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The conclusions and recommendations of this document are based upon applicable legislation and policy existing at the time the document was prepared. Changes to legislation and policy may alter conclusions and recommendations.

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

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Review of Soil Vapour Issues for Soil Relocation in British Columbia

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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 Professional (CSAP) Society in BC to prepare this report on "*A Review of Soil Vapour Issues for Soil Relocation in British Columbia*". The BC government recently enacted the Stage 14 Amendments to the Contaminated Sites Regulation (CSR). These Amendments, together with BC Ministry of Environment and Climate Change Strategy (BC ENV) *Protocol 19*, describe requirements for relocation of non-waste soils from CSR Schedule 2 sites, including criteria for when soil vapour characterization is required and application of vapour attenuation factors at receiving sites. Because of the potential significance of these new requirements and associated technical and regulatory uncertainty, CSAP retained MEMS to conduct a review of soil vapour issues in relation to appropriate vapour attenuation factors for receiving sites, criteria for determining when soil vapour investigation is required, and equilibration requirements when conducting soil vapour sampling of soil stockpiles. The purpose of the review is to bring together information and analysis that will lead to an improved understanding of these issues and where warranted support refined regulatory approaches.

This report is organized as follows:

1. Introduction – this section.
2. Regulatory Background Information.
3. Review of Vapour Attenuation Factors for Receiving Sites.
4. Review of Volatilization Mechanisms During Soil Excavation and Handling.
5. Review of Vapour Equilibration Requirements in *Protocol 19*.
6. Review of Criteria for Determining When Soil Vapour Investigation of Relocated Soil is Warranted.
7. Conclusions and Recommendations.

The principal co-investigators and co-authors of the guidance were Dr. Ian Hers of Hers Environmental Consulting, Inc., and Dr. David Williams 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

PCOC	potential contaminant of concern
CSM	conceptual site model
CSR	Contaminated Sites Regulation
J&E	Johnson & Ettinger
LNAPL	light non-aqueous phase liquid
MLE	multiple lines of evidence
NAPL	non-aqueous phase liquid
PHC	petroleum hydrocarbon
PID	photoionization detector
PCE	tetrachloroethylene
PVI	petroleum vapour intrusion
TCE	trichloroethylene
TMB	trimethylbenzene
TPH	total petroleum hydrocarbon
VI	vapour intrusion
VOC	volatile organic compound
VPH	volatile petroleum hydrocarbon

2.0 REGULATORY BACKGROUND INFORMATION

The Order in Council for the Stage 14 amendment of the BC Contaminated Sites Regulation (CSR) was approved by Cabinet on June 1, 2022, and the changes to soil relocation came into effect on March 1, 2023. On February 1, 2023, ENV issued *Protocol 19* For Contaminated Sites – Site Investigation and Reporting. *Protocol 19* describes sampling and analysis requirements for soil and soil vapour for non-waste soil (defined as "*soil with substance concentrations less than applicable standards for soil and soil vapour at a receiving site*") undergoing relocation.

The Stage 14 CSR amendments Ministerial Order 164/2022 indicate soil relocation is exempt from a soil vapour investigation if "*the soil does not contain any substance with a concentration greater than (i) the generic numerical soil standard for a low density residential land use, or (ii) the lowest value of the matrix numerical soil standards for a low density residential land use.*". The Ministerial Order suggests the threshold for soil vapour investigation is the lowest low density soil standard regardless of land use at the receiving site.

The Ministerial Order indicates that the soil to be relocated must not have any concentration of any substance in vapour emissions from the soil that is greater than the generic numerical vapour standard applicable to a receiving site that is used for a low-impact land use [wildlands, agricultural, urban park or residential]. This is interpreted to mean that soil vapour concentrations from both *in-situ* and *ex-situ* sampling are to be directly compared to the Schedule 3.3 vapour standards without attenuation.

Protocol 19 includes soil vapour investigation requirements for *in-situ* and stockpile sampling including the minimum depth of probe and spatial density of samples. For stockpiles, the requirements include a minimum wait time of one week after the stockpile has been placed prior to sampling, a minimum probe depth of 1 m below the stockpile soil surface, and a requirement to place plastic at ground surface around the probe to minimize air leakage. Additionally, equilibration of soil vapour concentrations should be demonstrated using a photoionization detector (PID). No details on how to determine equilibration of soil vapour are provided in *Protocol 19*.

3.0 REVIEW OF VAPOUR ATTENUATION FACTORS FOR RECEIVING SITES

A review of regulations and guidance on soil relocation or excess soil from select jurisdictions in Canada and US was conducted with a focus of uncovering requirements in relation to volatile contaminants and vapour pathway concerns (Appendix A). None of the jurisdictions reviewed currently regulate soil reuse through a soil vapour investigation.

Ontario has developed excess soil standards that include consideration of the vapour inhalation pathway. For shallow contamination sources, Ontario adopted the same empirical vapour attenuation factors for estimation of indoor air concentrations for excess soil (receiving) sites as for source sites, which are 0.02 for residential land use and 0.004 for commercial/industrial land use. For deeper contamination sources, the Ontario soil standards for excess soil were derived using a model that assumes a depleting contamination source, and consequently the attenuation factor varies over the exposure period (*i.e.*, a constant attenuation factor was not used). There were differences in the assumptions for the volume of contaminated soil for excess soil sites that resulted in differences in the soil standards between excess soil and source sites (Appendix A).

While several of the other jurisdictions reviewed have soil standards that regulate and classify soil or fill for the purpose of reuse, a detailed review of the derivation basis for these soil standards was not part of the scope of this review. While it is possible that soil standards in these jurisdictions include consideration of vapour intrusion at receiving sites, in general, vapour intrusion concerns associated with soil reuse were not discussed in the documents reviewed from these jurisdictions.

From a conceptual standpoint, the vapour attenuation factors in BC ENV *Protocol 22* are considered to generally apply to sites receiving relocated soil. While relatively large volumes of soil could be placed for soil relocation, the empirical basis for shallow attenuation factors, and modelling of deeper attenuation factors (> 1 m depth) in *Protocol 22* do not make specific assumptions on the volume of contaminated soil (Golder 2010). The volume of contaminated soil was not a relevant factor in the model used to derive attenuation factors adopted by Health Canada in their draft 2010 vapour intrusion guidance (Health Canada 2010). Dr. Ian Hers assisted ENV and Health Canada in derivation of attenuation factors.

The US EPA database of empirical attenuation factors used as a reference basis for the derivation of subslab attenuation factor in *Protocol 22* incorporates a relatively large range of contamination source types and sizes (US EPA 2012). The Johnson and Ettinger model, used to derive attenuation factors including those in Health Canada (2010), assumes a laterally infinite zone of contamination that is uniform and continuous below buildings, and that remains constant over time (mass does not deplete). While relatively large volumes of soil could be relocated to a site, the soil vapour impacts, or soil vapour contamination is expected to be dispersed and limited in extent within the relocated soil. In addition, some volatilization, and possibly biodegradation, will occur between sampling on a source site and (re-) excavation at the source site (either of *in-situ* soil or stockpiles), transport of soil, and placement of soil on the receiving sites (see Section 4 of this report). Attenuation in contaminant mass and substance concentrations will act to further reduce the risk of vapour concentrations exceeding standards on the receiving site.

Recent research on soil vapour transport in utilities (*e.g.*, sewers) indicates this pathway is potentially significant at some sites (MEMS 2022). The research indicates that vapour pathway transport *via* sewers or land drains is significant when utilities directly connect buildings to zones of groundwater with relatively higher levels of groundwater contamination or extensive soil contamination (*e.g.*, NAPL). In contrast, preferential migration of vapour in sewers or land drains is unlikely to be an operable pathway for the expected conceptual model of lightly contaminated soil that undergoes soil relocation, which is expected to have relatively low vapour concentrations of substances and dispersed, localized soil contamination sources. Therefore, preferential pathways, in our opinion, do not represent a heightened concern for soil relocation when placing re-located soil near utilities or if future utilities are constructed.

Current BC regulation must be followed for soil relocation. A possible framework is described for consideration as regulations may evolve, as follows:

- The scientific basis for vertical attenuation factors in *Protocol 22* are considered to generally apply also to relocated soil.
- For uncontrolled placement of relocated soil and where future development could include buildings with foundations, the *Protocol 22* subslab vapour to indoor air attenuation factor

(0.02) is considered applicable to all building types (excluding buildings with earthen floors, which are recommended to be precluded, although likely not of practical importance).

- Where future development will not include buildings, the outdoor air attenuation factor (0.0001) is recommended.
- Where a clean soil cap is constructed above soil that is relocated and where the base of the cap is a minimum of 1 m distance below the base of any future building, the attenuation factors in *Protocol 22* for greater than 1 m depth (from building foundation) are considered applicable.

Whenever attenuation factors are applied for either source sites or potentially future soil reuse, it is important that vapour concentrations are adequately characterized to meet the objective of protecting human health.

4.0 REVIEW OF VOLATILIZATION OF VOCS DURING SOIL EXCAVATION AND HANDLING

The volatilization of VOCs during soil excavation and handling indirectly has implications for vapour investigation triggers and soil relocation in that it is a process that potentially reduces VOC concentrations in relocated soil. Aerobic biodegradation could reduce PHC mass in aerated relocated soil. Consequently, these processes could have a bearing on selection of attenuation factors and/or precluding conditions to application of factors or provide some additional confidence in management approaches that do not explicitly include volatilization or biodegradation, but where these processes will further reduce potential exposure and risk to VOCs. For these reasons a review of the scientific literature was conducted.

The scientific literature on estimation of volatile emissions from soil during excavation and handling is relatively limited. Conceptually, key factors affecting VOC emissions include physical-chemical properties, chemical diffusion rate and concentration gradient, and soil disturbance as it affects the soil surface area exposed to volatilization (VOCs are defined as a broad range of volatile chemicals including PHCs, halogenated solvents, *etc.*). The effective diffusion coefficient is inversely proportional to soil moisture, which tends to be higher for fine-grained soil than coarse-grained soil. Mass depletion of PHCs occur through aerobic biodegradation, which can be stimulated through the aeration process that occurs through soil excavation, handling and deposition.

Key research in relation to US Environmental Protection Agency Superfund sites (US EPA 1990) and a model developed by DeVaull (1991) was identified. The US EPA characterized VOC emission rates resulting from excavation activities during remediation using two example sites (designated Site A and Site B), loosely based on actual Superfund sites (US EPA 1990). For Site A, VOC emissions were modelled for the following stages of a project: excavation, soil within the bucket, filling of a truck, transportation of the contaminated soil from the excavation zone, and chemical transport at the contaminated zone (not defined by US EPA 1990 but may mean *in-situ* processes). The modelling indicated that the key source of VOC emissions at Site A was related to the transportation of the contaminated soil from the excavation zone (60% was from this activity), whereas the excavation, within bucket, truck filling, and chemical transport at the contaminated zone accounted for smaller proportions of the VOC emissions. For Site B, most of the same factors were considered but additionally soil was subject to thermal desorption/incineration treatment (which was not included in the percentages that follow). The modelling indicated that the key source of VOC emissions was related to the dumping of the contaminated soil into the thermal desorption/incinerator system (50%) and the transportation from the excavation zone (31%). The other excavation activities accounted for a smaller proportion of the VOC emissions (US EPA 1990).

The US EPA (1992) also conducted a novel excavation study at the McColl Superfund site, located in Fullerton, California, in which the researchers excavated the contaminated material (mud or clay-like waste) in a ventilated enclosure to capture a total emissions value. The US EPA used the excavation rate, concentrations of VOCs and SO_2 leaving the enclosure, and ventilation rate to calculate the total emissions value as a function of excavation. DeVaull (2001) developed a model that estimates time-dependent VOC emissions during excavation of contaminated soil or waste and used the emissions data from the McColl site to validate the emissions model. The DeVaull model showed that VOC emissions during an excavation are dominated by the generation rate of new surface area and the emissions flux immediately following the generation of new surface area. For the assumed soil clod size (5 cm), excavation rate (9 to 47 bulk cubic yard (bcy)/hr) and excavation time (34-44 min), the emission rates were 99 to 179 mg-VOC/kg-soil. When compared to the initial maximum concentration (5,000 ug/g), the maximum emission loss over 34-44 minutes represented 3.6% of the initial mass. The relatively low loss rate may have been because soils were fine-grained.

While excavation was shown by DeVaull (2001) to only result in a small amount of mass reduction, the estimates were made over a short period of time and do not include volatilization during transportation, which US EPA (1990) concluded was proportionally more significant than excavation. While mass loss through soil reuse volatilization and biodegradation is highly site-specific, it will result in some concentration attenuation and reduction in risk at all sites. However, because, the emission rates associated with excavation and handling are highly variable, it is likely not possible to include these processes in attenuation models.

5.0 EQUILIBRATION OF SOIL VAPOUR CONCENTRATIONS IN STOCKPILES

Protocol 19 includes requirements for demonstrating vapour equilibration in stockpiles. Additionally, for stockpiles, there is a requirement to wait a minimum of one week after the stockpile has been placed prior to vapour sampling. To further assess these requirements, the concept of local and broad-scale equilibration of vapours is discussed below, and a numerical modeling study of diffusion in soil was completed (Appendix B).

5.1 Literature on Vapour Equilibration

Local equilibration of soil vapour concentrations immediately surrounding a probe is expected to occur relatively quickly after installation for drilling methods with minimal disturbance (*e.g.*, driven probe or auger). For example, to answer how long does it take for the sand pack to equilibrate with surrounding soil gas, DiGuilio *et al*. (2006) used a model to calculate equilibration times for different borehole diameter distances and soil water contents. For a 50 mm diameter borehole, the equilibration time plot for the sand pack shows a required time of a few minutes to a few hours. This, and other studies, and considerations relating to disturbance from drilling, has led to the following recommendations for equilibration times (MEMS 2022):

1. temporary driven probes: 30 minutes;
2. probes installed in holes advanced by direct push or auger, or rotosonic where no fluids (air or water) are used: 2 days;
3. probes installed in holes advanced by rotosonic where fluids are used, air rotary, or hydro-vac: site-specific: conduct time-series testing of CO_2 and O_2 using landfill gas type field meter and VOCs using PID and/or combustible gas detector to assess when concentrations stabilize.

The above studies were conducted in the general context of investigating contaminated sites, and not specifically stockpile sampling. However, principles and recommendations provided are considered to generally apply to stockpile characterisation.

5.2 Conceptual Site Model for Vapour Equilibration

The conceptual model for broader scale equilibration of soil vapour within a stockpile depends on the distribution of chemical sources and should consider how concentrations could change over time. The excavation, handling, and placement of soil in a stockpile is expected to result in mixing and volatilization of contaminants. Because only lightly contaminated non waste soils can potentially be reused, contamination sources are expected to be of relatively low mass and concentration in soil, localized and dispersed. As vapours diffuse away from a source and mass is depleted, source concentrations will decrease. Vapour concentrations proximate to sources could potentially increase in the short term, but over the longer term, are expected to decrease. Diffusion rates will vary depending upon soil composition, chemical-specific properties, soil moisture, and whether the stockpile is covered with plastic.

5.3 Modelled Migration in Stockpiles

To assess vapour concentrations in a stockpile, a finite difference numerical computer model for 2D concentration diffusion was used to evaluate time-dependent changes in concentrations (Appendix B). The modeling is an approximation as only diffusion is simulated, and processes such as sorption and biodegradation are not included. A relatively simple approach was consistent with the limited scope available for modeling. The modeling objective was to provide insight into migration behaviour of vapours in stockpiles but did not include developing quantitative thresholds.

The initial conditions are an arbitrary distribution of discrete, small sources in a stockpile, with zero concentration elsewhere in the stockpile. The model then predicts the time-dependent change in concentration throughout an uncovered stockpile assuming sources are transitory and there is no sorbed mass. Two soil types were modeled: sand and silt (loam). The results indicate decreasing concentrations near sources and relatively smaller increasing concentrations further from sources that reach a peak and then decrease. Overall, there is a significant decrease in concentrations and chemical mass over relatively short time (weeks). In a covered stockpile with no volatilization to atmosphere, the concentrations will approach a constant concentration within the stockpile (note some leakage through cover is expected to occur). The time to achieve quasi-equilibrium (>90%) is likely a few weeks in a small to medium sized stockpile.

The modeling is useful in showing that for dispersed, low mass sources, chemical concentrations in an uncovered stockpile will be continuously changing and temporally and spatially varying, and that equilibration as commonly understood will likely not occur in a reasonable amount of time. The implication is that time-series vapour concentrations are unlikely to come to equilibrium obtained over, for example, time scales of weeks or months. Time-series PID data is expected to be difficult to interpret and likely not useful or needed to demonstrate equilibrium.

A minimum wait time of one week after the stockpile is placed prior to sampling is not sufficient for vapour equilibrium to occur in a stockpile. However, as discussed above, achieving, or demonstrating vapour equilibrium is not considered practical or needed. In one week, some migration and re-distribution of vapours within a stockpile will have occurred. Although arbitrary, one week is considered a reasonable time to wait prior to sampling.

5.4 Site-specific Assessment of Equilibration

Soil vapour probes in stockpiles should be located to coincide with detectable or the relatively higher measured concentrations in soil to the extent possible. Best practices for soil gas sampling and wait times for equilibration to account for local disturbance during probe installation, if needed, should be followed. Wait times are provided in MEMS (2022), BC ENV (2020) and CCME (2016). When low disturbance installation methods are used, demonstration of equilibration is considered optional for *in-situ* and stockpile characterization. Longer-duration demonstration of equilibration is not considered warranted. Demonstration of local equilibrium during purging is recommended when probes are installed by methods with high disturbance such as air rotary or sonic drilling, when air or water is introduced in the soil.

6.0 REVIEW OF CRITERIA FOR DETERMINING WHEN SOIL VAPOUR INVESTIGATION OF RELOCATED SOIL IS WARRANTED

6.1 Overview of Issue

As described in Section 2, the criteria for a soil vapour assessment under the Stage 14 CSR amendments are: 1) for chlorinated solvents, any detectable concentration in soil at the source site, or 2) for non-chlorinated solvents, a soil concentration greater than the low-density residential land use standard of the receiving site.

The use of soil concentration data for evaluation of vapour intrusion is typically not preferred as measurement of the soil vapour concentration is a more direct, and typically accurate approach. However, in the context of soil relocation, it is more practical to screen soil using soil concentration data, and consequently, it is important to understand and potentially refine criteria used for this purpose. The objective of this section is to evaluate these criteria through theoretical partitioning relations and empirical data.

