CHAPTER 8
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8.0 PROPOSED RISK-BASED REMEDIATION CRITERIA

8.1 CCME Environmental Quality Criteria (Tier 1)

The CCME environmental quality criteria (EQC) for contaminated sites represent the first tier in establishing appropriate remediation criteria. The use of the CCME criteria of tier 1 will be restricted to relocation of soil from contaminated sites to "pristine" sites (or non-contaminated). This Tier is not intended for use as remediation criteria for sites which are contaminated and require remediation. The EQC include maximum concentrations of priority chemicals in soil and groundwater for specified land use. The EQC are provided in the CCME *Interim Canadian Environmental Quality Criteria for Contaminated Sites,* September 1991.

8.2 Generic Site Matrix (GSM)

In deriving soil remediation criteria, acceptable concentrations were first defined for the media associated with intake by the receptor. These are defined in Table 8.1. Note that in the case of the narcosis-based approach for VPH, LEPH and HEPH exposure to salmonid embryo larvae, the starting point concentration for back modelling was actually the tissue residue (i.e., mmol contaminant/kg body wt). Remediation criteria for soil and groundwater have been calculated for the exposure pathways shown in Figure 5.1 and 5.2 using the methodology described in Chapter 6. The results are presented as follows:

1) Soil remediation criteria for BTEX, naphthalene and benzo(a)pyrene based on outdoor soil ingestion, outdoor inhalation, indoor inhalation, drinking water consumption, freshwater aquatic life and livestock watering (Table 8.2a, 8.2b).

2) Risk-based soil remediation criteria for indicator parameters for the above exposure pathways and protection of salmonid embryo-larvae in contact with groundwater based on a narcosis approach (Table 8.3).

3) Groundwater remediation criteria based on groundwater protection at receptor points, and protective of indoor air inhalation resulting from volatilization from groundwater below a building (Table 8.4).

TABLE 8.1
Acceptable Groundwater or Surface Water Concentrations at the Receptor

Chemical	Drinking Water (mg/L)	Freshwater Aquatic Life (mg/L)	Livestock Watering (mg/L)
Concentrations used as the starting point to determine acceptable soil concentrations.			
benzene	0.005[1]	0.3[1]	6[3]
toluene	0.024[1]	0.3[1]	40[3]
ethylbenzene	0.0024[1]	0.7[1]	34[3]
xylene	0.3[1]	-	900[3]
naphthalene	0.01[4]	0.001[2]	65[3]
*benzo(a)pyrene	0.00001[1]	0.00001[2]	0.07[3]
VPH (C_5-C_9)	1.5[5]	0.1 mmol/kg bwt	--
LEPH (C_{10}-C_{18})	1[5]	0.1 mmol/kg bwt	--
HEPH (C_{19}-C_{32})	12[5]	0.1 mmol/kg bwt	--

1 CCME 1991. Interim Canadian Environmental Quality Criteria for Contaminated Sites. Canadian Council of Ministers of the Environment. CCME EPC-CS34.

2 BCE 1994. Water Quality Criteria. BC Environment.

3 Risk-based using HQ=1 (see Appendix VII for derivation).

4 BCE 1993. Water Quality Criteria for Polycyclic Aromatic Hydrocarbons (Naphthalene criteria value cited from New York State, 1985).

5 Derived from surrogates (see Chapter 6 on derivation of criteria for petroleum hydrocarbon fractions).

Table 8.2a
BTEX Concentrations in Soil (mg/kg)

	Benzene		Toluene		Ethylbenzene		Xylene	
	Residential and Other	Commercial	Residential and Other	Commercial	Residential and Other	Commercial	Residential and Other	Commercial
Soil Ingestion	662	8,880	48,000	2.45×10^6	24,000	1.23×10^6	4.8×10^5	2.45×10^7
Outdoor Inhalation	23.1	38.2	5,910	9,720	31,300	51,500	1.58×10^5	2.6×10^5
Indoor Inhalation	0.093	0.15	12	14	32	45	330	440
Drinking Water Protection[1]	0.01 (0.35)	0.01 (0.35)	2	2	1	1	25	25
Freshwater Aquatic Life[1,2]	1.15 (20)	1.15 (20)	13	13	> sat[5]	> sat[5]	N/A	N/A
Livestock Watering[1]	> sat[5]	> sat[5]	> sat[5]	> sat[5]	> sat[5]	> sat[5]	> sat[5]	> sat[5]
Soil Saturation[2]	1,242	1242	1,045	1,045	1,034	1,034	433	433
50% LEL	50	50	150	150	150	150	225	225
Indoor Inhalation-Odour Threshold[4]	40	40	250	250	850	850	45	45

1. Criteria based on: i) sand, ii) 10 m distance to receptor, iii) large source; and iv) 0 m unsaturated thickness (concentrations of benzene calculated for 0.5 m unsaturated thickness are shown in brackets).
2. Soil saturation concentration for "base-case" variables (see Appendix V and VI)
3. Based on protection of livestock health.
4. Odour thresholds used to derive the soil criteria are provided in Appendix V.
5. Greater than saturation limit.
6. Conservatively based on partitioning between phases at source.

Table 8.2b
Naphthalene and Benzo(a)pyrene Concentrations in Soil (mg/kg)

	Naphthalene		Benzo(a)pyrene	
	Residential and Other	Commercial	Residential and Other	Commercial
Soil Ingestion	960	49,100	2.63	35.3
Outdoor Inhalation of Vapour & Dust	1,800	2,970	1.54	2.56
Indoor Inhalation	16	28	2.3×10^6	1.2×10^7
Drinking Water Protection[1]	125(91)	125(91)	2×10^8	2×10^8
Freshwater Aquatic Life[1]	92(9)	92(9)	20	20
Livestock Watering	>sat[5]	>sat[5]	>sat[5]	>sat[5]
Soil Saturation	251	251	21	21
Aesthetic Threshold	1,000	1,000	10,000	10,000
Odour Threshold	2,800[4]	2,800[4]	>10,000	>10,000

1. Criteria based on: i) sand, ii) 10 m distance to receptor, iii) large source; and iv) 0 m unsaturated thickness (concentrations of benzene calculated for 0.5 m unsaturated thickness are shown in brackets).
2. Soil saturation concentration for "base-case" variables (see Appendix V and VI)
3. Based on protection of livestock health.
4. Odour thresholds used to derive the soil criteria are proivded in Appendix V.
5. Greater than saturation limit.

