using geomean		1.9E-03	4.1E-03	
Post-Tanking	Calc. using average		2.0E-05	6.5E-03	
	Calc. using geomean		1.8E-05	6.0E-03	

Table 2. Indoor Air Concentrations Outside of PHC-AEC

			Indoor Air (ug/m3)					
Pre-tanking/sealing			**Benzene**	**Xylenes**				
	AA17-1	26-Aug-17	2	1.8				
	AA18-1	10-Mar-18	1.9	6.9				
	AA18-1	16-Jun-18	1.8	350				

Site #21

Site Location: Vancouver, BC
Contamination Type: Chlorinated solvents
Site Type: Manufacturing
Soil type: Primarily silt, with occassionally sand seams
Depth to Groundwater: Generally 3-4 m depth; occassionally as shallow as 2 m
Available Data: Soil, groundwater, external soil vapour, subslab vapour, indoor air
Synopsis:
Former historical building was a small industrial building with partial basement and partial slab at grade foundation
Subslab TCE vapour concentrations at existing building #1 in October 2014 were 29, 5050 and 822 ug/m3 (average 494 ug/m3)
Indoor air TCE concentrations in March 2015 were 1.4, 11.2, 1.02, 1.05 and 0.76 ug/m3 (average 2.55 ug/m3).
Indoor air TCE concentrations in July 2015 were 1.4, 11.2, 1.02, 1.05 and 0.76 ug/m3 (average of 3.9 ug/m3).
Higher subslab and indoor air concentrations appeared to be correlated with location of sump
The subslab TCE attenuation factors were 0.005 (March 2015) and 0.008 (July 2015) data.
A new commercial building with slab at grade foundation was constructed
Three subslab sampling ports were constructed in the new slab at grade commercial building.
Analysis indicated TCE concentrations in subslab ports ranged from <0.5 to 288 ug/m3. Because concentrations attenuated using subslab factor of 0.02 were less than standard, no indoor air sampling was performed
Compiled Data: Subslab and indoor air
Building information: Existing building, partial basement, partial slab at grade; future building slab at grade
Comment:

Table F-1. Phase 2 Data Meta-data for Media Concentration Comparisons

	Groundwater - Soil Vapour			**Soil - Soil Vapour**		
Site	Time separation	Vertical separation	Lateral separation	Time separation	Vertical separation	Lateral separation
		m	m		m	m
8	2-3 yr	<=1	3-4	2-3 yr	<=0.5	2-9
10	N/A	N/A	N/A	2 yr	0.2	7-13
11	1 w	2	0	1 w	0.4	0
12	1 w	1	1	1 w	0.1	1
14	1 w	<1	0	1 w	<=1	5
15	N/A	N/A	N/A	~ 9 yr	0.6	3
16	1 yr	0.5	0	1 yr	1.2	1
17	N/A	N/A	N/A	1 w - 7 m	0.3	0
18	1 w - 1.5 yr	1.5-2	4-6	5 yr	<=1.2	4-6
19	N/A	N/A	N/A	1 w - 3 m	<=1	0

Notes: Site 9 insufficient data for analysis; Site 13 conducted detailed analysis based on site-wide analysis; Sites 20 and 21 only evaluated indoor air analysis and not paired data

APPENDIX G: ESTIMATION OF JOHNSON AND ETTINGER MODEL INPUTS

Appendix G – Estimation of Johnson and Ettinger Model Inputs

The controlling factors and recommended estimation methods for Johnson and Ettinger model inputs are provided in Table G-1. The information provided is at an overview level. For additional information, including the default input parameters used to derive the generic modeled vapour attenuation factors in Protocol 22, see Golder (2010). Health Canada (2023) also provides detailed information on modeling inputs. Information on ventilation rates and pressures in underground parking garages are provided in SABCS / Golder (2011).

Table G-1. Estimation Methods for Johnson and Ettinger Model Inputs

Input Parameter	How to estimate?
Depth below grade to soil vapour source (m)	Site investigation data
Depth below grade to base of building foundation (m)	Building design drawings, observations, measurements
Soil temperature (only applicable if soil-to-soil vapour or groundwater-to-soil vapour partitioning model is included) (oC)	Site measurements or from climate data; typically, is the annual average
Water-filled porosity (dimensionless). Controlling factors include infiltration, soil permeability, water-holding / retention capacity. The potential effect of building or hard scape surfaces on infiltration (e.g., rain shadow) should be considered when sampling (Tillman and Weaver 2007).	Measurements, models, or correlations from site data: can be measured in soil samples, modeled using water-retention models or pedotransfer functions or estimated from databases based on soil texture / type classes (US EPA 2004; Johnson 2005).
Total-filled porosity (dimensionless). Controlling factors include soil texture, grain size and compaction.	Measurements, models, or correlations from site data: can be calculated from measured bulk density and particle density, modeled from pedotransfer functions, or estimated from databases based on soil texture / type classes (US EPA 2004).
Soil bulk density (only applicable if soil-to-soil vapour partitioning model is included) (kg/L). Controlling factors include soil texture, grain size and compaction.	Measurements, models, or correlations from site data: can be measured in undisturbed samples, modeled from pedotransfer functions, or estimated from databases based on soil texture / type classes (US EPA 2004).
Soil organic carbon fraction (only applicable if soil-soil vapour partitioning model is included (dimensionless)	Measurements in unimpacted soil samples where total petroleum hydrocarbon concentrations are less than 1,000 ug/g