6.2 Partitioning Relations and Literature Review

6.2.1 Literature Review

Chiou (1989) presented theoretical considerations for partition uptake of non-ionic organic compounds by soil organic matter. US ACE (1998) describes laboratory experiments to assess the correlation between soil and soil vapour concentrations of common petroleum hydrocarbon aromatic and chlorinated aliphatic compounds. The findings of this study support the theory that linear partitioning exists between soil vapour and bulk soil VOC concentrations under environmental conditions, and that the organic carbon content is the dominant soil property controlling the capacity of a soil to retain VOCs. Absorption of VOCs into organic carbon is usually the dominant sorption mechanism down to an organic carbon content of about 0.1% (Brusseau, 1994; Rorech, 2001). However, in very dry soils (uncommon in subsurface settings), sorption of VOCs to mineral surfaces becomes an important process (Chiou and Shoup, 1985).

The linear equilibrium partitioning equation commonly used for evaluating non-ionic organic compound partitioning is (US EPA 2008):

$$C_{bulk} = \frac{C_{vapor}}{HLC\ \rho_b}\left(K_{oc}\ f_{oc}\ \rho_b + \ \theta_w + HLC\ \theta_a\right) \qquad \text{Eq. 1}$$

Where:

C_{bulk} = bulk soil concentration (mass/mass);
C_{vapour} = soil vapour concentration (mass/volume);
HLC = dimensionless Henry's Law constant;
ρ_b = dry soil bulk density (mass/volume);
Koc = organic carbon partition coefficient (volume/mass);
foc = fraction of organic carbon in soil (mass/mass);
θw = water-filled soil porosity (volume/volume);
θa = air-filled soil porosity (volume/volume); and
= n – θw, where n is the total porosity.

Theoretical equilibrium partitioning calculations between volatile chemicals in soil and soil vapour are highly approximate (US EPA 2008). The calculations assume local equilibrium between chemical sorbed to soil and soil vapour, no kinetic or mass transfer rate limitations between soil and soil vapour, and no biodegradation of the chemical in either sorbed, aqueous or vapour phases. The use of soil concentration data to estimate soil vapour concentrations can be affected by loss of volatiles in soil through volatilization and degradation (although field preservation can reduce losses), heterogeneity of soil chemical distribution and insufficient sensitivity of soil chemical analysis as detection limits can in some cases exceed concentrations of concern based on the vapour pathway.

There are few studies in literature where field scale partitioning has been evaluated. One study involved co-located measurements of soil and soil vapour for F1 concentrations at 22 sites (reported in Golder 2007). These data showed measured soil vapour concentrations that were at least one to two orders of magnitude lower than predicted vapour concentrations using the theoretical linear equilibrium partitioning equation (Eq. 1) (Figure 1). This data set was used to help support a 10X reduction factor in the attenuation factor used in the derivation of the CCME PHC Canada-wide Standards for the vapour pathway.

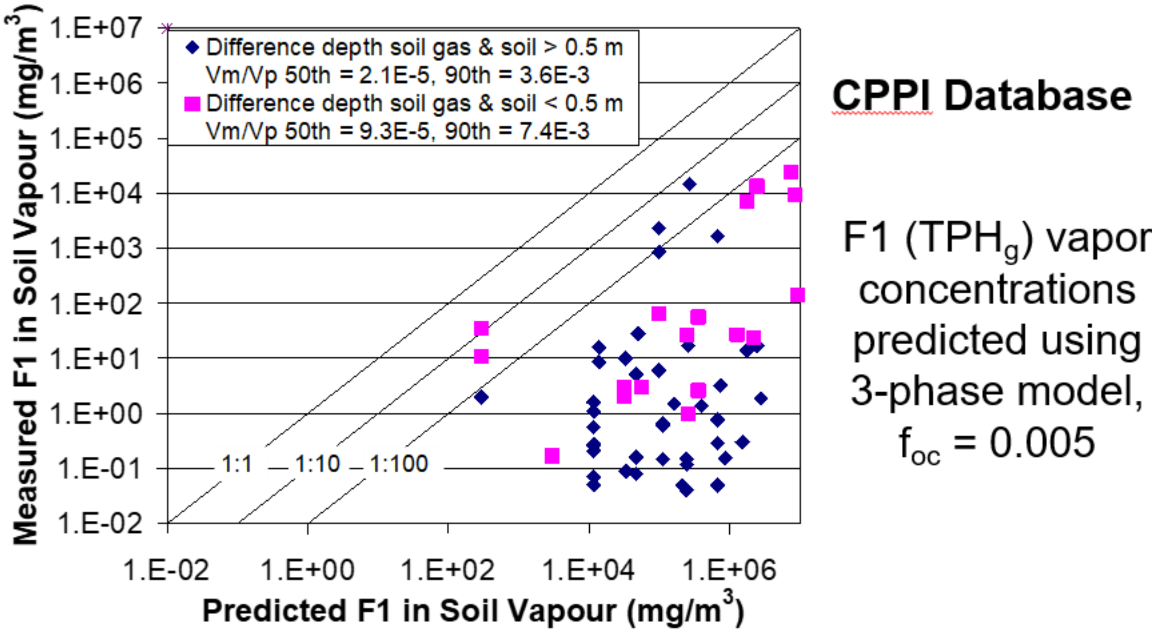


Figure 1. **Co-located Measured and Predicted F1 Vapour Concentrations from Soil Concentrations (Golder 2007). foc = fraction organic carbon. Vm = measured vapour concentration; Vp = predicted vapour concentration.**

Smith *et al*. (1990) present data on the sorption of trichloroethylene (TCE) vapour to vadose-zone above a contaminated water-table aquifer at Picatinny Arsenal. Analysis of soil and soil-gas samples collected from the field indicated that the ratio of the concentration of TCE in the vadose-zone soil to its concentration in the soil gas was 1-3 orders of magnitude greater than the ratio predicted using an equilibrium model (*i.e.,* more chemical mass was partitioned onto soil than soil gas than predicted). Smith *et al*. (1990) state that this apparent disequilibrium may have resulted from slow desorption of TCE from the organic matter of the vadose-zone soil relative to the dissipation of TCE vapour from the soil gas.

Analyses of soil and soil-gas samples collected from the field indicate that the ratio of the concentration of TCE in the vadose-zone soil to its concentration in the soil gas is 1-3 orders of magnitude greater than the ratio predicted by using an assumption of equilibrium partitioning.

6.2.2 Partitioning Analysis

Theoretical partitioning relations were evaluated following a two-step process. First, soil screening criteria (SSC) for the protection of vapour inhalation pathway were back-calculated using CSR Schedule 3.3 vapour standards and recommended attenuation factors for soil relocation when there is shallow contamination that is less than 1 m from receptor (Table 1 and Appendix C). The applicable vertical vapour attenuation factors are 0.02 for the indoor air pathway and residential, commercial, and industrial land use, and 0.0001 for the outdoor air pathway. The linear equilibrium partitioning relationship (Eq. 1) was used to calculate the soil concentration from the soil vapour concentration. An example calculation and input parameters for the calculation are provided in Appendix C.

Table 1 Soil Screening Criteria (SSC) for the Protection of the Vapour Inhalation Pathway for Select Substances for < 1 m to Subsurface Vapour Source (ug/g)*

Substance	*Soil screening criteria calculated from CSR Sch. 3.3 std, AF & partitioning calcs*				
	AF = 0.0001	*AF = 0.02*	*AF = 0.02*	*AF = 0.02*	*AF = 0.02*
	Outdoor	***Agricultural, Urban Park, Residential***	***Commercial***	***Industrial***	***Parkade***
Benzene	5.50E-02	2.75E-04	7.33E-04	1.83E-03	1.83E-03
dibromoethane, 1,2-	5.11E-02	2.55E-04	2.55E-04	2.55E-04	2.55E-04
dichloroethane, 1,2-	3.99E-01	2.00E-03	5.70E-03	1.85E-02	1.57E-02
dichloroethylene, 1,1-	7.12E-01	3.56E-03	1.07E-02	3.56E-02	2.67E-02
dichloroethylene, 1,2- cis	1.05E+00	5.24E-03	1.75E-02	4.80E-02	4.37E-02
Ethylbenzene	7.28E+01	3.64E-01	1.09E+00	3.28E+00	2.91E+00
naphthalene	1.30E+01	6.48E-02	1.94E-01	5.40E-01	5.40E-01
tetrachloroethylene	3.58E-01	1.79E-03	4.47E-03	1.56E-02	1.34E-02
Toluene	2.36E+02	1.18E+00	3.54E+00	1.06E+01	9.43E+00
trichloroethylene	2.14E-02	1.07E-04	3.21E-04	1.07E-03	8.01E-04
trimethylbenzene, 1,3,5-	3.05E-01	1.53E-03	4.36E-03	2.83E-02	1.09E-02
vinyl chloride	2.98E-03	1.49E-05	5.22E-05	1.49E-04	1.34E-04
VPHv	1.60E+02	7.98E-01	2.39E+00	9.18E+00	6.39E+00
Xylenes	7.47E+00	3.73E-02	1.12E-01	3.36E-01	2.99E-01

*See Appendix C for detailed list

The second step involved evaluation of the SSC in context of criteria for when a soil vapour investigation is required using a ratio approach (Table 2), as follows:

1. For chlorinated solvent compounds, the ratio of the detection limit to SSC (Ratio 1) was calculated (see Table 3 and Appendix C for detailed list).

2. For compounds other than chlorinated solvent compounds, the ratio of the low-density residential soil standard (RL_{LD}) to SSC (Ratio 2) was calculated (see Table 4 and Appendix C for detailed list).

For the first calculation, the detection limit for chlorinated VOC analysis in soil was 0.05 ug/g, selected based on input provided by two laboratories (ALSGlobal and Caro) on the standard detection limit applicable to most VOCs. Note it is possible to request lower detection limits from the laboratory, but implementation of methods with lower detection limits may not be practical or needed.

Table 2 Ratios Used in Theoretical Partitioning Analysis

Dimensionless Ratios of Soil Criteria	Estimation of SSC	Applicability Substances	Interpretation*
$Ratio\ 1\ (R1) = \frac{DL}{SSC}$	RL Sch. 3.3 vapour standards and outdoor use; AF = 1E-04 RL, CL, IL, PK Sch. 3.3 vapour standards; AF = 2E-02	Chlorinated Solvent	R1 > 1 suggests theoretically vapour pathway could be concern at below soil DL
$Ratio\ 2\ (R2) = \frac{RL_{LD}}{SSC}$	Same as above	Non-chlorinated Solvent	R2 > 1 suggests theoretically vapour pathway could be concern at below RL_{LD} standard
$Ratio\ 3\ (R3) = \frac{CL_{\square}}{SSC}$	RL Sch 3.3 vapour standards and outdoor use; AF = 1E-04	All	R3 > 1 suggests theoretically vapour pathway could be concern at below CL standard

* note theoretical partitioning relationships tend to be highly conservative

For the second calculation, the low-density residential standard for the site-specific factor was used in the calculation where available.

The division of compounds for chlorinated and non-chlorinated solvents was based on interpretation of soil relocation Ministerial Order on criteria for when soil vapour investigation is required. Note a detailed substance list is not provided in the Order.

Table 3 Ratio of Detection Limit to Vapour Pathway Soil Screening Criteria for Chlorinated Solvent Compounds (Ratio 1) for Select Substances*

Substance	Outdoor	Agricultural, Urban Park, Residential	Commercial	Industrial	Parkade
dichloroethylene, 1,2- cis	4.77E-02	9.54E+00	2.86E+00	1.04E+00	1.15E+00
dichloroethylene, 1,1-	7.03E-02	1.41E+01	4.68E+00	1.41E+00	1.87E+00
dichloroethane, 1,2-	1.25E-01	2.51E+01	8.77E+00	2.70E+00	3.19E+00
tetrachloroethylene	1.40E-01	2.80E+01	1.12E+01	3.20E+00	3.73E+00
trichloroethylene	2.34E+00	4.68E+02	1.56E+02	4.68E+01	6.24E+01
vinyl chloride	1.68E+01	3.35E+03	9.58E+02	3.35E+02	3.72E+02

*See Appendix C for detailed list

Table 4 Ratio of Low-Density Soil Standard to Vapour Pathway Soil Screening Criteria for Non-chlorinated Solvent Compounds (Ratio 2) for Select Compounds*

Substance	Outdoor	Agricultural, Urban Park, Residential	Commercial	Industrial	Parkade
toluene (Aquatic Life-Freshwater)	2.12E-03	4.24E-01	1.41E-01	4.71E-02	5.30E-02
toluene (Drinking Water)	2.54E-02	5.09E+00	1.70E+00	5.65E-01	6.36E-01
naphthalene (Invertebrates)	4.63E-02	9.26E+00	3.09E+00	1.11E+00	1.11E+00
ethylbenzene (Drinking Water)	2.06E-01	4.12E+01	1.37E+01	4.58E+00	5.15E+00
toluene (Invertebrates)	6.36E-01	1.27E+02	4.24E+01	1.41E+01	1.59E+01
benzene (Drinking Water)	6.36E-01	1.27E+02	4.77E+01	1.91E+01	1.91E+01
toluene (Aquatic Life-Marine)	8.48E-01	1.70E+02	5.65E+01	1.88E+01	2.12E+01
xylenes (Drinking Water)	8.71E-01	1.74E+02	5.80E+01	1.93E+01	2.18E+01
VPHv	1.25E+00	2.51E+02	8.35E+01	2.18E+01	3.13E+01
xylenes (Aquatic Life-Freshwater)	2.68E+00	5.36E+02	1.79E+02	5.95E+01	6.70E+01
ethylbenzene (Aquatic Life-Freshwater)	2.75E+00	5.49E+02	1.83E+02	6.10E+01	6.86E+01
ethylbenzene (Aquatic Life-Marine)	2.75E+00	5.49E+02	1.83E+02	6.10E+01	6.86E+01
ethylbenzene (Invertebrates)	2.75E+00	5.49E+02	1.83E+02	6.10E+01	6.86E+01
naphthalene (Aquatic Life-Freshwater)	5.79E+00	1.16E+03	3.86E+02	1.39E+02	1.39E+02

Table 4 Ratio of Low-Density Soil Standard to Vapour Pathway Soil Screening Criteria for Non-chlorinated Solvent Compounds (Ratio 2) for Select Compounds*

Substance	Outdoor	Agricultural, Urban Park, Residential	Commercial	Industrial	Parkade
naphthalene (Drinking Water)	7.72E+00	1.54E+03	5.15E+02	1.85E+02	1.85E+02
toluene (Human Ingestion)	1.48E+01	2.97E+03	9.89E+02	3.30E+02	3.71E+02
xylenes (Invertebrates)	2.01E+01	4.02E+03	1.34E+03	4.46E+02	5.02E+02
benzene (Aquatic Life-Freshwater)	4.55E+01	9.09E+03	3.41E+03	1.36E+03	1.36E+03
isopropylbenzene	4.86E+01	9.72E+03	3.89E+03	1.11E+03	1.30E+03
ethylbenzene (Human Ingestion)	5.49E+01	1.10E+04	3.66E+03	1.22E+03	1.37E+03
naphthalene (Human Ingestion)	6.56E+01	1.31E+04	4.37E+03	1.57E+03	1.57E+03
benzene (Aquatic Life-Marine)	1.18E+02	2.36E+04	8.87E+03	3.55E+03	3.55E+03
trimethylbenzene, 1,3,5-	4.91E+02	9.83E+04	3.44E+04	5.29E+03	1.38E+04
xylenes (Human Ingestion)	1.14E+03	2.28E+05	7.59E+04	2.53E+04	2.85E+04
benzene (Invertebrates)	1.82E+03	3.64E+05	1.36E+05	5.46E+04	5.46E+04
benzene (Human Ingestion)	2.73E+03	5.46E+05	2.05E+05	8.18E+04	8.18E+04

*See Appendix C for detailed list

The comparison for chlorinated solvent compounds reveals that for the outdoor air pathway, in almost all cases, the detection limit is lower than the vapour pathway SSC (*i.e.*, a ratio DL/SSC < 1) as shown in Figure 2. A ratio less than one indicates vapour inhalation is likely not a concern while ratios greater than one indicate a possible concern. For indoor air vapour intrusion scenarios and an attenuation factor of 0.02, the detection limit is higher than the SSC in some cases by several orders of magnitude. However, the theoretical partitioning relationships are considered highly conservative, and degree of conservatism is potentially several orders of magnitude. Given the factors that would mitigate potential soil vapour concentrations in relocated soil such as likely localized, dispersed soil contamination and attenuation mechanisms, the current criteria for when a vapour investigation is required (detectable concentrations) may be reasonable based on theoretical and practical considerations.

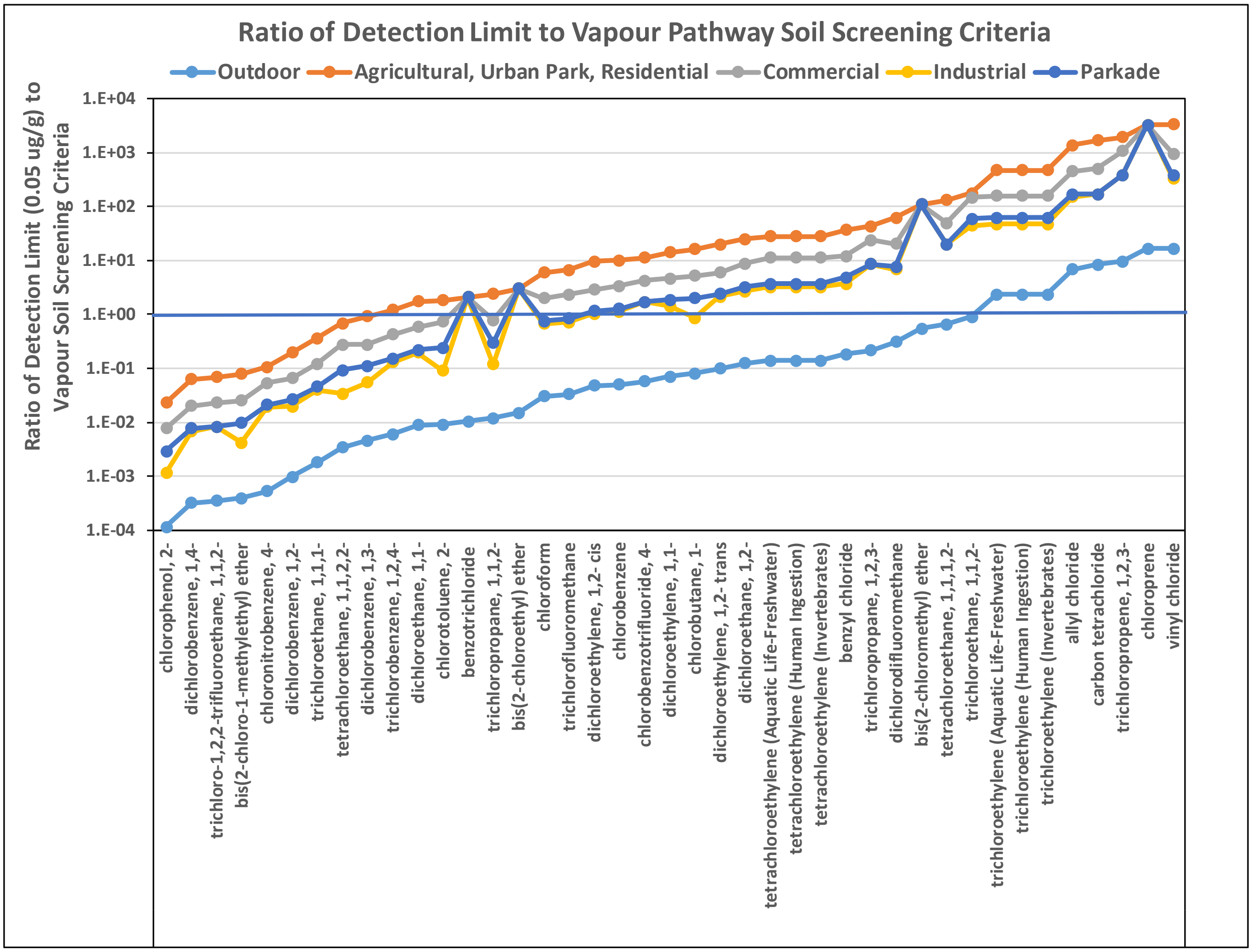


Figure 2. **Ratio of Detection Limit to Vapour Pathway Soil Screening Criteria (Ratio 2)**

The comparison for non-chlorinated solvent compounds reveals that the low-density residential land use (RL$_{LD}$) standard is higher than the back-calculated vapour pathway SSC for many substances and scenarios (Figure 3). However, for common PHC compounds such BTEX compounds and VPH, the soil standard is generally less than approximately 100X higher than the SSC when the lowest RL$_{LD}$ standard is applied. This means that the current criteria for when a vapour investigation is required (above residential soil standard) may be reasonable when the conservatism of the theoretical relationships are considered as demonstrated by the empirical partitioning analysis below. There are several compounds with very high ratios of low-density residential land use standard to back-calculated vapour pathway SSC (*e.g.*, tetrahydrofuran, dicyclopentadiene). These compounds may be more appropriately addressed through detection limit criteria for chlorinated solvent compounds.