Table 8.3
VPH, LEPH and HEPH Concentrations in Soil (mg/kg)

	VPH		LEPH		HEPH	
	Residential and Other	Commercial	Residential and Other	Commercial	Residential and Other	Commercial
Soil Ingestion	>10,000	>10,000	>10,000	>10,000	>10,000	>10,000
Outdoor Inhalation	2520	4150	>10,000	>10,000	>10,000	>10,000
Indoor Inhalation	3.8	4.8	275	450	>10,000	>10,000
Drinking Water Protection[1]	91	91	7,400	7,400	2×10^8	2×10^8
Freshwater Aquatic Life[1]	4,600	4,600	—	—	—	—
Aesthetic Threshold	1,000	1,000	5,000	5,000	10,000	10,000

1. Criteria based on: i) sand, ii) 10 m distance to receptor, iii) large source and iv) 0 m unsaturated thickness.

Table 8.4
Generic Site Matrix Criteria of Groundwater Concentrations at Source

	Protection of Drinking Water[3] (mg\L)	Protection of Freshwater[3] Aquatic Life (mg/L)	Protection of Indoor Air[4]	
			Residential (mg/L)	Commercial (mg/L)
Benzene	0.01	0.6	0.09	0.16
Toluene	0.25	2	12	22
Ethylbenzene	0.4	125	11	20
Xylene	3	—	170[3]	170[3]
Naphthalene	18	2	6	11
Benzo(a)pyrene	0.004[2]	0.004[2]	0.004[2]	0.004[2]
VPH (C_5-C_9)	15	100[1]	0.22	0.39
LEPH (C_{10}-C_{18})	300	—[2]	100	190
HEPH (C_{19}-C_{32})	—[2]	—[2]	N/A	N/A

1. Based on gasoline product and acceptable soil concentration of narcotic surrogates (benzene).
2. Solubility limit.
3. Concentration at source protective of downgradient receptor. Criteria based on: i) sand, ii) 10 m distance to receptor, and iii) large source.
4. Based on concentration in groundwater directly below building and at 3 m depth.

Note: Since issueing the draft for review and comment, we have investigated the use of less conservative surrogate (n-nonane instead of hexane) and HQ of 0.5 instead of 0.1. The resulting VPH concentration for residential indoor air scenario is approximately 3 mg/l for groundwater at the source (see Supplement I).

In terms of the soil remediation criteria under item (1), the unadjusted criteria plus relevant odour-based, safety-based (i.e., %LEL) and aesthetic criteria are presented in Tables 8.2 and 8.3. The methodology for deriving the safety and odour-based criteria was provided in Chapter 6.0 and Appendix V. The above criteria are then summarized in Table 8.5 where the most stringent values resulting from a specific pathway dictate the criterium for a given medium.

8.2.1 Soil Remediation Criteria

Soil remediation criteria are calculated for the exposure pathways presented in Chapter 5 with detailed results presented in the relevant appendices. The soil remediation criteria for the soil ingestion and inhalation pathways are risk-based while the soil remediation criteria for groundwater protection pathways are back-calculated using the CCME and BCE acceptable groundwater concentrations presented in Table 8.1.

The results for the indoor air inhalation pathway are based on an initial depth to contamination of 1 m and a depleting contaminant source. For non-threshold carcinogens, the acceptable soil concentration is based on the total intake averaged over lifetime while for threshold toxicants, the acceptable soil concentrations are based on the maximum intake obtained for the time step increments.

The odour-based acceptable soil concentrations were estimated for the indoor air inhalation pathway using low odour thresholds obtained from the literature (see Table V.3 in Appendix V) and maximum indoor air concentration from the gas infiltration model. The uncertainty associated with the odour-based soil criteria is high since they are based on odour thresholds that vary over several orders-of-magnitude and that are highly subjective in their derivation. For the indoor air inhalation pathway, the odour-based soil criteria exceeded the risk-based criteria for all chemicals except for xylene.

In summary, the calculated soil criteria for the different exposure pathways combined with odour-based, safety-based (i.e., % LEL) and saturation limits vary over several orders-of-magnitude depending on the exposure scenario that applies. The appropriate remediation criteria in soil at a specific site would be the lowest concentration for operable exposure pathways or aesthetic/physical (i.e., odour or safety-based)

TABLE 8.5
Generic Site Matrix of Soil Remediation Criteria for Petroleum Hydrocarbon Contaminated Sites

	Soil Ingestion		Outdoor Inhalation		Indoor Inhalation		Groundwater[1]			CCME	
	Residential (mg/kg)	Industrial Commercial (mg/kg)	Residential (mg/kg)	Industrial Commercial (mg/kg)	Residential (mg/kg)	Industrial Commercial (mg/kg)	Protective of Drinking Water (mg/kg)	Protective of Aquatic Freshwater Life (mg/kg)	Livestock[9] Watering (mg/kg)	Residential (mg/kg)	Industrial Commercial (mg/kg)
Benzene[5]	650	1000[3]	25	40	0.1	0.15	0.01 (0.35)	1.15 (20)	1000[3]	0.5	5
Toluene[4]	1000[3]	1000[3]	1000[3]	1000[3]	10	15	1	13	1000[3]	3	30
Ethylbenzene[4]	1000[3]	1000[3]	1000[3]	1000[3]	30	45	1	1000[3]	1000[3]	5	50
Xylene[4]	450[3]	450[3]	450[3]	450[3]	50[7]	50[7]	25	N/A	450[3]	5	50
Naphthalene[4]	250[3]	250[3]	250[3]	250[3]	15	30	90[11]	9[11]	250[3]	5	50
Benzo(a)pyrene[5]	2.5	20[3]	1.5	2.5	20[3,6]	20[3,6]	20[3,8]	20[3,8]	20[3,8]	1	10
VPH (C_5-C_9)[4]	1000[2]	1000[2]	1000[2]	1000[2]	3.8	4.5	100	1000[2]	1000[2]	-	-
LEPH (C_{10}-C_{18})[4]	5000[2]	5000[2]	5000[2]	5000[2]	275	450	5000[2]	5000[2]	5000[2]	-	-
HEPH (C_{19}-C_{32})[4]	10,000[2]	10,000[2]	10,000[2,6]	10,000[2,6]	10,000[2,6]	10,000[2,6]	10,000[2]	10,000[2,8]	10,000[2]	-	-