Table G-1. Estimation Methods for Johnson and Ettinger Model Inputs

Input Parameter	How to estimate?
Width of building footprint (m) Controlling factors include building HVAC system design / operation, compartments, interior partitions, and interconnectivity of ventilation within the building.	Building design drawings and information on the HVAC system should be obtained. Where warranted, a mechanical or HVAC engineer should be consulted. If the entire interior of the building is open and air is well mixed, the input can be the entire building width. If there is limited interconnectivity of ventilation between compartments, the input can be the dimensions of a compartment. Note the attenuation factor decreases as building area increases.
Length of building footprint (m)	See building width
Thickness of building foundation slab (m)	Building design drawings should be obtained or can be estimated. Not a sensitive input parameter.
Vapour mixing height (m) Controlling factors include the HVAC system design / operation, building height, number of storeys, thermal stratification, cross-floor leakage, pressure differentials, environmental factors such as indoor and outdoor temperatures, wind loading, and seasonal factors.	Building design drawings and information on the HVAC system should be obtained. Where warranted, a mechanical or HVAC engineer should be consulted. In a single storey building enclosure, if there is uniform mixing of vapours (usually assumed unless there is a very high ceiling), the vapour mixing height is the distance from floor to ceiling In a multi storey building, there is almost always some cross-floor leakage or mixing of air, and consequently, the vapour mixing height would be greater than the height of one storey, but likely less than two. See Golder (2010) and Health Canada (2023) for information and available data on vapour mixing height.
Crack width (cm)	Information on building foundation design should be obtained. Visual observations can be made. This is a difficult parameter to estimate. The crack width can be backcalculated from the building foundation area and crack ratio. Typical ranges for crack ratio are provided in Johnson (2005), Golder (2010) and Health Canada (2023).
Air change rate (hr-1) Controlling factors include the HVAC system design / operation, room or building size / height, cross-floor leakage, pressure differentials, environmental factors such as indoor and outdoor temperatures, wind loading, and seasonal factors.	Building design drawings and information on the HVAC system should be obtained. Where warranted, a mechanical or HVAC engineer should be consulted. The air change rate can be estimated from the BC Building Code and ASHRAE guidance. Typically, the air change rate is not directly provided, but must be estimated from design ventilation rate based on room use, occupancy and size. The air change rate could also be measured, e.g., see ASTM E741-23 “Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution”.
Pressure differential between indoor air and subslab fill or outdoor air (Pa)	Note if Qsoil, soil gas advection rate, or Qsoil/Qbuild, ratio of soil gas advection rate to building ventilation rate is directly input in model, the pressure differential is not used. However, pressure

Table G-1. Estimation Methods for Johnson and Ettinger Model Inputs

Input Parameter	How to estimate?
Controlling factors include the HVAC system design / operation, room use or zone, room or building size / height, cross-floor leakage, environmental factors such as indoor and outdoor temperatures, wind loading, and seasonal factors.	data can assist in estimation of these parameters. Building design drawings and information on the HVAC system should be obtained. Where warranted, a mechanical or HVAC engineer should be consulted. Approximate estimates of pressures can be made from type of HVAC system, e.g., all-air or exhaust only (see CSM). "Test and balance" reports include estimated pressures. Pressure differentials can be measured using a micromanometer (to about 1 Pa sensitivity). Temporal data should be obtained to quantify possible variability from HVAC operation and climatic factors. When the indoor-outdoor pressures are measured, specialized measures are needed to shield pressure leads along the outside of building (e.g., in gravel filled containers or other methods) and ideally should be measured along multiple sides of the building.
Soil-air permeability (m^2) Controlling factors include soil texture, grain size, pore structure, compaction, water/air content.	Note if Qsoil, soil gas advection rate, or Qsoil/Qbuild, ratio of soil gas advection rate to building ventilation rate is directly input in model, the pressure differential is not used. However, soil-air permeability data can assist in estimation of these parameters. Can be estimated from soil texture or water retention models or laboratory tests.
Qsoil (L/min) and Qsoil/Qbuild (dimensionless) Controlling factors include soil-air permeability, building size and dimensions, building foundation properties (openings), HVAC system design / operation, occupancy, use, building pressures, cross-floor leakage, environmental factors such as indoor and outdoor temperatures, wind loading, seasonal factors	Building design drawings and information on the HVAC system should be obtained. Where warranted, a mechanical or HVAC engineer should be consulted. This is a difficult parameter to estimate. Qbuild can be estimated from the building volume and air change rate. Research tracer studies provide insight on Qsoil/Qbuild values (Hers et al. 2003; Johnson 2005; Golder 2010; Health Canada 2023). As a starting point, the default Qsoil/Qbuild values used in the derivation of the Protocol 22 attenuation factors can be used (0.005 for residential buildings and 0.0005 for commercial buildings) where Qsoil is estimated from Qsoil/Qbuild and Qbuild values. Other scaling approaches can be considered (e.g., based on crack ratio or length). See Ontario MOECC (2021) and Health Canada (2023). Computational fluid dynamics (CFD) modeling could potentially be used but parameterization is complex. HVAC engineers may be able to assist in estimation.

Notes : Advanced geophysical or specialized laboratory testing methods are available for estimation of soil physical parameters; however, these methods go beyond the scope of this document.