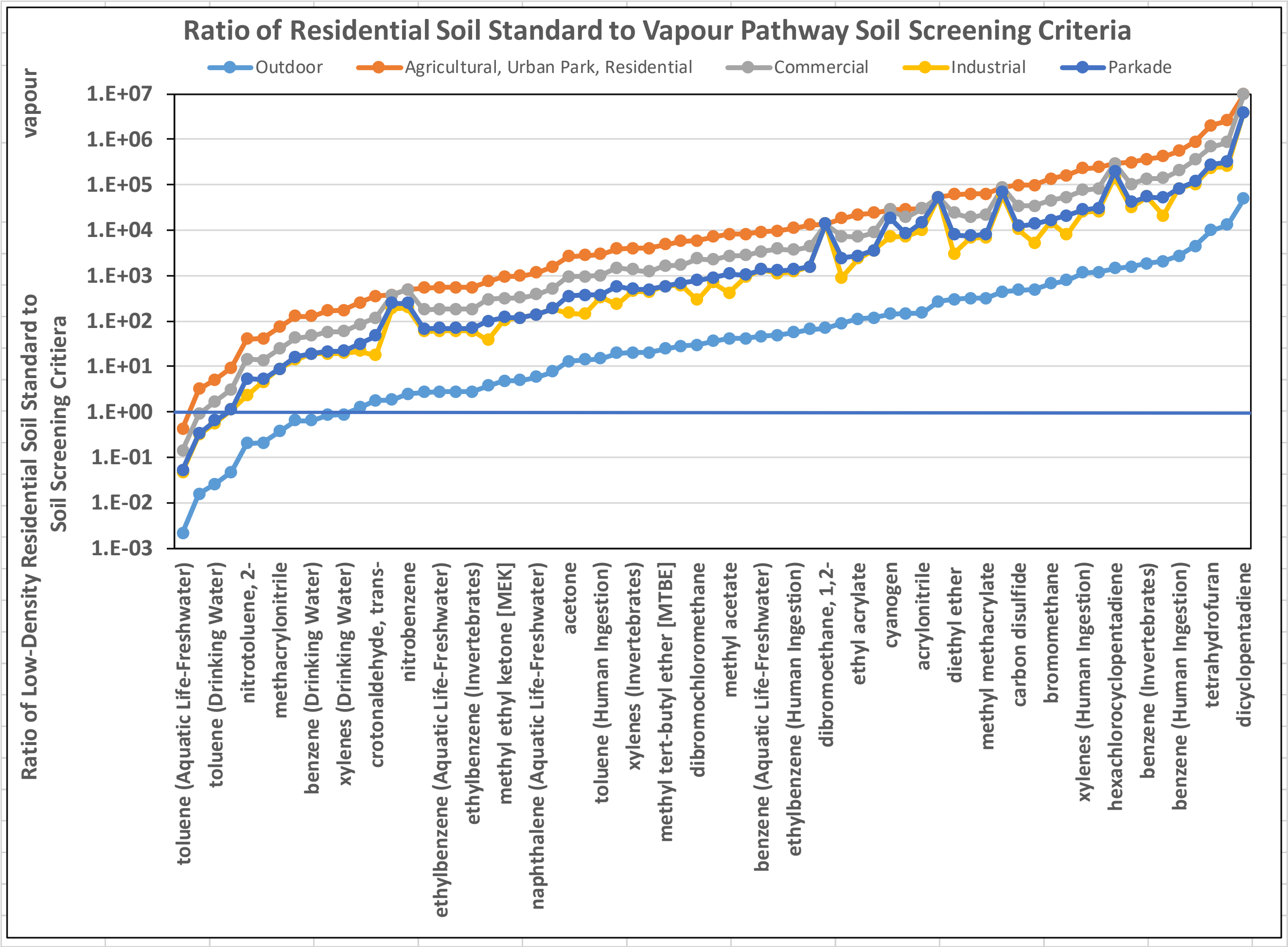


Figure 3. **Ratio of Low-Density Residential Soil Standard to Vapour Pathway Soil Screening Criteria (Ratio 2)**

6.3 Applicability of Outdoor Air VOC Inhalation Pathway for Soil Relocation

Based on current regulations, soils to be relocated to a site with only future outdoor inhalation exposure may require a soil vapour investigation, and no attenuation factor is applied to estimate breathing zone volatile concentrations. The finding of this study is that BC ENV *Protocol 22* attenuation factors should generally apply for soil reused at receiving sites, which is 0.0001 for the outdoor air pathway. In this context, two further questions are:

1. If an outdoor AF of 0.0001 is applied, would a vapour investigation be warranted for soil relocation?
2. What is the basis for *Protocol 22* outdoor air vapour attenuation factors?

Because waste soils may not be relocated, to provide insight into the first question, a theoretical analysis was conducted where the ratio of the commercial land use soil standard to the theoretical back-calculated soil standard for vapour pathway (Ratio 3) was calculated for the outdoor air pathway using an attenuation factor of 0.0001 (Table 5 and Appendix C). The results indicate widely varying results with ratios that are much less than one (indicating outdoor vapour inhalation is likely not a concern) to ratios that are much greater than one (indicating a possible concern). We note that the partitioning relationships are highly uncertain. In general, lower ratios were calculated for common petroleum hydrocarbon compounds compared to chlorinated solvent compounds. When the DW and AW water use standards apply, in almost all cases the ratios are close to or less than one (Table 5). This means even theoretical predicted vapour concentrations would never exceed standards for non-waste soils with PHCs. The results suggest a vapour investigation may not be warranted for the outdoor air pathway for PHCs when DW and AW water use standards apply in the context of soil relocation.

Table 5 Ratio of Commercial Soil Standard to Vapour Pathway Outdoor Soil Screening Criteria for Non-chlorinated Solvent Compounds (Ratio 3) for Select Compounds*

Substance	Outdoor
toluene (Aquatic Life-Freshwater)	2.12E-03
toluene (Drinking Water)	2.54E-02
ethylbenzene (Drinking Water)	2.06E-01
benzene (Drinking Water)	6.36E-01
toluene (Aquatic Life-Marine)	8.48E-01
xylenes (Drinking Water)	8.71E-01
VPHv	1.25E+00
naphthalene (Invertebrates)	1.54E+00
toluene (Invertebrates)	1.91E+00
xylenes (Aquatic Life-Freshwater)	2.68E+00
ethylbenzene (Aquatic Life-Freshwater)	2.75E+00
ethylbenzene (Aquatic Life-Marine)	2.75E+00
naphthalene (Aquatic Life-Freshwater)	5.79E+00
naphthalene (Drinking Water)	7.72E+00
ethylbenzene (Invertebrates)	8.92E+00
benzene (Aquatic Life-Freshwater)	4.55E+01

Table 5 Ratio of Commercial Soil Standard to Vapour Pathway Outdoor Soil Screening Criteria for Non-chlorinated Solvent Compounds (Ratio 3) for Select Compounds*

Substance	Outdoor
xylenes (Invertebrates)	8.04E+01
toluene (Human Ingestion)	8.48E+01
benzene (Aquatic Life-Marine)	1.18E+02
ethylbenzene (Human Ingestion)	3.43E+02
naphthalene (Human Ingestion)	3.86E+02
benzene (Invertebrates)	4.55E+03
xylenes (Human Ingestion)	6.70E+03
trimethylbenzene, 1,3,5-	8.19E+03
benzene (Human Ingestion)	1.82E+04

*See Appendix C for detailed list

To our knowledge, the derivation basis for outdoor air vapour attenuation factors in *Protocol 22* is not available. Compared to the vapour intrusion (indoor air) pathway, the outdoor air vapour inhalation pathway has received less attention in other regulatory jurisdictions. We are not aware of regulations or guidance with outdoor air vapour attenuation factors in other jurisdictions, although a detailed jurisdictional review was beyond the scope of this study. However, there are models that have been proposed for the derivation of soil criteria protective of volatile chemical migration to outdoor air (ASTM 2004) and regulatory examples, including the US EPA Soil Screening Guidance (US EPA 1996) and Health Canada Preliminary Quantitative Risk Assessment (PQRA) spreadsheet tool, although this tool is no longer supported by Health Canada. The CCME (2014) Protocol for the Derivation of Soil Vapour Quality Guidelines for Protection of Human Exposures *via* Inhalation of Vapours applies the ASTM (2004) model.

It is anticipated that in some cases there could be a disincentive to the beneficial reuse of non waste soils at sites where only the outdoor vapour inhalation pathway is relevant (*e.g.*, fill needed for roadworks or infrastructure projects) because of the requirements for a vapour investigation. Further evaluation of the outdoor air vapour inhalation pathway in the context of science-based attenuation factors, and in the specific application to soil relocation is considered warranted.

6.4 Empirical Data Analysis

The relations between soil, groundwater and soil vapour concentrations were evaluated for seven BC sites with publicly available data (Figures 4a to 4f). All data were for *in-situ* samples. Petroleum hydrocarbons (PHC) were constituents present at three sites, chlorinated solvents were present at two sites, and two sites were impacted by combinations of PHC 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, site geology was relatively complex with fill underlain by layered soil deposits.

The initial data filtering was 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. The vertical separation for soil-soil vapour pairs varied from as little as almost perfectly co-located (within 0.05 m) to approximately 4 m vertical separation (Figures 4a to 4f). When all data was considered, 58% of samples were within 1 m vertically while 42% of samples were greater than a meter apart. With respect to temporal comparisons, much of the paired data was concurrent within one year (Figures 4a to 4g). 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.

Data were screened out where both media types were less than the detection limit. Data was retained when one media type was non-detect and the other was detected. In most cases, the soil vapour concentrations were greater than the detection limit, and either or both the soil and groundwater concentrations were below the detection limit, although for one site, Site 6, there were detectable soil concentrations and non-detect soil vapour concentrations. For select substances, the soil vapour concentrations were estimated from groundwater concentrations and the Henry's Law constant, and from soil concentrations using the three-phase partitioning model in Appendix C. Particularly the estimates from soil concentrations are considered highly approximate and uncertain because of unknown soil properties (*e.g.*, fraction of organic carbon). The results are summarized as follows:

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. Limited or no correlation was observed between soil and soil vapour concentrations, with the "best" (while still poor) qualitative correlation observed at Site 7. The data does not support a quantitative correlation for establishing when a soil vapour assessment is required to support soil relocation. A better but still weak qualitative correlation was obtained between groundwater and soil vapour concentrations at several sites based on visual inspection of data.
3. Estimated soil vapour concentrations from soil partitioning were overpredicted at all sites, except one site with chlorinated solvent contamination (Site 4). For PHCs, the theoretical predicted soil vapour concentrations were one to two orders of magnitude (or more) greater than the measured concentrations. Estimated soil vapour concentrations from groundwater

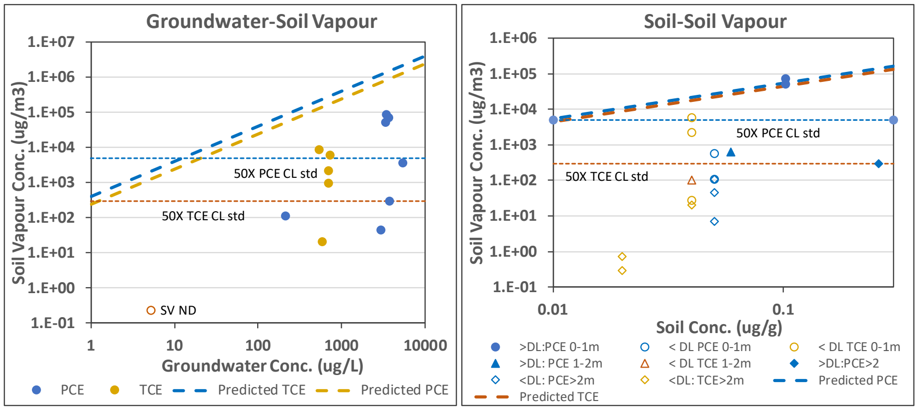
partitioning more closely matched measured concentrations, although in some cases groundwater also overpredicted the soil vapour concentrations.

There were several sites where most or almost all soil or groundwater concentrations were non-detect but where there were detectable concentrations in soil vapour. However, in general, the associated soil vapour concentrations were relatively low. To provide insight on the significance of these data, the soil vapour concentrations for non-detect soil or groundwater concentrations were attenuated by 50X and compared to the CSR Schedule 3.3. commercial land use standard for select substances. When all site data were analyzed, vapour concentrations for only two samples exceeded the attenuated standard. The data analysis generally supports the current decision criteria for when a soil vapour investigation is required for chlorinated solvent contamination (*i.e.,* detectable concentrations in soil).

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

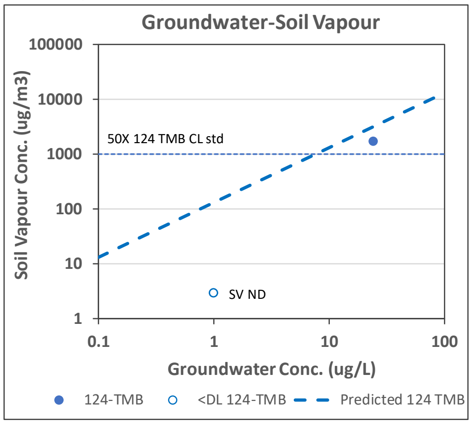
Soil vapour samples obtained from 0.2 to 1.2 m depth
Soil samples obtained from 0.38 to 5.2 m depth
Separation distance ranged from -0.75 to 4 m

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.

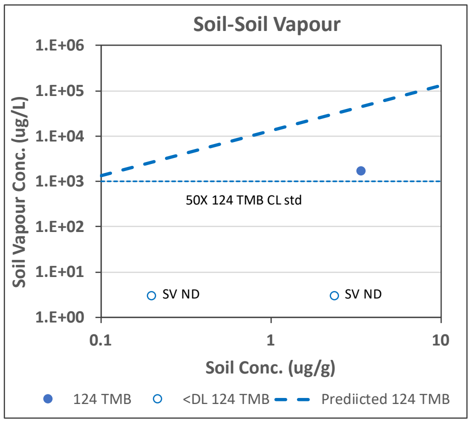
Site #2 **b**

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

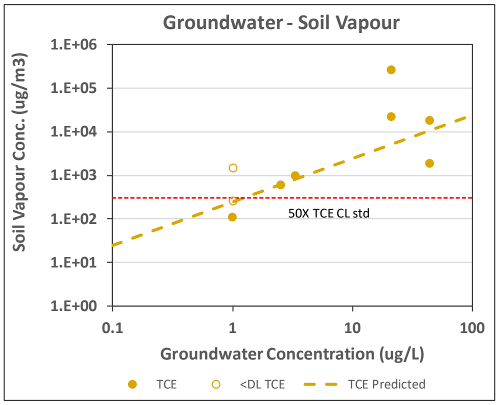


Soil vapour samples obtained from 0.75 to 1.3 m depth
Soil samples obtained from 1.95 to 2.05 m depth
Separation distance ranged from 0.75 to 1.3 m

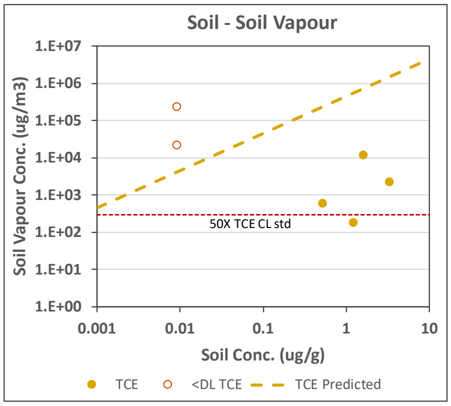
Site #3 **c**

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

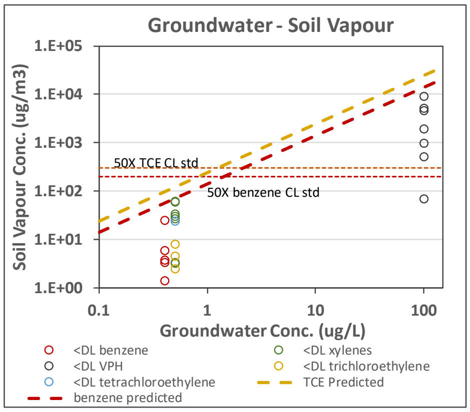


Soil vapour samples obtained from 0.5 to 1 m depth
Soil samples obtained from 1.6 to 4.6 m depth
Separation distance ranged from 0.7 to 4.05 m