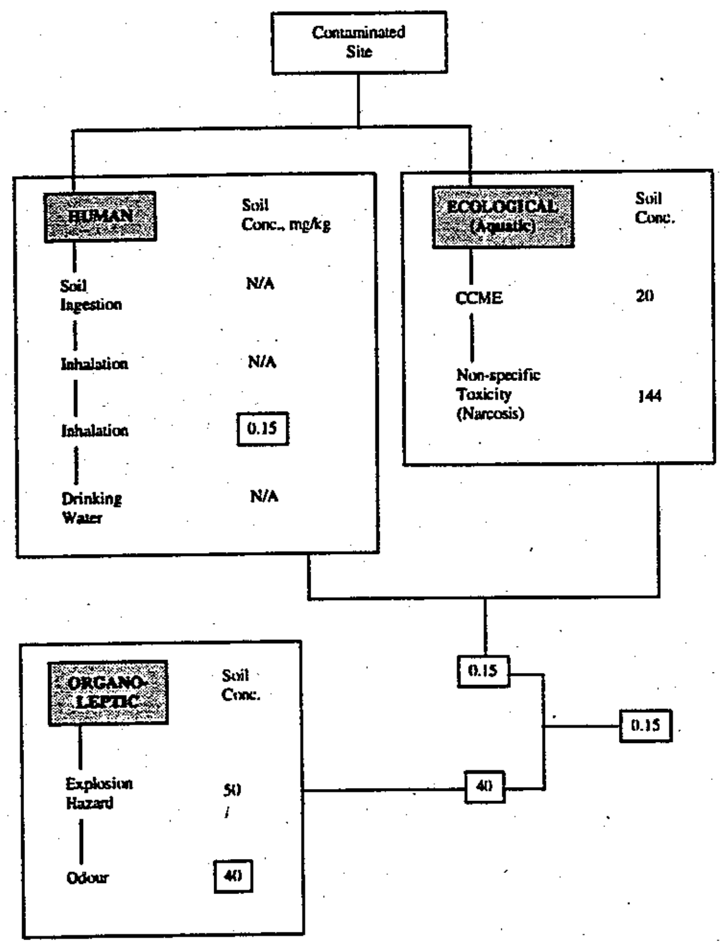
1. Groundwater criteria based on: i) sand, ii) 10 m distance to receptor, iii) large source and iv) 0 m unsaturated thickness (concentrations of benzene in brackets are for 0.5 m unsaturated thickness).
2. Adjusted based on visual aesthetic considerations.
3. Soil saturation concentration for "base-case" variables (see Appendix V and VI)
4. Calculated values correspond to a noncancer hazard quotient of 1
5. Calculated values correspond to an incremental cancer risk of 7 in a million
6. Not a relevant pathway due to essentially non-volatile nature of fraction
7. Adjusted based on odour considerations (see Table 7.7)
8. Not a relevant pathway due to essential non-soluble nature of chemical.
9. Based on protection of livestock health.

Note: Since issueing the draft for review and comment, we have investigated the use of less conservative surrogate (n-nonane instead of hexane) and HQ of 0.5 instead of 0.1. The resulting VPH concentration for residential indoor air scenario is about 50 mg/kg (see Supplement I).

considerations. In all cases, the saturation limit represents the upper range of acceptable remediation criteria. Exhibit 8.1 provides an illustration for selecting the appropriate remediation criteria for benzene while Table 8.5 provides recommended soil remediation criteria.

Exhibit 8.1 - Illustration of Selecting the Appropriate Soil Remediation Criterion for Benzene

A former service station site, located near a major river, is being developed for commercial use. The development plans include a 3-storey retail and office complex with at-grade parking. Except for some minor landscaping, the site will be covered by the building and paved parking areas. The community is serviced by the city water system and groundwater is not used for drinking water. What should the soil remediation criterion be for benzene?



8.2.2 Soil Remediation Criteria Based on Groundwater Pathway - Narcotic Approach

Derivation of soil remediation criteria based on risk presented to salmonid embryo-larvae, indicated that for the five chemicals selected as conservative surrogate narcotics (i.e., benzene, toluene, ethylbenzene, xylene and trimethylbenzene) and the generic exposure scenario, only benzene resulted in a soil source concentration which was less than the soil saturation limit (benzene: 144 mg/kg). For toluene and xylene, the soil source concentration defaulted to the soil saturation limits of 962 and 406 mg/kg, respectively. For ethylbenzene and trimethylbenzene, the physical-chemical transport properties indicate virtually no hydrocarbon would be transported to the receptor. For this reason, the substances were not modelled further; however, the intermediate results indicate they would be limited to soil saturation levels at source.

Thus, four of the five surrogate narcotic substances suggest the presence of free product at source would not present undue narcotic risk at the receptor point, given the groundwater transport model and generic exposure scenario. This assumes free product migration to the receptor point is not an issue. As per the policy towards free-product, the approach would require free product to either be removed, or addressed in the context of a full risk assessment.

Finally, with respect to the soil source concentration derived for benzene on the basis of a narcotic critical body residue, the back-calculated soil source concentration of 144 mg/kg corresponds to a total gasoline level of approximately 5800 mg/kg and VPH concentration of 4600 mg/kg, assuming a product benzene content of 2.5% by weight and VPH content of 80% by weight.

8.2.3 Groundwater Remediation Criteria

Groundwater remediation criteria are provided for the following two exposure pathways:

- groundwater concentrations at source that are protective of drinking water or aquatic receptors located down-gradient;
- groundwater concentrations directly below a building that are protective of indoor inhalation based on partitioning from groundwater and subsequent gas infiltration into building airspace.

The acceptable groundwater criteria are presented in Table 8.5.

The groundwater remediation criteria protective of drinking water and freshwater aquatic life are based on generic site conditions of sandy soil, 10 m distance to the receptor and zero and 0.5 m thickness of the unsaturated zone.

The groundwater remediation criteria protective of indoor air inhalation are based on a depth to groundwater equal to 3 m, and a non-depleting infinite contamination source. As shown in Table 8.5, the risk-based concentrations exceeded the groundwater solubility limit for xylene and benzo(a)pyrene. The results of the groundwater to building air exposure pathway are further described in Appendix V.

8.3 Results of Sensitivity Analysis

Sensitivity analyses were performed for soil ingestion, soil vapour inhalation and groundwater exposure pathway models. The main purpose of the analyses was to establish the relative influence of key input parameters on the remediation criteria derived. This information has been considered for the selection of "adjustable" parameters for the derivation of SSO criteria.

8.3.1 Indoor Air

The sensitivity analyses for the indoor air inhalation exposure pathway included parameters that are likely to vary significantly based on site conditions. The parameters included:

f_{oc}	=	organic carbon fraction
P_a	=	air filled porosity
H_b	=	building height
Ls_{init}	=	initial depth to contamination for depleting source
ED	=	exposure duration

In addition, a sensitivity analysis was conducted for the range of timesteps chosen to model the depleting source.

Other parameters such as crack width (W_c), crack spacing (S), building underpressurization (P_b), depth of influence for advective flow (D) could potentially vary from site to site but were not found to significantly affect the modelling results, and therefore were not included in the sensitivity analysis. A sensitivity analysis was not conducted for the air exchange rate per hour (AEH) as this parameter is correlated with building height.

The sensitivity analysis was conducted for benzene, a non-threshold carcinogen, and naphthalene, a threshold toxicant. The results of the sensitivity analyses are presented in Figures 8.1 and 8.2, while detailed results are presented in Appendix V. The sensitivity analysis was conducted by varying only the parameter of interest. Values for remaining parameters were the base-case input variables presented in Chapter 6.

The results of the sensitivity analysis for the soil gas infiltration model are ranked below in terms of highest to lowest sensitivity.

Benzene

1) Air-filled Porosity
2) Height of Building
3) Exposure Duration
4) Organic Carbon Fraction
5) Initial Depth to Contamination
6) Time-Step

Naphthalene

1) Air-filled Porosity
2) Height of Building
3) Organic Carbon Fraction
4) Initial Depth to Contamination

8.3.2 Groundwater Exposure Pathway

The sensitivity analyses for the groundwater exposure pathway included parameters that are likely to vary significantly based on site conditions. The parameters included:

f_{oc}	= organic carbon fraction;
Z_m	= thickness of mixing zone;
I_{net}	= net infiltration rate;
T_s, T_{us}	= biodegradation half-lives for the saturated and unsaturated zones;
b	= thickness of unsaturated zone.
V_d	= Darcy velocity

Parameters that may vary somewhat from site to site but are not likely to significantly influence the modelling results, such as porosity, dispersivity and bulk soil density, were not included in the sensitivity analysis. Other parameters that were not included in the sensitivity analysis were those that describe the size of the source and the distance to the receptor. The size of the source had little influence on the modelling result, as shown in Appendix VI, whereas the distance to the receptor has a significant influence because of the exponential nature of biodegradation. For BTEX, naphthalene and the surrogates selected for VPH, LEPH and HEPH, little or no contamination is estimated to be transported beyond 100 m for the generic site conditions used.

The sensitivity analyses were performed for benzene and naphthalene as these two compounds have more than an order of magnitude difference of retardation in soil (Log K_{oc}, Table 6.4). The default generic site conditions were used for the sensitivity analysis. These conditions include:

V_d	= Darcy velocity = 12.6 m/year;
b	= unsaturated depth = 0.5 m for benzene;
x	= distance from source to receptor = 10 m; and
point source	= 1m by 3 m

The results of the groundwater model sensitivity analysis are summarized in Figure 8.3 and 8.4. Detailed results can be found in Appendix VI. As shown, the estimated remediation criteria for protection of groundwater are highly sensitive to organic fraction in soil (f_{oc}), average thickness of the unsaturated zone (b) and biodegradation half-lives ($t_{1/2}$), and not particularly sensitive to the assumed thickness of the mixing zone (Z_m). Benzene, having an order of magnitude lower retardation in soil than naphthalene, is highly sensitive to net infiltration rates; whereas, naphthalene is not. The reverse is true for change in darcy velocity, for which naphthalene is highly sensitive but benzene is not.

8.4 Recommended Parameter Adjustment for Derivation of SSO Remediation Criteria

The model input parameters and the proposed allowable adjustment ranges are provided in Exhibit 8.2 and 8.3.