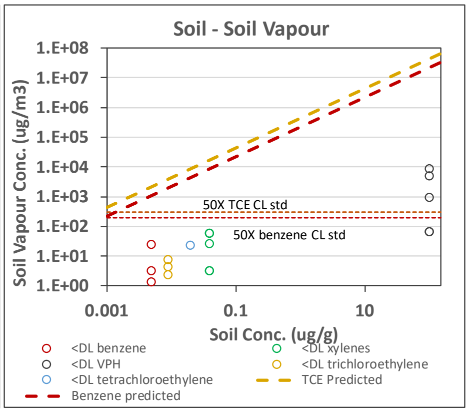
Site #4 **d**

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



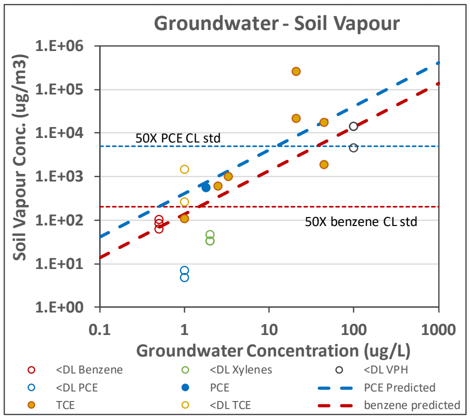
Soil vapour samples obtained from 0.4 to 0.6 m depth
Soil samples obtained from 0.65 to 1.35 m depth
Separation distance ranged from 0.2 to 0.95 m

Site #5 e

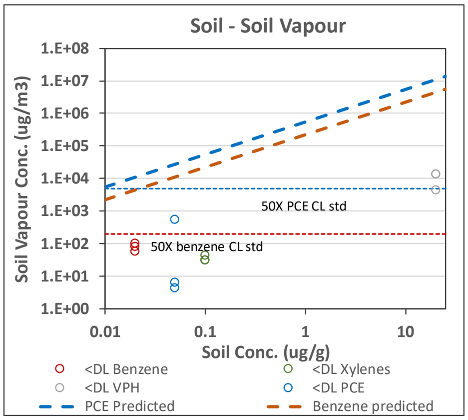
Site Location: Burnaby, BC

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

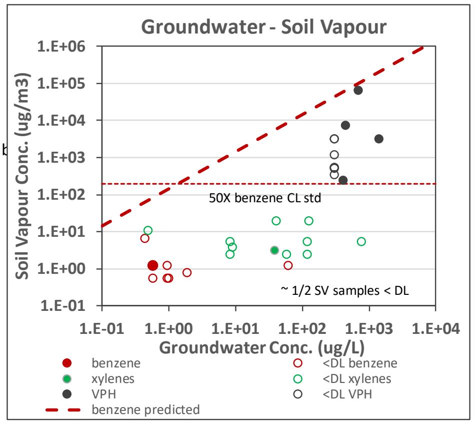


Soil vapour samples obtained from 1 to 1.1 m depth
Soil samples obtained from 0.84 to 2.75 m depth
Separation distance ranged from -0.26 to 1.74 m

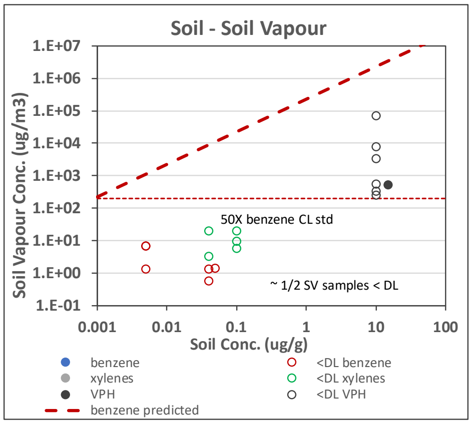
Site #6 f

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

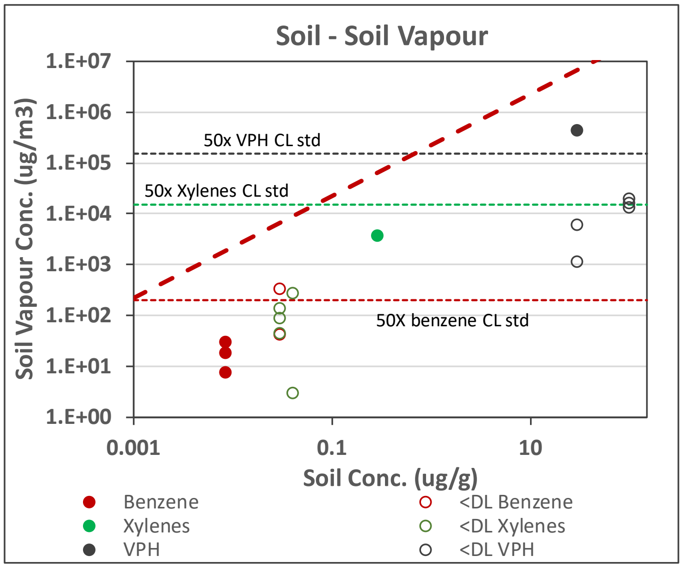


Soil vapour samples obtained from 2.3 to 5.9 m depth
Soil samples obtained from 2.8 to 6.3 m depth
Separation distance ranged from 0.1 to 3.4 m

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

Figure 4a-g. **Empirical Analysis of Comparison of Paired Groundwater-Soil Vapour and Soil-Soil Vapour Data (physical-chemical parameters are provided in the MEMS Stage 2 report, June 2024)**

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Background

The BC government recently enacted the Stage 14 Amendments to the Contaminated Sites Regulation (CSR). These Amendments, together with BC Ministry of Environment and Climate Change Strategy (BC ENV) *Protocol 19*, describe requirements for relocation of non-waste soils from CSR Schedule 2 sites including thresholds or criteria for when soil vapour characterization is required, application of vapour attenuation factors at receiving sites and soil vapour sampling (equilibration) of stockpiles. The conclusions drawn and recommendations with regards to these issues are summarized below.

7.2 Volatilization of VOCs During Soil Excavation and Handling

A literature review indicated volatilization losses through soil excavation and handling can be significant. Mass and concentration attenuation that occurs through volatilization and biodegradation will reduce potential vapour inhalation risk associated with residual contamination.

Because the degree of volatilization and biodegradation is highly site-specific, it would be difficult to generalize and include these processes in attenuation models and regulatory processes.

7.3 Equilibration of Vapour Concentrations in Stockpiles

Soil vapour sampling protocols should account for disturbance caused during installation of the soil gas probe whether in undisturbed or disturbed (stockpiled soil) ground. When installation methods with relatively low disturbance are used, it is considered acceptable practice to sample the probe after waiting a sufficient time to allow for quasi local equilibrium to occur without having to demonstrate equilibration through field soil gas (PID) testing provided that standard practices for purging are followed. When methods with higher disturbance are used, local equilibration should be demonstrated through field soil gas testing.

Broad-scale equilibration of vapour concentrations in stockpiles is not an achievable objective as concentrations will constantly change and generally decrease over time. Therefore, a general requirement to demonstrate equilibration based on PID testing is not considered warranted. A wait time of one week after stockpile placement prior to soil vapour sampling is considered reasonable.

7.4 Attenuation Factors

A review of regulations and guidance on soil relocation or excess soil from select jurisdictions in Canada and US was completed. None of the jurisdictions reviewed regulate soil reuse through a soil vapour investigation. Ontario has developed excess soil standards that include consideration of the vapour inhalation pathway. For shallow contamination sources, Ontario adopted the same empirical vapour attenuation factors for estimation of indoor air concentrations for excess soil (receiving) sites as for source sites, which are 0.02 for residential land use and 0.004 for commercial/industrial land use.[1] For deeper contamination sources, the Ontario soil standards for excess soil were derived using a model that assumes a depleting contamination source, and consequently attenuation factors were not derived or calculated. While several US jurisdictions have guidance and soil standards for soil reuse, none of the information reviewed specifically address the vapour inhalation pathway in context of soil reuse. Regulations for soil relocation in several US jurisdictions incorporate a principle that soil being relocated should not degrade the soil quality at the receiving site.

In our opinion, the currently used vertical attenuation factors in BC ENV *Protocol 22* should apply to soil reuse. For relocation of soil potentially in contact with buildings, an attenuation factor of 0.02 is considered appropriate and is recommended for vapour investigation at receiving sites.

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[1] Note this project scope did not include evaluation of attenuation factors including possible approaches similar to Ontario (or other jurisdictions) with variable attenuation factors depending on land use or building type. Attenuation factors are planned to be further evaluated in a follow-on project.

7.5 Criteria for Determining When Soil Vapour Investigation of Relocated Soil is Warranted

The use of soil concentration data for evaluation of vapour intrusion is typically not preferred as measurement of soil vapour concentrations is a more direct, and typically accurate approach. However, in the context of soil relocation, it is more practical to screen soil using soil concentration data, and consequently, it is important to understand and potentially refine criteria used for this purpose.

The comparison for **chlorinated solvent detection limits** in soil to back-calculated soil criteria protective of vapour inhalation pathway (**Ratio 1**) indicate for the outdoor air pathway it is unlikely that chlorinated solvents at the detection limit could be a concern. For the indoor vapour intrusion pathways, the Ratio 1 values vary widely, and for some substances, are significantly greater than one (indicating a potential concern); however, theoretical partitioning relationships are considered conservative in the context of soil relocation.

The comparison for **non-chlorinated solvent compound low-density residential standards** to back-calculated soil criteria protective of the vapour pathway (**Ratio 2**) indicate calculated ratios that vary widely depending on applicable site-specific factors; however, for the most conservative low density residential standards and PHC compounds, Ratio 2 values are generally within 100 times a value of one. When the conservatism of the theoretical soil partitioning relationship is considered, this indicates a likely protective screening approach. For Ratio 2, like Ratio 1, the outdoor air pathway is generally not a concern.

Theoretical analysis focused on the outdoor air vapour pathway was conducted by comparing **commercial land use soil standards** to back-calculated soil criteria protective of the vapour pathway (**Ratio 3**). This analysis suggests the outdoor air inhalation pathway is unlikely to be a concern for relocated PHC non-waste soil in most circumstances, and that a vapour investigation for the outdoor air pathway is likely not necessary. Further analysis of the outdoor air pathway concern including outdoor attenuation factors is recommended.

The following conclusions are drawn from the data analysis:

1. The theoretical data analysis in general supports the existing thresholds in the CSR Stage 14 amendments for determining when a soil vapour assessment is required for soil relocation.
2. The empirical data analysis does not support further quantitative refinement of thresholds based on general poor correlation between soil and soil vapour concentration data.
3. Greater specificity is recommended in defining applicable receiving site-specific factors for determining applicable low-density residential land use standards.

4. Select non-chlorinated solvent compounds (*e.g.*, bromated compounds) with high Ratio 2 values should be included in the chlorinated solvent class of compounds for determining when a vapour assessment is needed.
5. Vapour characterization for the purpose of soil relocation is likely not required when only the outdoor air pathway applies at the receiving site, for PHC compounds and non-waste soils.

A potentially useful observation from the empirical analysis is that estimated soil vapour concentrations from soil partitioning were overpredicted at all sites, except one site with chlorinated solvent contamination (Site 4). For PHCs, the theoretical predicted soil vapour concentrations were one to two orders of magnitude (or more) greater than the measured concentrations.

8.0 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: REVIEW OF SOIL REUSE INFORMATION FROM SELECT REGULATORY JURISDICTIONS

Appendix A – Review of Soil Reuse Information from Select Regulatory Jurisdictions

A review of regulations and guidance on soil relocation or reuse from select jurisdictions in Canada and US, and a paper focussed on European practice, was conducted with a focus of uncovering requirements in relation to volatile contaminants and vapour pathway concerns. General requirements for soil reuse are also summarized.

Ontario

The following regulations and guidance address excess soil:

- Ontario Regulation 406/19, On-Site and Excess Soil Management.
    - https://www.ontario.ca/laws/regulation/190406
- Ontario MOECC. Rules for Soil Management and Excess Soil Quality Standards, 2022.
    - https://files.ontario.ca/mecp-soil-rules-en-2022-12-29-v2.pdf
- Ontario MOECC. Rationale Document for Development of Excess Soil Quality Standards Date: December 08, 2020.
    - https://files.ontario.ca/mecp-rational-document-excess-soil-en-2020-12-21.pdf
- Ontario MOECC. Rationale Document for Reuse of Excess Soil at Receiving Sites.
    - http://www.downloads.ene.gov.on.ca/envision/env_reg/er/documents/2017/013-0299_Rationale.pdf

There are soil standards for excess soil use based on 1) 350 m^3 or less, or 2) unlimited volume. The 350 m^3 or less soil standards are the soil standards previously developed in Ontario for application at source sites. The unlimited volume standards are new standards specific to excess soil.

For shallow contamination scenarios, and for all excess soil volumes, instead of a model, empirical subslab to indoor air vapour attenuation factors were used in the soil standard derivation process, which were 0.02 for residential land-use and 0.004 for commercial/industrial land use. Consequently, the standards for source sites and excess (receiving) soil sites were identical for shallow contamination scenarios for the vapour inhalation pathway scenario.

For deeper soil contamination scenarios, a depleting soil contamination source was modelled for the vapour inhalation pathway. The assumed volume of contaminated soil below the building was 350 m^3 in the development of the source site standards. For soil relocation, adjusted modelled standards were considered required for volumes > 350 m^3. With larger volumes of soil, there is less contaminant depletion. This combined with the $1x10^{-6}$ risk threshold for carcinogenic chemicals resulted in very low unlimited volume standards. For example, the benzene soil standard for almost every standards scenario is the detection limit (0.02 ug/g). For the deeper soil contamination scenario, an attenuation factor was not directly used in the derivation process (nor can be backcalculated) because a depleting soil contamination source was assumed, as described above.

In support of the On-Site and Excess Soil Management Regulation, MOECC developed the Beneficial Reuse Assessment Tool (the "BRAT"). The BRAT is an Excel-based spreadsheet model that allows for the development of site-specific excess soil quality standards by modifying (1) a limited number of physical characteristics of the excess soil and the reuse site and/or (2) the soil to groundwater (S-GW) exposure pathways using leachate analysis. The BRAT also allows the Qualified Person to modify certain exposure pathways by using predefined "site use characteristics". Ontario Regulation 406/19, On-Site and Excess Soil Management, requires that a sampling and analysis plan be prepared. Ontario MOECC Rules for Soil Management and Excess Soil Quality Standards (2022) describe sampling requirements including density of samples. There are no sampling requirements in relation to soil vapour.

Quebec

Three regulations with possible application to soil reuse were briefly reviewed:

- Chapter Q-2, r. 47.01, *"Regulation respecting the traceability of excavated contaminated soils".*
- Chapter Q-2, r. 18, *"Regulation respecting the burial of contaminated soils".*
- Chapter Q-2, r. 46, *"Regulation respecting contaminated soil storage and contaminated soil transfer stations".*

The purpose of Regulation 47.01 is to limit and control the contamination caused or likely to be caused by excavated contaminated soils, through the implementation of traceability measures to ensure that such soils are discharged in a site where they may be received.

There appears to be no reference to soil vapour concerns in the above regulations.

Massachusetts

Under the Massachusetts Contingency Plan ("MCP", 310 CMR 40.0000), a "Similar Soils" Regulation and Policy governs requirements for management of soil which is demonstrated to have little or no contamination. The managed soil must not be significantly more contaminated than the soil at the receiving location. Additionally, concentration thresholds regulate soil disposal requirements. A specific testing protocol for soil reuse does not appear to exist under the Massachusetts regulations.

New Jersey

The New Jersey Department of Environmental Protection (NJDEP) *"Guidance for Beneficial Use of Soil and Non-Soil Material in the Remediation of Contaminated Sites and Closure of Solid Waste Landfills"*, June 2008. https://www.nj.gov/dep/srp/guidance/alternative_fill/afp_guide.pdf

provides guidance on the beneficial use of contaminated soil and non-soil materials, that might otherwise become solid waste, in a way that is protective of human health, safety and the environment. In general, beneficial use material can only contain the same contaminants as those found at the receiving site. For the evaluation of discrete sample data, the maximum concentration of a contaminant in the beneficial use material from the originating site cannot exceed the 75th percentile of the contaminant concentration at the receiving site. The 75th percentile was selected to provide a measure of conservatism and yet allow some exceedance of the average at the receiving site by individual values in the imported material.

Pennsylvania

The Pennsylvania Department of Environmental Protection (DEP) "*Management of Fill Policy*" describes fill classification, testing requirements and Clean Fill Concentration Limits (CFCLs). Clean fill can be reused on site or another site. Any person placing clean fill which has been affected by a release of a regulated substance must certify the origin of the fill material and the results of analytical testing. Materials identified as regulated fill are a waste and must be managed in accordance with residual waste regulations. The *Management of Fill Policy* includes statistical-based soil sampling requirements.

New York

New York Department of Environmental Conservation regulates soil reuse based on source and type, and where warranted, results of soil analyses (6 CRR-NY 360.12NY-CRR). There are several classes of fill depending on the results (general fill, restricted fill, limited fill). On basis of fill type and testing, a Beneficial Use Determination (BUD) can be made pursuant to 6 NYCRR Part 360.12, and if eligible, the waste material ceases to be considered a solid waste when used as described in the BUD. Once the soil receives a BUD, it allows the clean soil to move in commerce including in land banks as storage for sites that require soil.

European Paper

Hale *et al*. (2021) present a survey of European jurisdictions on reuse of urban soils. The construction and demolition of infrastructure can produce a surplus of excavated soils that often ends up at landfills. This practice is not sustainable, and approaches are needed to reduce soil waste and minimize environmental and human health hazards. Reusing excavated soil offers the following benefits: (1) reduction in transportation distance, (2) reduction in costs associated with disposal, (3) preservation of landfill capacity, (4) conservation of mined natural resources, and (5) reduction of environmental and ecological impacts. The reuse of surplus excess soil requires consideration of geoenvironmental and geotechnical considerations. General principles embodied in legislation of several countries includes designation of surplus soils as waste; however, such soils can be reused offsite if: (1) the soil quality of the recipient site is maintained, *i.e.*, chemical properties of the excavated soil are consistent with the geochemical background of the recipient site, (2) the quality of the water resources at the recipient site are maintained and its ecosystems are preserved, and (3) chemical features of excavated soils are compatible with the expected use at the recipient site. Some countries have specific multi-tier classification of soil based on contamination thresholds and corresponding requirements for reuse. There was no reference to soil vapour in this paper.