Figure 8.1
Sensitivity Analyses - Benzene
Protection of Indoor Air Inhalation

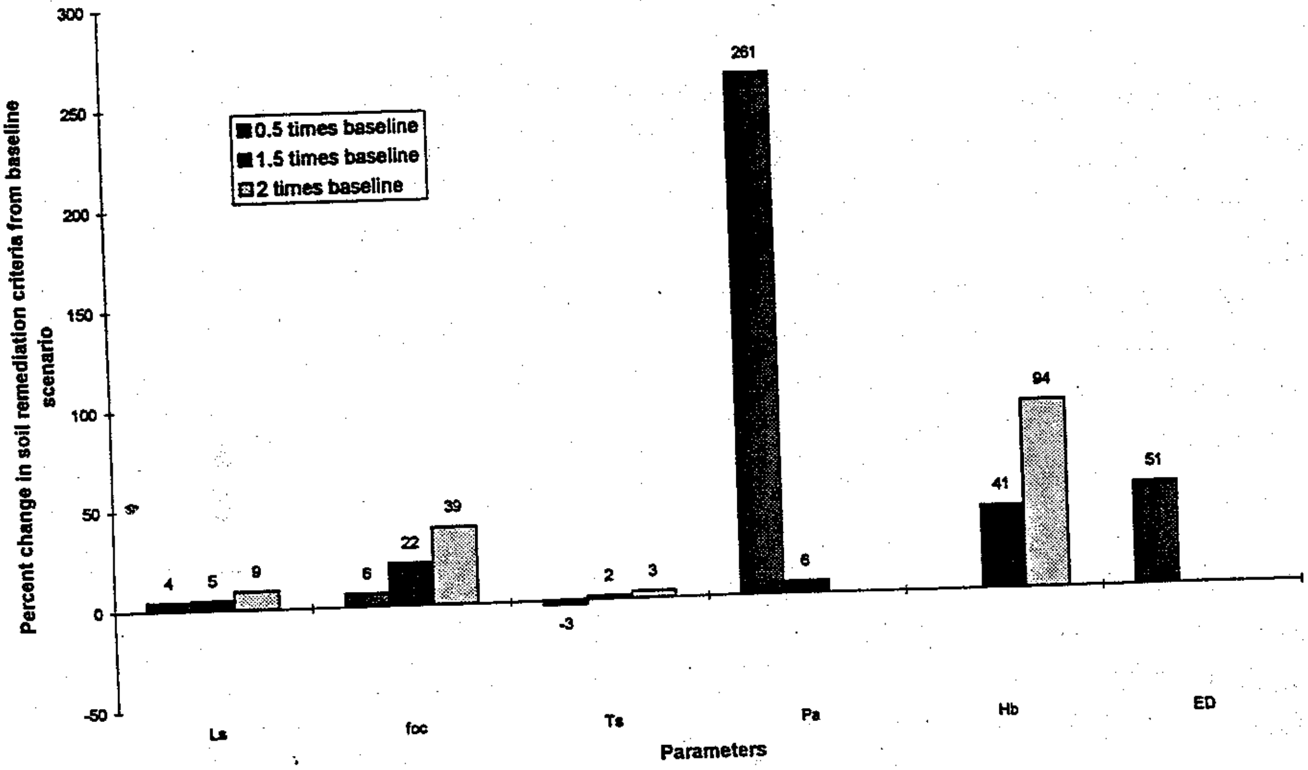


Figure 8.2
Sensitivity Analyses - Naphthalene
Protection of Indoor Air Inhalation

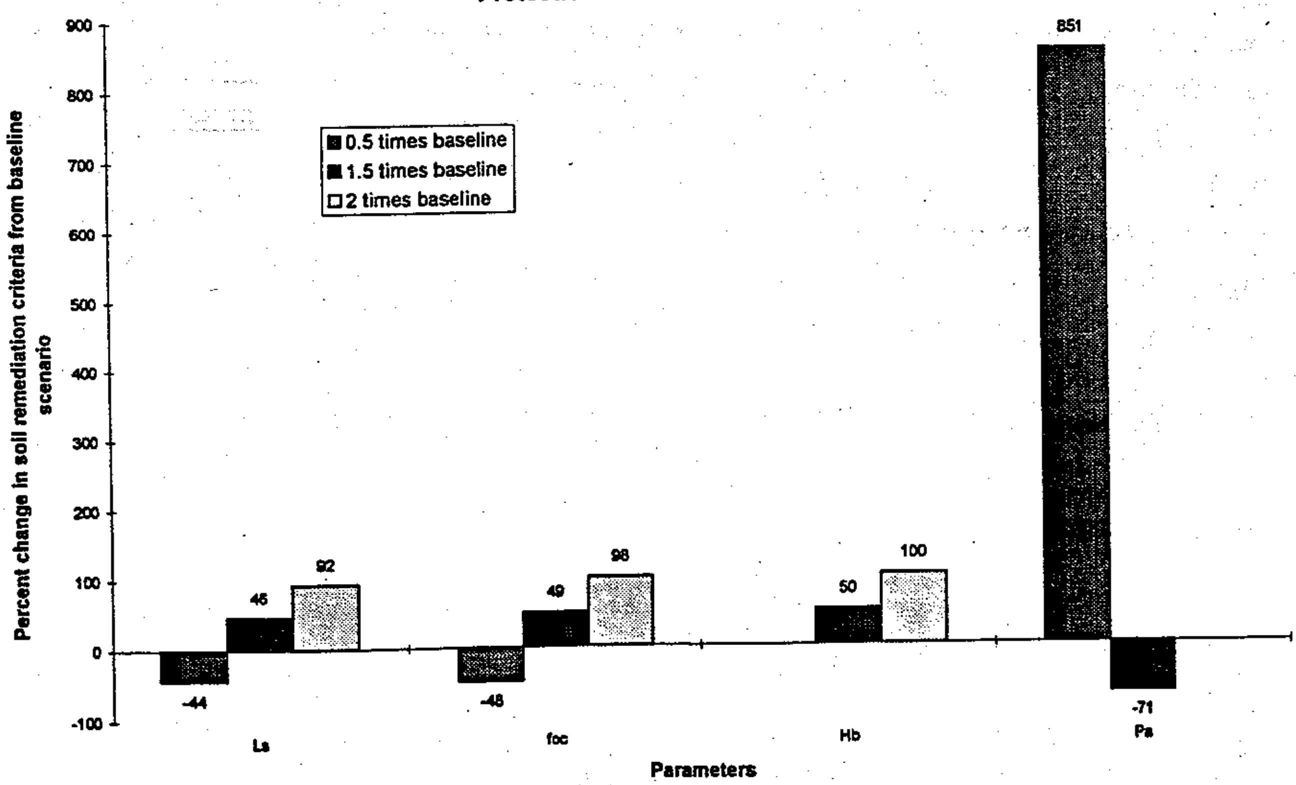


Figure 8.3
Sensitivity Analyses - Benzene
Point Source, Distance from source to receptor = 10m,
Protection of Drinking Water (Criterion = 0.005mg/L)

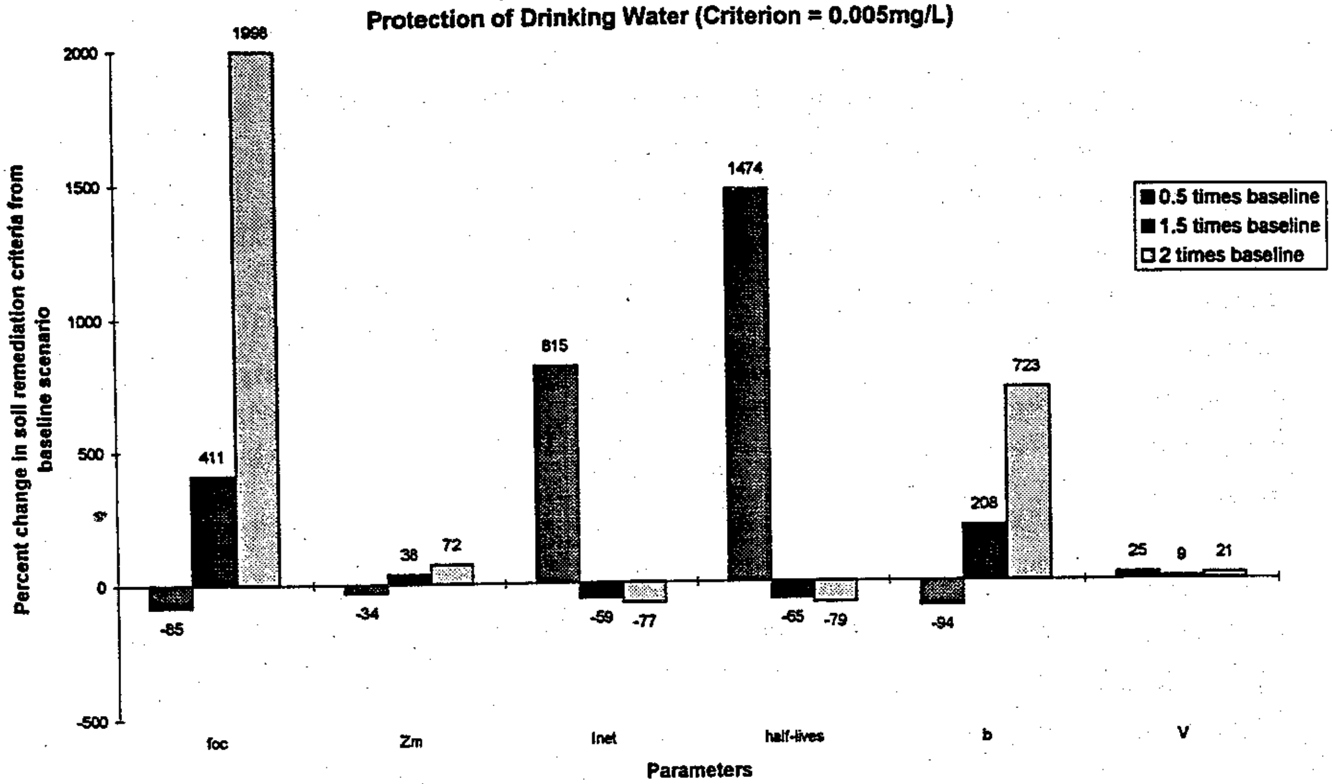


Figure 8.4
Sensitivity Analyses - Naphthalene
Point Source, Unsaturated Depth = 0m, Distance from source to receptor = 10m
Protection of Aquatic Life (Criterion = 0.001mg/L)

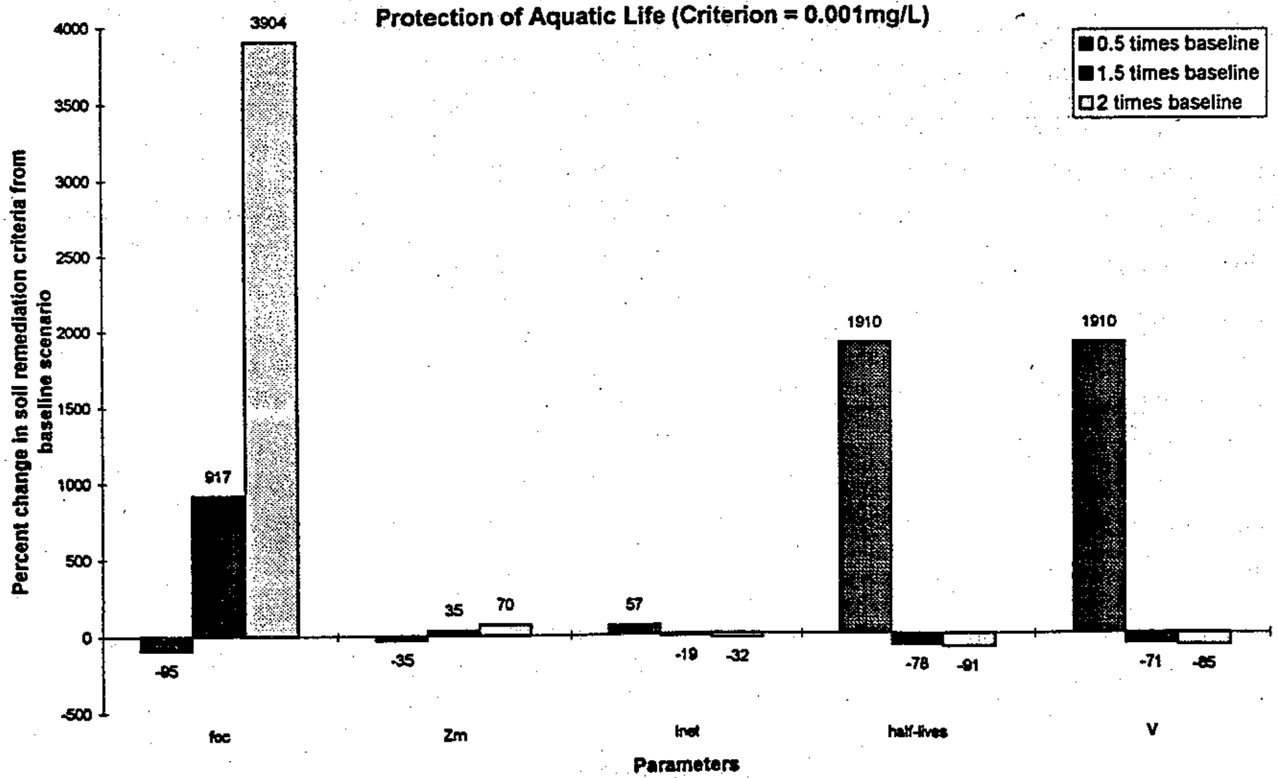


Exhibit 8.2 - Adjustable Groundwater Model Parameters for SSO Remediation Criteria