APPENDIX B: SOIL VAPOUR DIFFUSION NUMERICAL MODELING

Appendix B – Soil Vapour Diffusion Numerical Modeling

A 2D finite difference numerical model for transient concentration vapour diffusion was created in EXCEL using the iteration function. The equation for 2D transient diffusion is as follows (Eq. 1):

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\delta X^2} + D_y \frac{\partial^2 C}{\delta Y^2} \quad \text{Eq. 1}$$

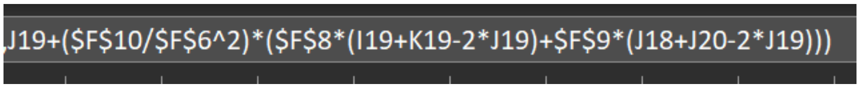
The finite difference equation based on explicit solution is as follows (Eq. 2):

$$\frac{1}{\Delta t}\left[C_{i,j}^{n+1} - C_{i,j}^{n}\right] = \frac{D_x}{\Delta X^2}\left[\, C_{i+1,j}^{n} - 2C_{i,j}^{n} + C_{i-1,j}^{n}\right\} + \frac{D_y}{\Delta Y^2}\left[\, C_{i,j+1}^{n} - 2C_{i,j}^{n} + C_{i,j-1}^{n}\right\} \quad \text{Eq. 2}$$

Assuming a rectangular grid where $\Delta X = \Delta Y$ results in (Eq. 3):

$$C_{i,j}^{n+1} = C_{i,j}^{n} + \frac{\Delta t}{\Delta X^2}\left[\, D_x\left[\, C_{i+1,j}^{n} - 2C_{i,j}^{n} + C_{i-1,j}^{n}\right\} + D_y\left[\, C_{i,j+1}^{n} - 2C_{i,j}^{n} + C_{i,j-1}^{n}\right\}\right] \quad \text{Eq. 3}$$

A cell from the spreadsheet programming the above is as follows (Eq 4.):



```
J19+($F$10/$F$6^2)*($F$8*(I19+K19-2*J19)+$F$9*(J18+J20-2*J19)))
```

Eq. 4

Where:

$F$10 = Δt, sec

$F$6 = Δx^2, m^2

$F$8 = D_x, m^2/s

$F$9 = D_y, m^2/s

All remaining cells in above equation are concentrations (ug/m^3)

The stability criterion for an explicit solution is (Eq. 5):

$$\Delta t \ll \Delta x^2 / 2Dx, \quad \Delta t \ll \Delta y^2 / 2Dy \quad \text{Eq. 5}$$

The initial conditions are specified interior node concentrations. The boundary conditions are constant zero concentration at the sides and top of the model domain (stockpile). Consequently, there is mass lost from the sides and top of stockpile. The bottom boundary condition is a no flow or transport boundary, which is achieved through a "mirror image" boundary. This is considered realistic because there will be little mass loss through the base of the stockpile.

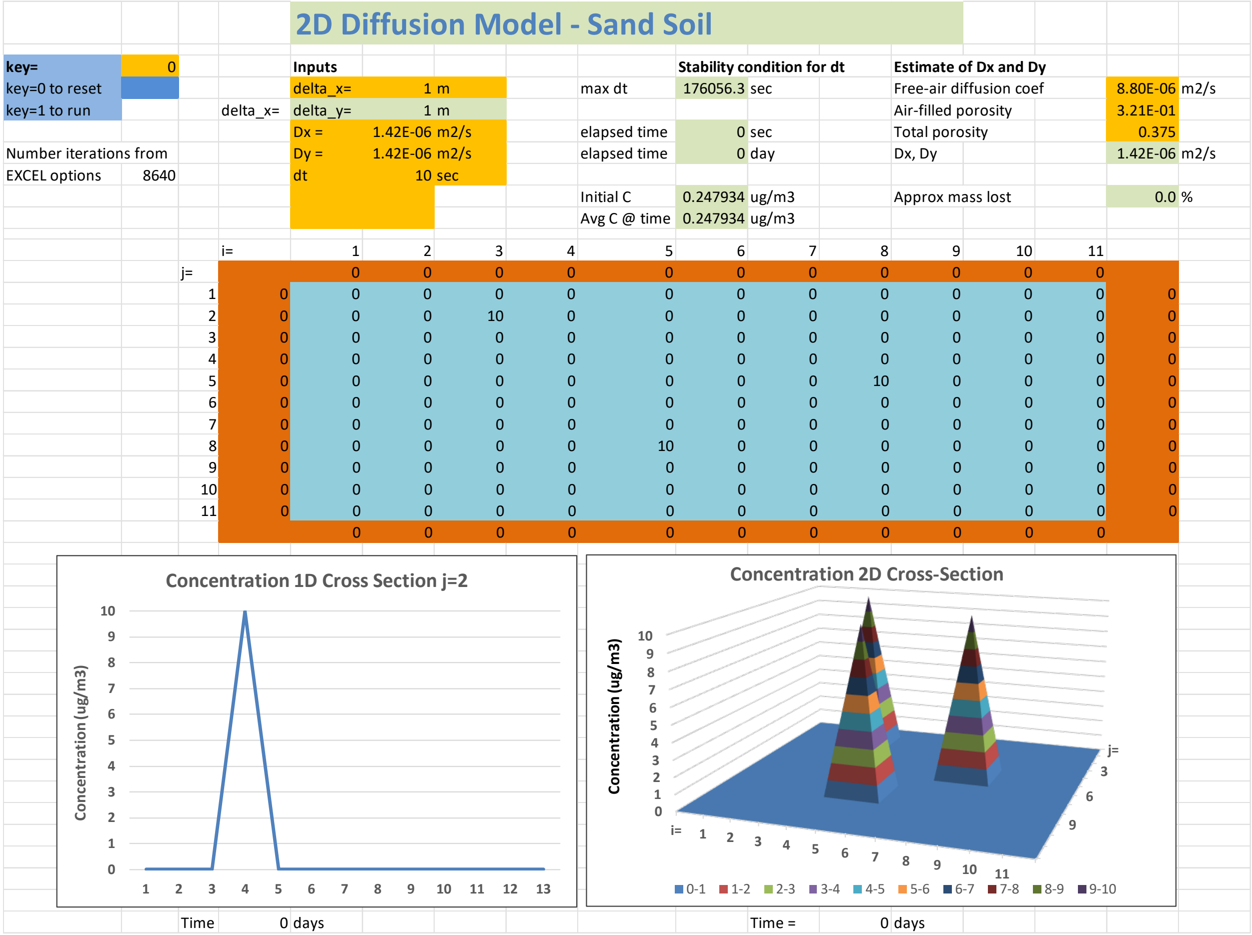
The model assumes that the initial conditions are a stockpile with elevated vapour concentrations at discrete locations within the stockpile. The concentrations are allowed to dissipate through diffusion only. There is zero mass associated with the concentration. This is an unrealistic assumption but is considered reasonable for a low mass / concentration scenario with discrete, localized sources, which is the expectation for soil undergoing relocation. The model does not consider biodegradation, which could increase the rate of concentration attenuation and source degradation. It also does not include sorption, which will slow the rate of vapour diffusion. It would be possible to modify the model formulation to include an apparent diffusivity term that includes sorption, but this was not considered warranted for this study.

Model simulations were performed for a hypothetical stockpile with height and width both of 11 m. The model is discretized into 1 m by 1 m grids. The initial conditions are a concentration of 10 ug/m^3 at three arbitrarily chosen locations within the soil stockpile and zero concentration at all other locations. The time step is set to 10 s, and the number of iterations set in EXCEL Options setting is 8640. This means each time the model run (by pressing the F9 key), there is one day of elapsed time.

The model was run for two soil scenarios, a sand soil, which is relatively dry, and loam soil, with higher moisture content. The input parameters for air-filled and total porosity for these soils were obtained from the US EPA Superfund Johnson and Ettinger spreadsheet.

The results, shown in the figures below, indicate a significant decline in concentrations occur for the sand soil scenario. For loam, the results indicate slower concentration attenuation. The concentration plots show a decline in concentrations at the node with the initial elevated concentration, and a temporary increase in concentration at immediately adjacent nodes, i.e., initial increase in concentration and then a decrease.

While the results are specific to the assumptions incorporated in the modeling and are not intended to provide quantitative criteria, they suggest that hot-spot concentrations in stockpiles will attenuate relatively quickly when sources are negligible (time scale of weeks). The results generally indicate concentrations in stockpiles will vary spatially and temporally and that broad-scale equilibration of concentrations is unlikely to occur.



2D Diffusion Model - Sand Soil

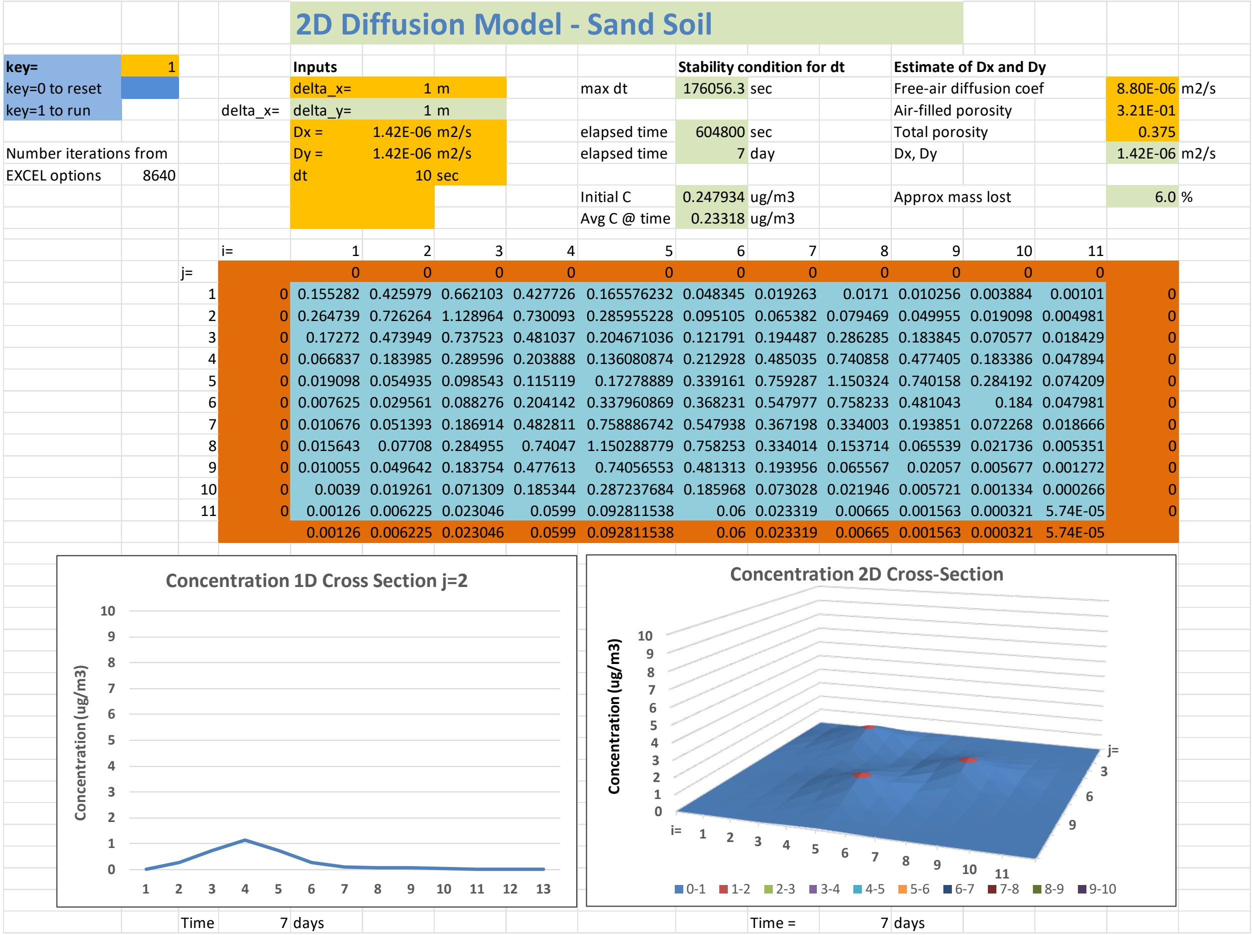
key=	0		Inputs			Stability condition for dt			Estimate of Dx and Dy		
key=0 to reset			delta_x=	1	m	max dt	176056.3	sec	Free-air diffusion coef	8.80E-06	m2/s
key=1 to run		delta_x=	delta_y=	1	m				Air-filled porosity	3.21E-01	
			Dx =	1.42E-06	m2/s	elapsed time	0	sec	Total porosity	0.375	
Number iterations from			Dy =	1.42E-06	m2/s	elapsed time	0	day	Dx, Dy	1.42E-06	m2/s
EXCEL options	8640		dt	10	sec						
						Initial C	0.247934	ug/m3	Approx mass lost	0.0	%
						Avg C @ time	0.247934	ug/m3			

	i=	1	2	3	4	5	6	7	8	9	10	11	
j=		0	0	0	0	0	0	0	0	0	0	0	
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	10	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	10	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	10	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0
		0	0	0	0	0	0	0	0	0	0	0	

Time 0 days

Time = 0 days

Figure B1. Initial Conditions for Sand and Silt Scenarios



2D Diffusion Model - Sand Soil

key= 1
key=0 to reset
key=1 to run

Number iterations from EXCEL options 8640

Inputs
delta_x= 1 m
delta_x= delta_y= 1 m
Dx = 1.42E-06 m2/s
Dy = 1.42E-06 m2/s
dt 10 sec

Stability condition for dt
max dt 176056.3 sec
elapsed time 604800 sec
elapsed time 7 day
Initial C 0.247934 ug/m3
Avg C @ time 0.23318 ug/m3

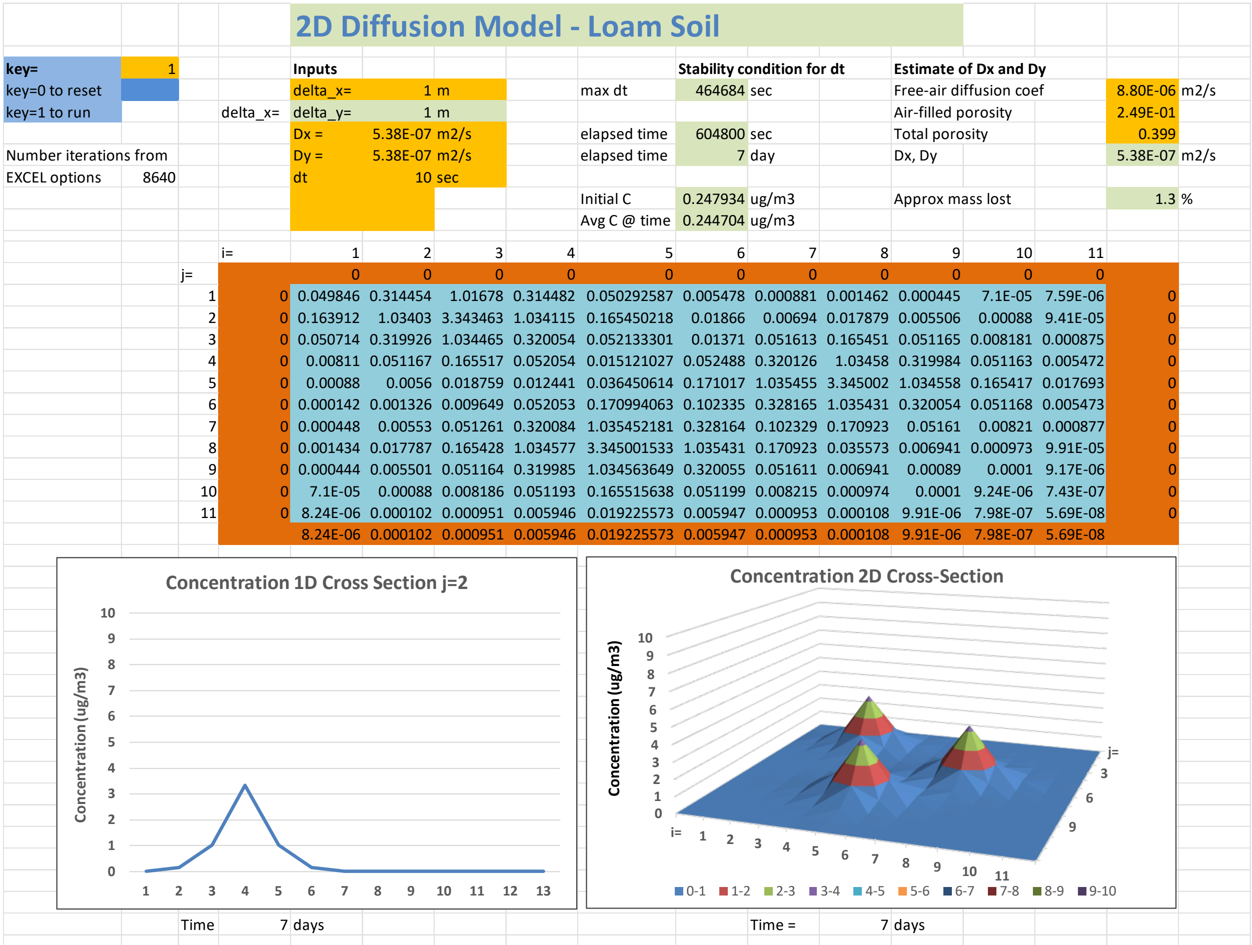
Estimate of Dx and Dy
Free-air diffusion coef 8.80E-06 m2/s
Air-filled porosity 3.21E-01
Total porosity 0.375
Dx, Dy 1.42E-06 m2/s
Approx mass lost 6.0 %

	i=	1	2	3	4	5	6	7	8	9	10	11	
j=		0	0	0	0	0	0	0	0	0	0	0	
1	0	0.155282	0.425979	0.662103	0.427726	0.165576232	0.048345	0.019263	0.0171	0.010256	0.003884	0.00101	0
2	0	0.264739	0.726264	1.128964	0.730093	0.285955228	0.095105	0.065382	0.079469	0.049955	0.019098	0.004981	0
3	0	0.17272	0.473949	0.737523	0.481037	0.204671036	0.121791	0.194487	0.286285	0.183845	0.070577	0.018429	0
4	0	0.066837	0.183985	0.289596	0.203888	0.136080874	0.212928	0.485035	0.740858	0.477405	0.183386	0.047894	0
5	0	0.019098	0.054935	0.098543	0.115119	0.17278889	0.339161	0.759287	1.150324	0.740158	0.284192	0.074209	0
6	0	0.007625	0.029561	0.088276	0.204142	0.337960869	0.368231	0.547977	0.758233	0.481043	0.184	0.047981	0
7	0	0.010676	0.051393	0.186914	0.482811	0.758886742	0.547938	0.367198	0.334003	0.193851	0.072268	0.018666	0
8	0	0.015643	0.07708	0.284955	0.74047	1.150288779	0.758253	0.334014	0.153714	0.065539	0.021736	0.005351	0
9	0	0.010055	0.049642	0.183754	0.477613	0.74056553	0.481313	0.193956	0.065567	0.02057	0.005677	0.001272	0
10	0	0.0039	0.019261	0.071309	0.185344	0.287237684	0.185968	0.073028	0.021946	0.005721	0.001334	0.000266	0
11	0	0.00126	0.006225	0.023046	0.0599	0.092811538	0.06	0.023319	0.00665	0.001563	0.000321	5.74E-05	0
		0.00126	0.006225	0.023046	0.0599	0.092811538	0.06	0.023319	0.00665	0.001563	0.000321	5.74E-05	

Time 7 days

Time = 7 days

Figure B2. Predicted Concentrations for Sand after One Week



2D Diffusion Model - Loam Soil

key= 1
key=0 to reset
key=1 to run
Number iterations from EXCEL options 8640

Inputs
delta_x= 1 m
delta_x= delta_y= 1 m
Dx = 5.38E-07 m2/s
Dy = 5.38E-07 m2/s
dt 10 sec

Stability condition for dt
max dt 464684 sec
elapsed time 604800 sec
elapsed time 7 day
Initial C 0.247934 ug/m3
Avg C @ time 0.244704 ug/m3

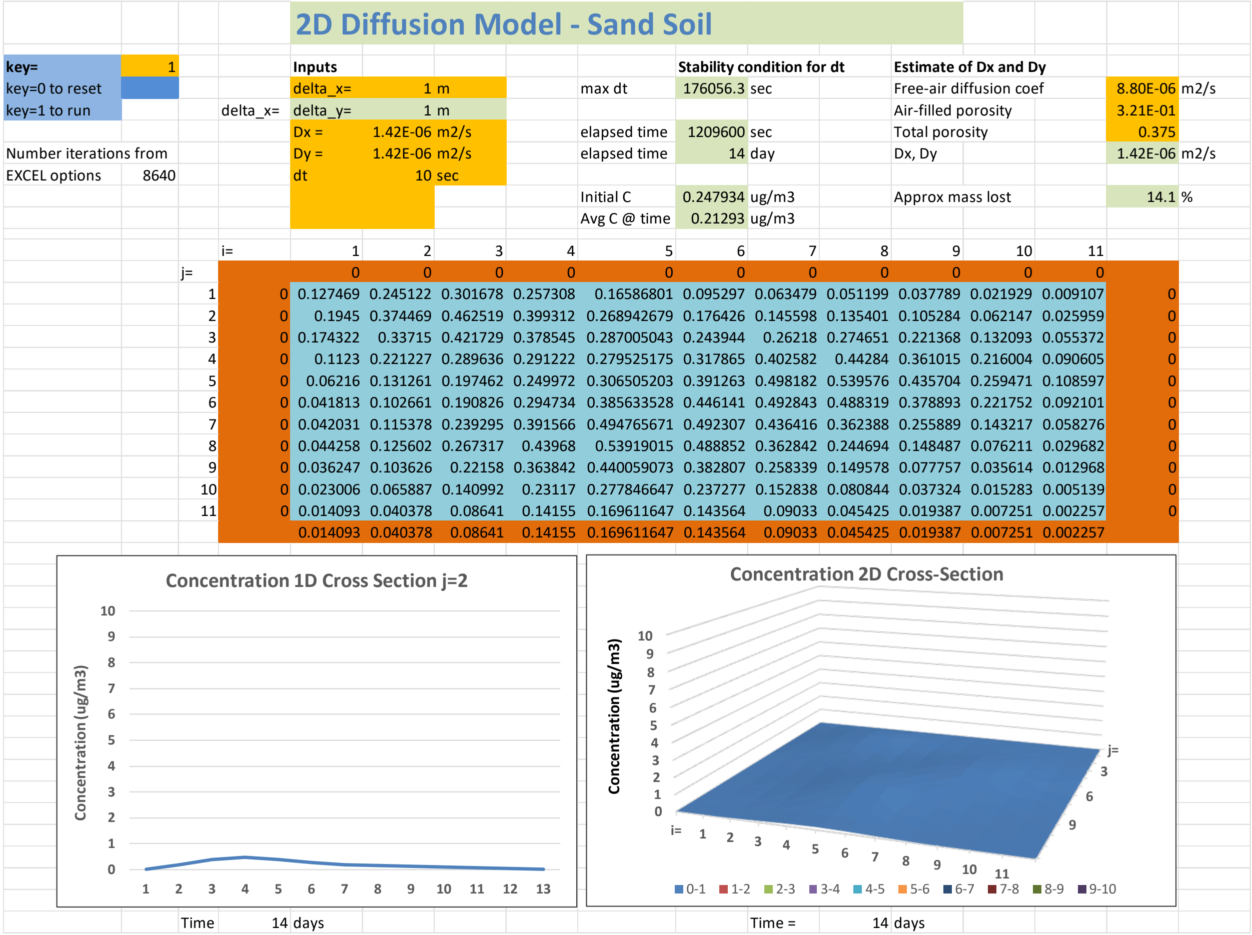
Estimate of Dx and Dy
Free-air diffusion coef 8.80E-06 m2/s
Air-filled porosity 2.49E-01
Total porosity 0.399
Dx, Dy 5.38E-07 m2/s
Approx mass lost 1.3 %

	i=	1	2	3	4	5	6	7	8	9	10	11	
j=		0	0	0	0	0	0	0	0	0	0	0	
1	0	0.049846	0.314454	1.01678	0.314482	0.050292587	0.005478	0.000881	0.001462	0.000445	7.1E-05	7.59E-06	0
2	0	0.163912	1.03403	3.343463	1.034115	0.165450218	0.01866	0.00694	0.017879	0.005506	0.00088	9.41E-05	0
3	0	0.050714	0.319926	1.034465	0.320054	0.052133301	0.01371	0.051613	0.165451	0.051165	0.008181	0.000875	0
4	0	0.00811	0.051167	0.165517	0.052054	0.015121027	0.052488	0.320126	1.03458	0.319984	0.051163	0.005472	0
5	0	0.00088	0.0056	0.018759	0.012441	0.036450614	0.171017	1.035455	3.345002	1.034558	0.165417	0.017693	0
6	0	0.000142	0.001326	0.009649	0.052053	0.170994063	0.102335	0.328165	1.035431	0.320054	0.051168	0.005473	0
7	0	0.000448	0.00553	0.051261	0.320084	1.035452181	0.328164	0.102329	0.170923	0.05161	0.00821	0.000877	0
8	0	0.001434	0.017787	0.165428	1.034577	3.345001533	1.035431	0.170923	0.035573	0.006941	0.000973	9.91E-05	0
9	0	0.000444	0.005501	0.051164	0.319985	1.034563649	0.320055	0.051611	0.006941	0.00089	0.0001	9.17E-06	0
10	0	7.1E-05	0.00088	0.008186	0.051193	0.165515638	0.051199	0.008215	0.000974	0.0001	9.24E-06	7.43E-07	0
11	0	8.24E-06	0.000102	0.000951	0.005946	0.019225573	0.005947	0.000953	0.000108	9.91E-06	7.98E-07	5.69E-08	0
		8.24E-06	0.000102	0.000951	0.005946	0.019225573	0.005947	0.000953	0.000108	9.91E-06	7.98E-07	5.69E-08	

Time 7 days

Time = 7 days

Figure B3. Predicted Concentrations for Loam after One Week



2D Diffusion Model - Sand Soil

key= 1
key=0 to reset
key=1 to run
Number iterations from EXCEL options 8640

Inputs
delta_x= 1 m
delta_x= delta_y= 1 m
Dx = 1.42E-06 m2/s
Dy = 1.42E-06 m2/s
dt 10 sec

Stability condition for dt
max dt 176056.3 sec
elapsed time 1209600 sec
elapsed time 14 day
Initial C 0.247934 ug/m3
Avg C @ time 0.21293 ug/m3

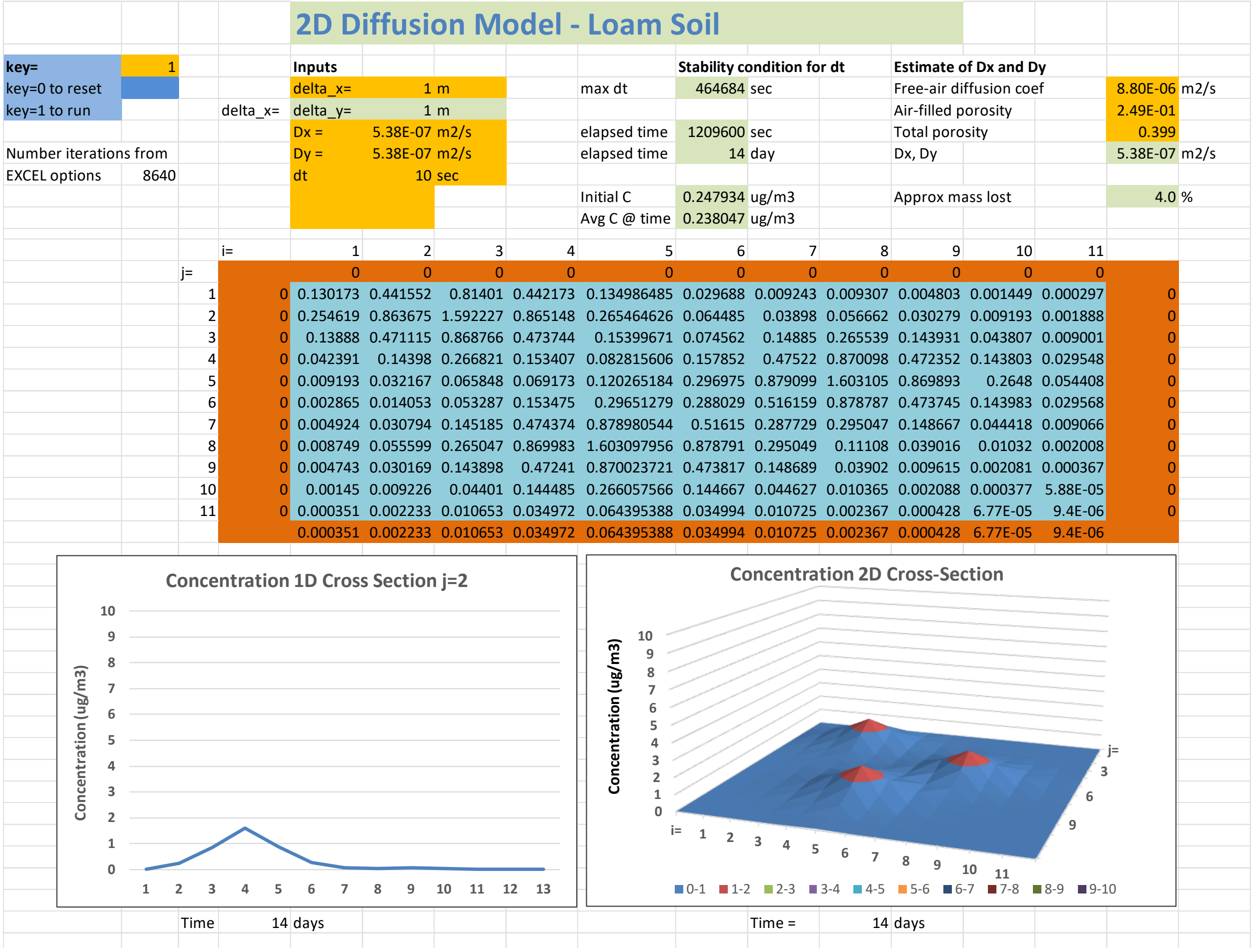
Estimate of Dx and Dy
Free-air diffusion coef 8.80E-06 m2/s
Air-filled porosity 3.21E-01
Total porosity 0.375
Dx, Dy 1.42E-06 m2/s
Approx mass lost 14.1 %

	i=	1	2	3	4	5	6	7	8	9	10	11	
j=		0	0	0	0	0	0	0	0	0	0	0	
1	0	0.127469	0.245122	0.301678	0.257308	0.16586801	0.095297	0.063479	0.051199	0.037789	0.021929	0.009107	0
2	0	0.1945	0.374469	0.462519	0.399312	0.268942679	0.176426	0.145598	0.135401	0.105284	0.062147	0.025959	0
3	0	0.174322	0.33715	0.421729	0.378545	0.287005043	0.243944	0.26218	0.274651	0.221368	0.132093	0.055372	0
4	0	0.1123	0.221227	0.289636	0.291222	0.279525175	0.317865	0.402582	0.44284	0.361015	0.216004	0.090605	0
5	0	0.06216	0.131261	0.197462	0.249972	0.306505203	0.391263	0.498182	0.539576	0.435704	0.259471	0.108597	0
6	0	0.041813	0.102661	0.190826	0.294734	0.385633528	0.446141	0.492843	0.488319	0.378893	0.221752	0.092101	0
7	0	0.042031	0.115378	0.239295	0.391566	0.494765671	0.492307	0.436416	0.362388	0.255889	0.143217	0.058276	0
8	0	0.044258	0.125602	0.267317	0.43968	0.53919015	0.488852	0.362842	0.244694	0.148487	0.076211	0.029682	0
9	0	0.036247	0.103626	0.22158	0.363842	0.440059073	0.382807	0.258339	0.149578	0.077757	0.035614	0.012968	0
10	0	0.023006	0.065887	0.140992	0.23117	0.277846647	0.237277	0.152838	0.080844	0.037324	0.015283	0.005139	0
11	0	0.014093	0.040378	0.08641	0.14155	0.169611647	0.143564	0.09033	0.045425	0.019387	0.007251	0.002257	0
		0.014093	0.040378	0.08641	0.14155	0.169611647	0.143564	0.09033	0.045425	0.019387	0.007251	0.002257	

Time 14 days

Time = 14 days

Figure B4. Predicted Concentrations for Sand after Two Weeks



2D Diffusion Model - Loam Soil

key=	1		**Inputs**			**Stability condition for dt**		**Estimate of Dx and Dy**	
key=0 to reset			delta_x=	1 m	max dt	464684 sec		Free-air diffusion coef	8.80E-06 m2/s
key=1 to run		delta_x=	delta_y=	1 m				Air-filled porosity	2.49E-01
			Dx =	5.38E-07 m2/s	elapsed time	1209600 sec		Total porosity	0.399
Number iterations from			Dy =	5.38E-07 m2/s	elapsed time	14 day		Dx, Dy	5.38E-07 m2/s
EXCEL options	8640		dt	10 sec					
					Initial C	0.247934 ug/m3		Approx mass lost	4.0 %
					Avg C @ time	0.238047 ug/m3			

	i=	1	2	3	4	5	6	7	8	9	10	11	
j=		0	0	0	0	0	0	0	0	0	0	0	
1	0	0.130173	0.441552	0.81401	0.442173	0.134986485	0.029688	0.009243	0.009307	0.004803	0.001449	0.000297	0
2	0	0.254619	0.863675	1.592227	0.865148	0.265464626	0.064485	0.03898	0.056662	0.030279	0.009193	0.001888	0
3	0	0.13888	0.471115	0.868766	0.473744	0.15399671	0.074562	0.14885	0.265539	0.143931	0.043807	0.009001	0
4	0	0.042391	0.14398	0.266821	0.153407	0.082815606	0.157852	0.47522	0.870098	0.472352	0.143803	0.029548	0
5	0	0.009193	0.032167	0.065848	0.069173	0.120265184	0.296975	0.879099	1.603105	0.869893	0.2648	0.054408	0
6	0	0.002865	0.014053	0.053287	0.153475	0.29651279	0.288029	0.516159	0.878787	0.473745	0.143983	0.029568	0
7	0	0.004924	0.030794	0.145185	0.474374	0.878980544	0.51615	0.287729	0.295047	0.148667	0.044418	0.009066	0
8	0	0.008749	0.055599	0.265047	0.869983	1.603097956	0.878791	0.295049	0.11108	0.039016	0.01032	0.002008	0
9	0	0.004743	0.030169	0.143898	0.47241	0.870023721	0.473817	0.148689	0.03902	0.009615	0.002081	0.000367	0
10	0	0.00145	0.009226	0.04401	0.144485	0.266057566	0.144667	0.044627	0.010365	0.002088	0.000377	5.88E-05	0
11	0	0.000351	0.002233	0.010653	0.034972	0.064395388	0.034994	0.010725	0.002367	0.000428	6.77E-05	9.4E-06	0
		0.000351	0.002233	0.010653	0.034972	0.064395388	0.034994	0.010725	0.002367	0.000428	6.77E-05	9.4E-06	

Time 14 days

Time = 14 days

Figure B5. **Predicted Concentrations for Loam after Two Weeks**

APPENDIX C: PARTITIONING CALCULATIONS

Appendix C – Partitioning Calculations

1.0 SAMPLE CALCULATIONS

1.1 Equations

Equation 1a: Partitioning[1] *(Vapour Concentration via Soil Concentration)*

$$Cv = \frac{1000 \times C_{soil} \times H \times \rho_b}{\theta_w + K_{oc} \times f_{oc} \times \rho_b + H \times \theta_a}$$

Equation 1b: Partitioning[2] *(Soil Concentration via Vapour Concentration)*

$$C_{soil} = \frac{(\theta_w + K_{oc} \times f_{oc} \times \rho_b + H \times \theta_a) \times C_v}{1000 \times H \times \rho_b}$$

Equation 2: Generalized Attenuation Factors[3]

$$C_{V-O} = C_{V-SS} \times {}^{VAF}/_{AAD}$$

Equation 3: Soil Screening Value – No Attenuation

$$C_{soil'} = \frac{(\theta_w + K_{oc} \times f_{oc} \times \rho_b + H \times \theta_a) \times C_{v'}}{1000 \times H \times \rho_b}$$

Equation 4: Soil Screening Value – Application of Vertical Attenuation

$$C_{soil'} = \frac{(\theta_w + K_{oc} \times f_{oc} \times \rho_b + H \times \theta_a) \times \frac{C_{v'}}{VAF}}{1000 \times H \times \rho_b}$$

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[1] Health Canada 2010
[2] Health Canada 2010
[3] BC ENV 2017b

Equation 5: Soil Screening Value – Application of Vertical and Lateral / Biodegradation Attenuation

$$C_{soil'} = \frac{(\theta_w + K_{oc} \times f_{oc} \times \rho_b + H \times \theta_a) \times \frac{\frac{C_{v'}}{VAF}}{AAD}}{1000 \times H \times \rho_b}$$

Where:

CV = soil vapour concentration (mg/m3)
Cv′ = vapour standard (µg/m3)
Csoil = total soil concentration (mg/kg) (all phases)
Csoil ‘= soil screening value (mg/kg or µg/g) (all phases)
H = Henry's Law constant (dimensionless)
ϱb = dry bulk density (g/cm3)
Koc = organic carbon-water partitioning coefficient (mg/kg OC per mg/L water)
foc = fraction organic carbon (g/g)
θa = air-filled porosity (dimensionless)
θw = water-filled porosity (dimensionless)
CV-O = estimated substance concentration in outdoor vapour (µg/m3)
CV-SS = measured or estimated substance concentration in subsurface/subslab vapour (µg/m3)
VAF = vertical vapour attenuation factor (unitless)
AAD = attenuation adjustment divisor (unitless) (inclusive of lateral attenuation adjustment and biodegradation attenuation adjustment divisors).