Parameter	Definition (units)	Default	SSO
s	maximum solubility	chemical specific	co-solubility
n_u	water filled porosity	0.1	*
β	dry bulk density of soil	1.75 g/cm³	*
H	Henry's Law constant	chemical specific	*
n_a	air filled porosity	0.2	*
b	thickness of unsaturated zone	0m, 0.5m	site-specific (increments of 0.5m)
α_u	dispersivity in unsaturated zone	$0.1 \times b$	*
K_{oc}	organic carbon partitioning coefficient (cm^3/g)	chemical specific	*
f_{oc}	fraction of organic carbon in soil	0.006	max 0.02
I_{net}	net infiltration rate	0.546 m/year	*
V	Darcy velocity in saturated zone	12.6 m/year	min 5 m/year
Z_m	thickness of mixing zone	0.1 X	*
α_x,	dispersivity in x-direction	α_x=0.1 x;	*
α_y,	dispersivity in y-direction	$\alpha_y=0.1\alpha_x$	*
D_x	longitudinal dispersion coefficient	5×10^{-7} m^2/s	*
D_y	lateral dispersion coefficient	5×10^{-8} m^2/s	*
x	distance from source to receptor	10m	max 100 m
M_e	effective porosity (dimensionless)	0.2	*
n	total porosity (dimensionless)	0.3	*
$t_{1/2}$	decay (biodegradation) half-life	chemical specific	*
Y,Z,X	source dimensions in the x, y and z directions (m)		site-specific
X	source dimension length (m)	1m, 5m	*
Y	source dimension width (m)	3 m, 30m	*
Z	source dimension thickness (m)	1m	*
	Surrogate Ratios	see Table 5.4	site specific

* Non-Adjustable Parameter

Exhibit 8.3 - Adjustable Soil Gas Infiltration Model Parameters for SSO Remediation Criteria

Parameter	Definition (units)	Default	SSO
K_{oc}	organic carbon partition coefficient (mg/kg-OC per mg/L-water)	chemical specific	*
f_{oc}	organic carbon content of soil (kg-OC/kg-soil)	0.006	max 0.02
P_a	air-filled soil porosity (unitless)	0.2	adjustable
P_w	water-filled soil porosity (unitless)	0.2	adjustable
H'	Henry's Law constant (unitless-conversion factor of 42.3 based on 15 deg C)	chemical specific	*
H	Henry's constant (atm m^3/mol)	chemical specific	*
D_a	diffusion in air (m2/sec)	chemical specific	*
P_t	total porosity (unitless)	0.4	adjustable
$\{L_s\}_{i=1}$	initial depth from underside of slab to top of contamination zone (m)	1	adjustable
M,B	slope and intercept for estimation of diffusion coefficient	chemical specific	*
TMP_s	temperature soil (deg C)	15	*
C_{am}	ambient air concentration (ug/m^3)	0	*
C_a	air porosity of concrete (unitless)	0.5	*
C_t	total porosity of concrete (unitless)	0.1	*
C_{ca}	air porosity of dust-filled concrete cracks (unitless)	0.45	*
C_{ct}	total porosity of dust-filled concrete cracks (unitless)	0.5	*
S_c	spacing of cracks (m)	3	*
W_c	average crack width (mm)	1	*
T_s	thickness of concrete floor slab (m)	0.1(res),0.15(com)	*
μ	viscosity of air @ 18 C (g/sec*cm)	0.000183	*
P_b	building underpressurization or vacuum (Pa)	5	*
TI	time increment (years)	0.25	*
k_{soil}	permeability of soil below concrete slab (darcy)	50	adjustable
D	advective flow depth of influence (m)	0.3	adjustable
β	soil dry bulk density	1.7	*
AEH	air exchanges per hour (1/hr)	1	adjustable
H_b	height of building (m)	3	max 4.5

* Non-Adjustable Parameter

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9.0 UNCERTAINTY AND LIMITATIONS OF RECOMMENDED CRITERIA

In deriving risk-based remediation criteria for contaminated sites several assumptions have been made. Each of the assumptions add uncertainty to the derived criteria which lead to limitations in their use. The limitations reflect the degree of conservation used (or lack thereof), in formulating assumptions.

This chapter presents a discussion of the sources of uncertainties and the degree of conservation introduced, for deriving remediation criteria; and provides some recommendations regarding "safety factors" that may be considered in light of inherent limitations, and recommendations for further research or development that may be considered. The main uncertainties associated with deriving the remediation criteria may be grouped into the following four groups:

1. Inherent uncertainty associated with the use of surrogates;
2. Uncertainty introduced by the assumptions use for the generic exposure scenarios;
3. Uncertainty associated with the exposure modelling; and
4. Uncertainty associated with quality assurance in calculations.

Uncertainties associated with improper definitions of exposure scenarios improper fate & transport model application and errors in calculation are best dealt with by peer review and cannot be quantified. Uncertainties associated with selection of parameter values can be described and quantified through sensitivity analysis. The following is a brief discussion of each group of uncertainty.

9.1 Inherent Uncertainties of the Surrogate Approach

9.1.1 Human Health-Based Approach

The "surrogate approach" for criteria development employed in this study is first based on the assumption that surrogate chemicals in a petroleum hydrocarbon mixture can describe the toxicity, and health risks, associated with the entire carbon mass of the surrogate's respective petroleum hydrocarbon *class* (i.e., alkane or aromatic class). The principle is further extended to assume that the aromatic and alkane surrogates can adequately describe the toxicity of the entire carbon mass for a given hydrocarbon *fraction* (i.e., VPH, LEPH and HEPH). Clearly, uncertainty surrounds these assumptions in the form of i) a lack of complete toxicological information on which the assumption is predicated, and ii) variability in composition and therefore relative abundance of the surrogate chemical in the mixture. This approach and the above-noted uncertainties contrast sharply with the absence of such assumptions involved in the "whole product approach", where toxicity for the entire mixture is known (Section 5.3). However, since environmental hydrocarbon contamination may often differ substantially from the original hydrocarbon product released to the environment, the whole product approach has limited application. The surrogate approach offers more flexibility than the whole product approach in its application to environmental contaminant mixtures. Consequently, adoption of the surrogate approach necessitates adoption of a concomitant degree of uncertainty inherent with these assumptions.