1.2 Soil Screening Value Sample Calculation for Benzene

1.2.1 Input Parameters

Table C1 Sample Calculation Input Parameters

Benzene Specific Values			
Henry's Law Constant (H)		0.227[a]	
Organic Carbon Coefficient (Koc [L/kg])		146[a]	
Receiving Environment Soil Standard (µg/g)		0.035[b]	
Receiving Environment Vapour Standard (µg/m^3)		1.5[b]	
Receiving Location Input Parameters			
Land Use		Residential (Low Density)	
Texture		Coarse	
Soil Physical Data[c,d]			
Bulk Density (ϱb [(g/cm^3])		1.7	
Fraction of Organic Carbon (foc [g/g])		0.005	
Volumetric Water Content (θw [cm^3/cm^3])		0.119	
Volumetric Air Content (θa [cm^3/cm^3])		0.241	
Receiving Location Vapour Assessment Parameters			
Primary	Exposure Scenario	Agriculture, Urban Park, Industrial	
	Sample Location	Subsurface	
	Sample Depth (m)	1	
Attenuation Factors			
Primary Exposure Scenario	Apply Vertical Vapour Attenuation Factor (VAF)	Yes	0.0028
	Apply Biodegradation Attenuation Adjustment Divisor (BAAD)	No	
	Apply Parkade Attenuation Adjustment Divisor (PAAD)	No	
	Apply Lateral Attenuation Adjustment Divisor (LAAD)	Yes	
	Lateral Offset Distance (m)	30	10

[a] BC ENV Protocol 13 (2019).

[b] Schedule 3.1 (B.C. Reg. 375-96); soil standard for residential (low density) and groundwater used for drinking water.

[c] CCME (2006)

[d] BC ENV (2016)

Sample Calculation 1: No Attenuation - Agricultural, Urban Park, Residential

$$C_{soil\prime} = \frac{(\theta_w + K_{oc} \times f_{oc} \times \rho_b + H \times \theta_a) \times C_{v\prime}}{1000 \times H \times \rho_b}$$

$$C_{soil\prime} = \frac{(\frac{0.119\text{cm}^3}{\text{cm}^3} + \frac{146\text{L}}{\text{kg}} \times 0.005\ g/g \times 1.7\text{g/cm}^3 + 0.227 \times 0.241\text{cm}^3/\text{cm}^3) \times (\frac{1.5\mu\text{g/m}^3}{1000\ \mu\text{g/mg}})}{1000 \times 0.227 \times 1.7\text{g/cm}^3}$$

$$C_{soil\prime} = 5.5\ x\ 10^{-6}\ ug/g$$

Sample Calculation 2: Application of Vertical Attenuation (1 m Subsurface) - Agricultural, Urban Park, Residential

$$C_{soil\prime} = \frac{(\theta_w + K_{oc} \times f_{oc} \times \rho_b + H \times \theta_a) \times \frac{C_{v\prime}}{VAF}}{1000 \times H \times \rho_b}$$

$$C_{soil\prime} = \frac{(\frac{0.119\text{cm}^3}{\text{cm}^3} + \frac{146\text{L}}{\text{kg}} \times 0.005\ g/g \times 1.7\text{g/cm}^3 + 0.227 \times 0.241\text{cm}^3/\text{cm}^3) \times \frac{(\frac{1.5\mu\text{g/m}^3}{1000\ \mu\text{g/mg}})}{0.0028}}{1000 \times 0.227 \times 1.7\text{g/cm}^3}$$

$$C_{soil\prime} = 1.96\ x\ 10^{-3}\ ug/g$$

Table C2 Soil Screening Criteria (SSC) for the Protection of the Vapour Inhalation Pathway

Substance	*< 1 m Subsurface*				
	Soil screening criteria calculated from CSR Sch. 3.3 std, AF & partitioning calcs				
	AF = 0.0001	*AF = 0.02*	*AF = 0.02*	*AF = 0.02*	*AF = 0.02*
	Outdoor	*Agricultural, Urban Park, Residential*	*Commercial*	*Industrial*	*Parkade*
acetaldehyde	-	-	-	-	-
acetone	1.15E+03	5.73E+00	1.58E+01	1.00E+02	4.30E+01
acetone cyanohydrin	-	-	-	-	-
acetonitrile	-	-	-	-	-
acrolein	3.03E-02	1.52E-04	1.52E-04	1.52E-04	1.52E-04
acrylonitrile	1.00E-01	5.02E-04	5.02E-04	1.51E-03	1.00E-03
allyl chloride	7.37E-03	3.69E-05	1.11E-04	3.32E-04	2.95E-04
ammonia (as N)	-	-	-	-	-
benzene (Aquatic Life-Freshwater)	5.50E-02	2.75E-04	7.33E-04	1.83E-03	1.83E-03
benzene (Aquatic Life-Marine)	5.50E-02	2.75E-04	7.33E-04	1.83E-03	1.83E-03
benzene (Drinking Water)	5.50E-02	2.75E-04	7.33E-04	1.83E-03	1.83E-03
benzene (Human Ingestion)	5.50E-02	2.75E-04	7.33E-04	1.83E-03	1.83E-03
benzene (Invertebrates)	5.50E-02	2.75E-04	7.33E-04	1.83E-03	1.83E-03
benzotrichloride	4.78E+00	2.39E-02	2.39E-02	2.39E-02	2.39E-02
benzyl chloride	2.74E-01	1.37E-03	4.11E-03	1.37E-02	1.03E-02
bis(2-chloro-1-methylethyl) ether	1.28E+02	6.40E-01	2.00E+00	1.20E+01	5.20E+00
bis(2-chloroethyl) ether	3.33E+00	1.66E-02	1.66E-02	1.66E-02	1.66E-02
bis(2-chloromethyl) ether	9.17E-02	4.58E-04	4.58E-04	4.58E-04	4.58E-04
bromobenzene	7.45E+00	3.73E-02	1.24E-01	3.42E-01	3.10E-01
bromodichloromethane	1.11E+00	5.57E-03	1.39E-02	1.11E-01	4.17E-02
bromoform	9.54E-01	4.77E-03	1.59E-02	4.50E-02	3.97E-02
bromomethane	2.98E-02	1.49E-04	4.46E-04	1.34E-03	1.19E-03
butadiene, 1,3-	4.62E-03	2.31E-05	2.31E-05	3.46E-05	2.89E-05
carbon disulfide	3.11E+00	1.56E-02	4.45E-02	1.45E-01	1.22E-01

Table C2 Soil Screening Criteria (SSC) for the Protection of the Vapour Inhalation Pathway

Substance	*< 1 m Subsurface*				
	Soil screening criteria calculated from CSR Sch. 3.3 std, AF & partitioning calcs				
	AF = 0.0001	***AF = 0.02***	***AF = 0.02***	***AF = 0.02***	***AF = 0.02***
	Outdoor	*Agricultural, Urban Park, Residential*	*Commercial*	*Industrial*	*Parkade*
carbon tetrachloride	5.97E-03	2.98E-05	9.95E-05	2.98E-04	2.98E-04
chlorine (Cl2)	7.25E-02	3.62E-04	3.62E-04	3.62E-04	3.62E-04
chloro-1,1-difluoroethane, 1-	-	-	-	-	-
chlorobenzene	9.91E-01	4.95E-03	1.49E-02	4.46E-02	3.96E-02
chlorobenzotrifluoride, 4-	8.79E-01	4.40E-03	1.17E-02	2.93E-02	2.93E-02
chlorobutane, 1-	6.18E-01	3.09E-03	9.66E-03	5.80E-02	2.51E-02
chlorodifluoromethane	-	-	-	-	-
chloroethane	-	-	-	-	-
chloroform	1.67E+00	8.34E-03	2.50E-02	7.51E-02	6.67E-02
chloromethane	-	-	-	-	-
chloronitrobenzene, 4-	9.43E+01	4.71E-01	9.43E-01	2.59E+00	2.36E+00
chlorophenol, 2-	4.33E+02	2.17E+00	6.50E+00	4.33E+01	1.73E+01
chloroprene	3.05E-03	1.52E-05	1.52E-05	1.52E-05	1.52E-05
chloropropane, 2-	-	-	-	-	-
chlorotoluene, 2-	5.50E+00	2.75E-02	6.87E-02	5.50E-01	2.06E-01
crotonaldehyde, trans-	1.99E+00	9.97E-03	2.99E-02	1.99E-01	7.48E-02
cyanide (Aquatic Life-Freshwater)	-	-	-	-	-
cyanide (Aquatic Life-Marine)	-	-	-	-	-
cyanide (Drinking Water)	-	-	-	-	-
cyanide (Human Ingestion)	-	-	-	-	-
cyanide (Invertebrates)	-	-	-	-	-
cyanide (Livestock)	-	-	-	-	-
cyanogen	1.07E-01	5.34E-04	5.34E-04	2.14E-03	8.01E-04
cyanogen bromide	-	-	-	-	-

Table C2 Soil Screening Criteria (SSC) for the Protection of the Vapour Inhalation Pathway

Substance	*< 1 m Subsurface*				
	Soil screening criteria calculated from CSR Sch. 3.3 std, AF & partitioning calcs				
	AF = 0.0001	***AF = 0.02***	***AF = 0.02***	***AF = 0.02***	***AF = 0.02***
	Outdoor	***Agricultural, Urban Park, Residential***	***Commercial***	***Industrial***	***Parkade***
cyanogen chloride	-	-	-	-	-
dibromo-3-chloropropane, 1,2-	1.08E+00	5.41E-03	5.41E-03	1.08E-02	8.12E-03
dibromobenzene, 1,4-	1.07E+01	5.34E-02	1.60E-01	1.07E+00	4.01E-01
dibromochloromethane	2.92E+00	1.46E-02	3.65E-02	2.92E-01	1.09E-01
dibromoethane, 1,2-	5.11E-02	2.55E-04	2.55E-04	2.55E-04	2.55E-04
dibromomethane	-	-	-	-	-
dichloro-2-butene, 1,4-	-	-	-	-	-
dichlorobenzene, 1,2-	5.09E+01	2.54E-01	7.63E-01	2.54E+00	1.91E+00
dichlorobenzene, 1,3-	1.09E+01	5.45E-02	1.82E-01	9.08E-01	4.54E-01
dichlorobenzene, 1,4-	1.58E+02	7.92E-01	2.47E+00	7.42E+00	6.43E+00
dichlorodifluoromethane	1.62E-01	8.12E-04	2.44E-03	7.31E-03	6.50E-03
dichloroethane, 1,1-	5.69E+00	2.84E-02	8.53E-02	2.56E-01	2.27E-01
dichloroethane, 1,2-	3.99E-01	2.00E-03	5.70E-03	1.85E-02	1.57E-02
dichloroethylene, 1,1-	7.12E-01	3.56E-03	1.07E-02	3.56E-02	2.67E-02
dichloroethylene, 1,2- cis	1.05E+00	5.24E-03	1.75E-02	4.80E-02	4.37E-02
dichloroethylene, 1,2- trans	5.05E-01	2.52E-03	8.42E-03	2.31E-02	2.10E-02
dichloromethane	8.90E+00	4.45E-02	1.48E-01	4.08E-01	3.71E-01
dichloropropane, 1,2-	1.36E-01	6.78E-04	1.69E-03	5.93E-03	5.08E-03
dichloropropane, 1,3-	1.44E-01	7.21E-04	2.16E-03	1.44E-02	5.77E-03
dichloropropene, 1,3- (cis + trans)	7.79E-02	3.89E-04	1.17E-03	3.89E-03	3.11E-03
dicyclopentadiene	3.12E-02	1.56E-04	1.56E-04	3.90E-04	3.90E-04
diethyl ether	9.99E+00	5.00E-02	1.25E-01	9.99E-01	3.75E-01
dimethylamine	-	-	-	-	-
dimethylaniline, N,N- [DMA]	8.00E+00	4.00E-02	1.00E-01	8.00E-01	3.00E-01

Table C2 Soil Screening Criteria (SSC) for the Protection of the Vapour Inhalation Pathway

Substance	*< 1 m Subsurface*				
	Soil screening criteria calculated from CSR Sch. 3.3 std, AF & partitioning calcs				
	AF = 0.0001	***AF = 0.02***	***AF = 0.02***	***AF = 0.02***	***AF = 0.02***
	Outdoor	***Agricultural, Urban Park, Residential***	***Commercial***	***Industrial***	***Parkade***
epichlorohydrin	-	-	-	-	-
epoxybutane, 1,2-	-	-	-	-	-
ethyl acetate	1.26E+01	6.30E-02	1.80E-01	5.85E-01	4.95E-01
ethyl acrylate	7.22E-01	3.61E-03	1.13E-02	3.38E-02	2.93E-02
ethyl methacrylate	-	-	-	-	-
ethylbenzene (Aquatic Life-Freshwater)	7.28E+01	3.64E-01	1.09E+00	3.28E+00	2.91E+00
ethylbenzene (Aquatic Life-Marine)	7.28E+01	3.64E-01	1.09E+00	3.28E+00	2.91E+00
ethylbenzene (Drinking Water)	7.28E+01	3.64E-01	1.09E+00	3.28E+00	2.91E+00
ethylbenzene (Human Ingestion)	7.28E+01	3.64E-01	1.09E+00	3.28E+00	2.91E+00
ethylbenzene (Invertebrates)	7.28E+01	3.64E-01	1.09E+00	3.28E+00	2.91E+00
ethylene oxide	-	-	-	-	-
furan	1.91E-02	9.54E-05	2.86E-04	1.91E-03	7.15E-04
hexachlorobutadiene	1.03E-01	5.17E-04	7.76E-04	2.07E-03	1.81E-03
hexachlorocyclopentadiene	6.57E-02	3.28E-04	3.28E-04	6.57E-04	4.93E-04
hexachloroethane	2.03E+00	1.02E-02	3.05E-02	8.47E-02	8.47E-02
isopropylbenzene	3.09E+01	1.54E-01	3.86E-01	1.35E+00	1.16E+00
methacrylonitrile	4.07E+00	2.03E-02	6.10E-02	1.69E-01	1.69E-01
methyl acetate	3.66E+02	1.83E+00	5.49E+00	3.66E+01	1.37E+01
methyl acrylate	-	-	-	-	-
methyl ethyl ketone [MEK]	1.99E+03	9.97E+00	2.99E+01	8.97E+01	7.97E+01
methyl isobutyl ketone [MIBK]	-	-	-	-	-
methyl mercaptan	-	-	-	-	-
methyl methacrylate	6.33E+01	3.16E-01	9.04E-01	2.94E+00	2.49E+00
methyl tert-butyl ether [MTBE]	1.64E+02	8.21E-01	2.46E+00	6.84E+00	6.84E+00

Table C2 Soil Screening Criteria (SSC) for the Protection of the Vapour Inhalation Pathway

Substance	*< 1 m Subsurface*				
	Soil screening criteria calculated from CSR Sch. 3.3 std, AF & partitioning calcs				
	AF = 0.0001	***AF = 0.02***	***AF = 0.02***	***AF = 0.02***	***AF = 0.02***
	Outdoor	***Agricultural, Urban Park, Residential***	***Commercial***	***Industrial***	***Parkade***
methylcyclohexane	-	-	-	-	-
methylstyrene, alpha-	5.16E+01	2.58E-01	6.87E-01	4.30E+00	1.72E+00
naphthalene (Aquatic Life-Freshwater)	1.30E+01	6.48E-02	1.94E-01	5.40E-01	5.40E-01
naphthalene (Drinking Water)	1.30E+01	6.48E-02	1.94E-01	5.40E-01	5.40E-01
naphthalene (Human Ingestion)	1.30E+01	6.48E-02	1.94E-01	5.40E-01	5.40E-01
naphthalene (Invertebrates)	1.30E+01	6.48E-02	1.94E-01	5.40E-01	5.40E-01
n-decane	-	-	-	-	-
n-hexane	-	-	-	-	-
nitrobenzene	1.22E+01	6.12E-02	6.12E-02	1.53E-01	1.22E-01
nitrotoluene, 2-	7.53E+01	3.77E-01	1.04E+00	6.59E+00	2.83E+00
phosphine	-	-	-	-	-
propylene oxide	8.45E-01	4.23E-03	1.35E-02	4.23E-02	3.38E-02
pyridine	9.52E+02	4.76E+00	1.67E+01	4.76E+01	4.52E+01
styrene	2.07E+02	1.03E+00	3.10E+00	9.30E+00	8.27E+00
tetrachloroethane, 1,1,1,2-	7.57E-02	3.78E-04	1.01E-03	2.52E-03	2.52E-03
tetrachloroethane, 1,1,2,2-	1.46E+01	7.29E-02	1.82E-01	1.46E+00	5.47E-01
tetrachloroethylene (Aquatic Life-Freshwater)	3.58E-01	1.79E-03	4.47E-03	1.56E-02	1.34E-02
tetrachloroethylene (Human Ingestion)	3.58E-01	1.79E-03	4.47E-03	1.56E-02	1.34E-02
tetrachloroethylene (Invertebrates)	3.58E-01	1.79E-03	4.47E-03	1.56E-02	1.34E-02
tetrahydrofuran	1.51E+00	7.56E-03	2.16E-02	6.48E-02	5.40E-02
toluene (Aquatic Life-Freshwater)	2.36E+02	1.18E+00	3.54E+00	1.06E+01	9.43E+00
toluene (Aquatic Life-Marine)	2.36E+02	1.18E+00	3.54E+00	1.06E+01	9.43E+00
toluene (Drinking Water)	2.36E+02	1.18E+00	3.54E+00	1.06E+01	9.43E+00
toluene (Human Ingestion)	2.36E+02	1.18E+00	3.54E+00	1.06E+01	9.43E+00

Table C2 Soil Screening Criteria (SSC) for the Protection of the Vapour Inhalation Pathway

Substance	*< 1 m Subsurface*				
	Soil screening criteria calculated from CSR Sch. 3.3 std, AF & partitioning calcs				
	AF = 0.0001	***AF = 0.02***	***AF = 0.02***	***AF = 0.02***	***AF = 0.02***
	Outdoor	***Agricultural, Urban Park, Residential***	***Commercial***	***Industrial***	***Parkade***
toluene (Invertebrates)	2.36E+02	1.18E+00	3.54E+00	1.06E+01	9.43E+00
trichloro-1,2,2-trifluoroethane, 1,1,2-	1.44E+02	7.21E-01	2.16E+00	6.01E+00	6.01E+00
trichlorobenzene, 1,2,4-	8.29E+00	4.14E-02	1.18E-01	3.85E-01	3.26E-01
trichloroethane, 1,1,1-	2.77E+01	1.38E-01	4.15E-01	1.25E+00	1.11E+00
trichloroethane, 1,1,2-	5.61E-02	2.81E-04	3.37E-04	1.12E-03	8.42E-04
trichloroethylene (Aquatic Life-Freshwater)	2.14E-02	1.07E-04	3.21E-04	1.07E-03	8.01E-04
trichloroethylene (Human Ingestion)	2.14E-02	1.07E-04	3.21E-04	1.07E-03	8.01E-04
trichloroethylene (Invertebrates)	2.14E-02	1.07E-04	3.21E-04	1.07E-03	8.01E-04
trichlorofluoromethane	1.50E+00	7.51E-03	2.15E-02	6.98E-02	5.90E-02
trichloropropane, 1,1,2-	4.20E+00	2.10E-02	6.30E-02	4.20E-01	1.68E-01
trichloropropane, 1,2,3-	2.33E-01	1.16E-03	2.10E-03	5.82E-03	5.82E-03
trichloropropene, 1,2,3-	5.22E-03	2.61E-05	4.70E-05	1.31E-04	1.31E-04
triethylamine	-	-	-	-	-
trimethylbenzene, 1,2,4-	-	-	-	-	-
trimethylbenzene, 1,3,5-	3.05E-01	1.53E-03	4.36E-03	2.83E-02	1.09E-02
vinyl acetate	9.65E+00	4.83E-02	1.45E-01	4.83E-01	3.62E-01
vinyl bromide	-	-	-	-	-
vinyl chloride	2.98E-03	1.49E-05	5.22E-05	1.49E-04	1.34E-04
VPHv	1.60E+02	7.98E-01	2.39E+00	9.18E+00	6.39E+00
xylenes (Aquatic Life-Freshwater)	7.47E+00	3.73E-02	1.12E-01	3.36E-01	2.99E-01
xylenes (Drinking Water)	7.47E+00	3.73E-02	1.12E-01	3.36E-01	2.99E-01
xylenes (Human Ingestion)	7.47E+00	3.73E-02	1.12E-01	3.36E-01	2.99E-01
xylenes (Invertebrates)	7.47E+00	3.73E-02	1.12E-01	3.36E-01	2.99E-01

Table C3 Ratio of Detection Limit to Vapour Pathway Soil Screening Criteria for Chlorinated Solvent Compounds

Substance	Outdoor	Agricultural, Urban Park, Residential	Commercial	Industrial	Parkade
chlorophenol, 2-	1.15E-04	2.31E-02	7.69E-03	1.15E-03	2.88E-03
dichlorobenzene, 1,4-	3.16E-04	6.32E-02	2.02E-02	6.74E-03	7.77E-03
trichloro-1,2,2-trifluoroethane, 1,1,2-	3.47E-04	6.93E-02	2.31E-02	8.32E-03	8.32E-03
bis(2-chloro-1-methylethyl) ether	3.91E-04	7.81E-02	2.50E-02	4.17E-03	9.61E-03
chloronitrobenzene, 4-	5.30E-04	1.06E-01	5.30E-02	1.93E-02	2.12E-02
dichlorobenzene, 1,2-	9.83E-04	1.97E-01	6.55E-02	1.97E-02	2.62E-02
trichloroethane, 1,1,1-	1.81E-03	3.61E-01	1.20E-01	4.01E-02	4.52E-02
tetrachloroethane, 1,1,2,2-	3.43E-03	6.86E-01	2.74E-01	3.43E-02	9.15E-02
dichlorobenzene, 1,3-	4.59E-03	9.18E-01	2.75E-01	5.51E-02	1.10E-01
trichlorobenzene, 1,2,4-	6.03E-03	1.21E+00	4.22E-01	1.30E-01	1.54E-01
dichloroethane, 1,1-	8.79E-03	1.76E+00	5.86E-01	1.95E-01	2.20E-01
chlorotoluene, 2-	9.10E-03	1.82E+00	7.28E-01	9.10E-02	2.43E-01
benzotrichloride	1.05E-02	2.09E+00	2.09E+00	2.09E+00	2.09E+00
trichloropropane, 1,1,2-	1.19E-02	2.38E+00	7.93E-01	1.19E-01	2.97E-01
bis(2-chloroethyl) ether	1.50E-02	3.01E+00	3.01E+00	3.01E+00	3.01E+00
chloroform	3.00E-02	5.99E+00	2.00E+00	6.66E-01	7.49E-01
trichlorofluoromethane	3.33E-02	6.65E+00	2.33E+00	7.17E-01	8.47E-01
dichloroethylene, 1,2- cis	4.77E-02	9.54E+00	2.86E+00	1.04E+00	1.15E+00
chlorobenzene	5.05E-02	1.01E+01	3.37E+00	1.12E+00	1.26E+00
chlorobenzotrifluoride, 4-	5.69E-02	1.14E+01	4.27E+00	1.71E+00	1.71E+00
dichloroethylene, 1,1-	7.03E-02	1.41E+01	4.68E+00	1.41E+00	1.87E+00
chlorobutane, 1-	8.09E-02	1.62E+01	5.18E+00	8.63E-01	1.99E+00
dichloroethylene, 1,2- trans	9.90E-02	1.98E+01	5.94E+00	2.16E+00	2.38E+00
dichloroethane, 1,2-	1.25E-01	2.51E+01	8.77E+00	2.70E+00	3.19E+00
tetrachloroethylene (Aquatic Life-Freshwater)	1.40E-01	2.80E+01	1.12E+01	3.20E+00	3.73E+00
tetrachloroethylene (Human Ingestion)	1.40E-01	2.80E+01	1.12E+01	3.20E+00	3.73E+00
tetrachloroethylene (Invertebrates)	1.40E-01	2.80E+01	1.12E+01	3.20E+00	3.73E+00

Table C3 Ratio of Detection Limit to Vapour Pathway Soil Screening Criteria for Chlorinated Solvent Compounds

Substance	Outdoor	Agricultural, Urban Park, Residential	Commercial	Industrial	Parkade
benzyl chloride	1.82E-01	3.65E+01	1.22E+01	3.65E+00	4.86E+00
trichloropropane, 1,2,3-	2.15E-01	4.29E+01	2.39E+01	8.59E+00	8.59E+00
dichlorodifluoromethane	3.08E-01	6.16E+01	2.05E+01	6.84E+00	7.69E+00
bis(2-chloromethyl) ether	5.45E-01	1.09E+02	1.09E+02	1.09E+02	1.09E+02
tetrachloroethane, 1,1,1,2-	6.61E-01	1.32E+02	4.96E+01	1.98E+01	1.98E+01
trichloroethane, 1,1,2-	8.91E-01	1.78E+02	1.48E+02	4.45E+01	5.94E+01
trichloroethylene (Aquatic Life-Freshwater)	2.34E+00	4.68E+02	1.56E+02	4.68E+01	6.24E+01
trichloroethylene (Human Ingestion)	2.34E+00	4.68E+02	1.56E+02	4.68E+01	6.24E+01
trichloroethylene (Invertebrates)	2.34E+00	4.68E+02	1.56E+02	4.68E+01	6.24E+01
allyl chloride	6.78E+00	1.36E+03	4.52E+02	1.51E+02	1.70E+02
carbon tetrachloride	8.38E+00	1.68E+03	5.03E+02	1.68E+02	1.68E+02
trichloropropene, 1,2,3-	9.57E+00	1.91E+03	1.06E+03	3.83E+02	3.83E+02
Chloroprene	1.64E+01	3.28E+03	3.28E+03	3.28E+03	3.28E+03
vinyl chloride	1.68E+01	3.35E+03	9.58E+02	3.35E+02	3.72E+02

Table C4 Ratio of Low-Density Soil Standard to Vapour Pathway Soil Screening Criteria for Non-chlorinated Solvent Compounds

Substance	Outdoor	Agricultural, Urban Park, Residential	Commercial	Industrial	Parkade
toluene (Aquatic Life-Freshwater)	2.12E-03	4.24E-01	1.41E-01	4.71E-02	5.30E-02
pyridine	1.58E-02	3.15E+00	9.00E-01	3.15E-01	3.32E-01
toluene (Drinking Water)	2.54E-02	5.09E+00	1.70E+00	5.65E-01	6.36E-01
naphthalene (Invertebrates)	4.63E-02	9.26E+00	3.09E+00	1.11E+00	1.11E+00
nitrotoluene, 2-	1.99E-01	3.98E+01	1.45E+01	2.28E+00	5.31E+00
ethylbenzene (Drinking Water)	2.06E-01	4.12E+01	1.37E+01	4.58E+00	5.15E+00
methacrylonitrile	3.69E-01	7.38E+01	2.46E+01	8.85E+00	8.85E+00
toluene (Invertebrates)	6.36E-01	1.27E+02	4.24E+01	1.41E+01	1.59E+01
benzene (Drinking Water)	6.36E-01	1.27E+02	4.77E+01	1.91E+01	1.91E+01
toluene (Aquatic Life-Marine)	8.48E-01	1.70E+02	5.65E+01	1.88E+01	2.12E+01
xylenes (Drinking Water)	8.71E-01	1.74E+02	5.80E+01	1.93E+01	2.18E+01
VPHv	1.25E+00	2.51E+02	8.35E+01	2.18E+01	3.13E+01
crotonaldehyde, trans-	1.76E+00	3.51E+02	1.17E+02	1.76E+01	4.68E+01
dibromo-3-chloropropane, 1,2-	1.85E+00	3.69E+02	3.69E+02	1.85E+02	2.46E+02
nitrobenzene	2.45E+00	4.90E+02	4.90E+02	1.96E+02	2.45E+02
xylenes (Aquatic Life-Freshwater)	2.68E+00	5.36E+02	1.79E+02	5.95E+01	6.70E+01
ethylbenzene (Aquatic Life-Freshwater)	2.75E+00	5.49E+02	1.83E+02	6.10E+01	6.86E+01
ethylbenzene (Aquatic Life-Marine)	2.75E+00	5.49E+02	1.83E+02	6.10E+01	6.86E+01
ethylbenzene (Invertebrates)	2.75E+00	5.49E+02	1.83E+02	6.10E+01	6.86E+01
dimethylaniline, N,N- [DMA]	3.75E+00	7.50E+02	3.00E+02	3.75E+01	1.00E+02
methyl ethyl ketone [MEK]	4.77E+00	9.53E+02	3.18E+02	1.06E+02	1.19E+02
hexachloroethane	4.92E+00	9.84E+02	3.28E+02	1.18E+02	1.18E+02
naphthalene (Aquatic Life-Freshwater)	5.79E+00	1.16E+03	3.86E+02	1.39E+02	1.39E+02
naphthalene (Drinking Water)	7.72E+00	1.54E+03	5.15E+02	1.85E+02	1.85E+02
acetone	1.31E+01	2.62E+03	9.51E+02	1.49E+02	3.49E+02
dibromobenzene, 1,4-	1.40E+01	2.81E+03	9.36E+02	1.40E+02	3.74E+02
toluene (Human Ingestion)	1.48E+01	2.97E+03	9.89E+02	3.30E+02	3.71E+02

Table C4 Ratio of Low-Density Soil Standard to Vapour Pathway Soil Screening Criteria for Non-chlorinated Solvent Compounds

Substance	Outdoor	Agricultural, Urban Park, Residential	Commercial	Industrial	Parkade
methylstyrene, alpha-	1.94E+01	3.88E+03	1.45E+03	2.33E+02	5.82E+02
xylenes (Invertebrates)	2.01E+01	4.02E+03	1.34E+03	4.46E+02	5.02E+02
bromobenzene	2.01E+01	4.03E+03	1.21E+03	4.39E+02	4.83E+02
methyl tert-butyl ether [MTBE]	2.44E+01	4.87E+03	1.62E+03	5.84E+02	5.84E+02
dichloromethane	2.81E+01	5.62E+03	1.68E+03	6.13E+02	6.74E+02
dibromochloromethane	2.91E+01	5.82E+03	2.33E+03	2.91E+02	7.76E+02
propylene oxide	3.55E+01	7.10E+03	2.22E+03	7.10E+02	8.87E+02
methyl acetate	4.10E+01	8.20E+03	2.73E+03	4.10E+02	1.09E+03
styrene	4.11E+01	8.22E+03	2.74E+03	9.14E+02	1.03E+03
benzene (Aquatic Life-Freshwater)	4.55E+01	9.09E+03	3.41E+03	1.36E+03	1.36E+03
isopropylbenzene	4.86E+01	9.72E+03	3.89E+03	1.11E+03	1.30E+03
ethylbenzene (Human Ingestion)	5.49E+01	1.10E+04	3.66E+03	1.22E+03	1.37E+03
naphthalene (Human Ingestion)	6.56E+01	1.31E+04	4.37E+03	1.57E+03	1.57E+03
dibromoethane, 1,2-	6.85E+01	1.37E+04	1.37E+04	1.37E+04	1.37E+04
bromodichloromethane	8.98E+01	1.80E+04	7.19E+03	8.98E+02	2.40E+03
ethyl acrylate	1.11E+02	2.22E+04	7.09E+03	2.36E+03	2.73E+03
benzene (Aquatic Life-Marine)	1.18E+02	2.36E+04	8.87E+03	3.55E+03	3.55E+03
cyanogen	1.40E+02	2.81E+04	2.81E+04	7.02E+03	1.87E+04
hexachlorobutadiene	1.45E+02	2.90E+04	1.93E+04	7.25E+03	8.29E+03
acrylonitrile	1.49E+02	2.99E+04	2.99E+04	9.95E+03	1.49E+04
acrolein	2.64E+02	5.27E+04	5.27E+04	5.27E+04	5.27E+04
diethyl ether	3.00E+02	6.01E+04	2.40E+04	3.00E+03	8.01E+03
bromoform	3.15E+02	6.29E+04	1.89E+04	6.66E+03	7.55E+03
methyl methacrylate	3.16E+02	6.32E+04	2.21E+04	6.81E+03	8.04E+03
butadiene, 1,3-	4.33E+02	8.67E+04	8.67E+04	5.78E+04	6.93E+04
carbon disulfide	4.82E+02	9.63E+04	3.37E+04	1.04E+04	1.23E+04
trimethylbenzene, 1,3,5-	4.91E+02	9.83E+04	3.44E+04	5.29E+03	1.38E+04

Table C4 **Ratio of Low-Density Soil Standard to Vapour Pathway Soil Screening Criteria for Non-chlorinated Solvent Compounds**

Substance	Outdoor	Agricultural, Urban Park, Residential	Commercial	Industrial	Parkade
bromomethane	6.72E+02	1.34E+05	4.48E+04	1.49E+04	1.68E+04
furan	7.87E+02	1.57E+05	5.24E+04	7.87E+03	2.10E+04
xylenes (Human Ingestion)	1.14E+03	2.28E+05	7.59E+04	2.53E+04	2.85E+04
ethyl acetate	1.19E+03	2.38E+05	8.33E+04	2.56E+04	3.03E+04
hexachlorocyclopentadiene	1.45E+03	2.89E+05	2.89E+05	1.45E+05	1.93E+05
vinyl acetate	1.55E+03	3.11E+05	1.04E+05	3.11E+04	4.14E+04
benzene (Invertebrates)	1.82E+03	3.64E+05	1.36E+05	5.46E+04	5.46E+04
dichloropropane, 1,3-	2.08E+03	4.16E+05	1.39E+05	2.08E+04	5.20E+04
benzene (Human Ingestion)	2.73E+03	5.46E+05	2.05E+05	8.18E+04	8.18E+04
dichloropropane, 1,2-	4.43E+03	8.85E+05	3.54E+05	1.01E+05	1.18E+05
tetrahydrofuran	9.92E+03	1.98E+06	6.94E+05	2.31E+05	2.78E+05
dichloropropene, 1,3- (cis + trans)	1.28E+04	2.57E+06	8.56E+05	2.57E+05	3.21E+05
dicyclopentadiene	4.81E+04	9.62E+06	9.62E+06	3.85E+06	3.85E+06

Table C5 **Ratio of Commercial Soil Standard to Vapour Pathway Outdoor Soil Screening Criteria for Non-chlorinated Solvent Compounds**

Substance	Outdoor
toluene (Aquatic Life-Freshwater)	2.12E-03
toluene (Drinking Water)	2.54E-02
ethylbenzene (Drinking Water)	2.06E-01
pyridine	2.63E-01
benzene (Drinking Water)	6.36E-01
toluene (Aquatic Life-Marine)	8.48E-01
xylenes (Drinking Water)	8.71E-01
VPHv	1.25E+00
naphthalene (Invertebrates)	1.54E+00
toluene (Invertebrates)	1.91E+00
nitrotoluene, 2-	1.99E+00
xylenes (Aquatic Life-Freshwater)	2.68E+00
ethylbenzene (Aquatic Life-Freshwater)	2.75E+00
ethylbenzene (Aquatic Life-Marine)	2.75E+00
naphthalene (Aquatic Life-Freshwater)	5.79E+00
methacrylonitrile	6.15E+00
crotonaldehyde, trans-	7.52E+00
naphthalene (Drinking Water)	7.72E+00
ethylbenzene (Invertebrates)	8.92E+00
nitrobenzene	3.68E+01
dibromo-3-chloropropane, 1,2-	3.69E+01
benzene (Aquatic Life-Freshwater)	4.55E+01
dimethylaniline, N,N- [DMA]	5.63E+01
hexachloroethane	7.38E+01
methyl ethyl ketone [MEK]	7.53E+01
xylenes (Invertebrates)	8.04E+01
toluene (Human Ingestion)	8.48E+01

Table C5 **Ratio of Commercial Soil Standard to Vapour Pathway Outdoor Soil Screening Criteria for Non-chlorinated Solvent Compounds**

Substance	Outdoor
benzene (Aquatic Life-Marine)	1.18E+02
methyl tert-butyl ether [MTBE]	1.22E+02
dibromochloromethane	1.37E+02
dichloromethane	1.68E+02
acetone	1.74E+02
propylene oxide	1.77E+02
dibromobenzene, 1,4-	2.34E+02
styrene	2.42E+02
bromobenzene	2.68E+02
methylstyrene, alpha-	2.91E+02
dibromoethane, 1,2-	2.94E+02
ethylbenzene (Human Ingestion)	3.43E+02
naphthalene (Human Ingestion)	3.86E+02
bromodichloromethane	4.94E+02
acrylonitrile	5.97E+02
methyl acetate	6.83E+02
isopropylbenzene	8.10E+02
ethyl acrylate	1.38E+03
butadiene, 1,3-	2.06E+03
cyanogen	2.34E+03
hexachlorobutadiene	2.42E+03
acrolein	3.30E+03
bromoform	4.19E+03
diethyl ether	4.50E+03
benzene (Invertebrates)	4.55E+03
methyl methacrylate	4.74E+03
xylenes (Human Ingestion)	6.70E+03

Table C5 **Ratio of Commercial Soil Standard to Vapour Pathway Outdoor Soil Screening Criteria for Non-chlorinated Solvent Compounds**

Substance	Outdoor
carbon disulfide	8.03E+03
trimethylbenzene, 1,3,5-	8.19E+03
bromomethane	1.01E+04
furan	1.31E+04
ethyl acetate	1.59E+04
benzene (Human Ingestion)	1.82E+04
hexachlorocyclopentadiene	2.28E+04
dichloropropane, 1,2-	2.58E+04
vinyl acetate	2.59E+04
dichloropropane, 1,3-	3.12E+04
dichloropropene, 1,3- (cis + trans)	9.63E+04
tetrahydrofuran	1.32E+05
dicyclopentadiene	6.41E+05