The application of the surrogate approach to the derivation of risk-based criteria for VPH, LEPH and HEPH was based on the following conservative assumptions:

- Selection of surrogates with high toxicity and high mobility; and
- Hazard indices for surrogates of 0.1.

Note: *Since issuring the draft report for review and comment, the use of less conservative surrogate (n-nonane instead of hexane) and hazard index of 0.5 instead of 0.1 was investigated. The results of these alternates are presented in Supplement I.*

The proportion of surrogates in a "hypothetical" petroleum hydrocarbon mixture was based on approximately average concentrations found in common petroleum hydrocarbon products.

The exact degree of uncertainty in criteria arising from adoption of the surrogate approach and its ensuing toxicological assumptions is not quantifiable due to lack of complete toxicological information on all components of a mixture. However, in response to these circumstances, the two assumptions described above bias the uncertainty towards the conservative case.

9.1.2 Uncertainty Associated with Narcosis-Based Approach for Aquatic Organisms

For derivation of remediation criteria based on narcotic toxicity of hydrocarbon mixtures toward salmonid embryo, the uncertainty associated with toxicity of surrogates is not a critical issue as it was for human health. This is because underlying concept of the narcotic approach is narcotic-based effects (both lethal and sub-lethal) occur as a consequence of the "number of molecules", and not from specifically acting bio-chemical reactions. Therefore, those substances which operate in a narcotic mode are considered equipotent.

Consequently, the important characteristics which determine risk to the salmonid embryo-larvae are those parameters which govern exposure (i.e., fate and transport parameters) rather than toxicity. To this end, water solubility and the octanol water partition coefficient (K_{ow}) are key in determining groundwater contaminant transport from source to receptor. Therefore, surrogate narcotic chemicals selected for transport modelling were chosen to have a water solubility and K_{ow} that would maximize transport to, and accumulation within, the embryo-larval receptor. This is a conservative strategy for derivation of criteria.

Additional conservatism was introduced by adopting a chronic body burden of neutral narcotics of 0.1 mmol/kg, which is about ⅕ of the chronic body burden which is turn is estimated as $^1/_{10}$ of reported lethal body burden values.

An exception to the implied conservatism in using surrogates with low Kow and solubility occur with substances having unique polar functional groups making them more soluble and rapidly transported. The conservative steps described in the previous paragraphs will to some extent off-site the uncertainty noted here, although quantification of this uncertainty is best addressed through application of these principles in case studies.

9.2 Generic Exposure Scenarios

In developing the remediation based criteria, it was necessary to first define and adopt various generic exposure scenarios for which the ensuing exposure and risks could then be estimated. In doing so it was necessary to consider both the appropriateness and applicability of the scenarios in the context of contaminated sites in British Columbia.

The direction provided by BCE and other participants of the round table discussion meetings, was to develop generic site criteria that would be protective of human health and freshwater aquatic habitats at the majority of the contaminated sites in B.C. (subjectively estimated at 90%), in terms of size, distance from receptor, darcy velocity, and other parameter values used. It was argued that sites falling outside the range of values selected for generic site conditions, would be readily recognized as such, and would be addressed by either SSO or RA/RM derived criteria.

However, qualitatively one should expect that 5 to 10% of the contaminated sites may require lower soil and groundwater remediation criteria in order to protect the appropriate receptors.

9.2.1 Human Exposure Scenarios

Key considerations in selecting exposure scenarios for risk-based criteria include the type and number of pathways, and the distance between the source and the receptor.

The distance over which the contaminant was transported and could be attenuated strongly influences the values selected for acceptable risk-based criteria. Use of a long distance could result in criteria being insufficiently protective of scenarios where a shorter transport distance and less contaminant attenuation and degradation occurs. Likewise, a transport distance which is too short could yield overly conservative GSM criteria leading to most sites having to be considered under the SSO or RA/RM approach. Since data on transport distances for province-wide contaminated sites was not available, a subjective assessment was made. The following general distances were adopted to define the above generic human exposure scenarios, which are subjectively estimated to cover approximately 90% of contaminated sites in B.C.:

- Soil Gas Inhalation Indoors (vertical distance below floor slab) 1 m
- Groundwater Ingestion (horizontal distance to receptor) 10 m
- Soil Ingestion and Fugitive Dust Inhalation (distance to receptor) 0 m

In addition to being widely applicable because of their conservative nature, these adopted scenarios are also likely to address conditions within property boundaries of the site. Therefore, these scenarios reduce the likelihood of criteria exceedances as a consequence of future developments wherein new receptors and contaminant exposure pathways are introduced (e.g., installation of a new drinking water well).

The level of conservatism introduced by the selection of these short distances is partially off-set by the fact that each pathway is considered in isolation, and potential combined exposure from several operable pathways is not considered.

9.2.2 Aquatic Receptor Exposure Scenario

Adoption of the exposure scenario for aquatic receptors involved consideration of salmonid embryo-larvae in sediment beds through which groundwater was discharging. The location of the receptor was both a consequence of the choice of receptor (a sensitive lifestage of commercially important and sensitive species) and the desire to constrain the criteria development to a conservative scenario.

Thus in the present case the exposure scenario is considered conservative because:

i) Distance for contaminant transport is relatively short and does not allow excessive attenuation and degradation as a consequence of transport time.

ii) The receptor location does not involve consideration of contaminant dilution by the water column; rather, the exposure concentration is that defined in the groundwater as it forms the sediment porewater discharging through sediment beds.

iii) The receptor chosen is considered to represent the most sensitive species and lifestage.

The rationale for selecting the salmonid embryo-larva was based on the general sensitivity of the fish species sensitivity of the life-stage and the point of exposure being relatively independent of dilution effects of the water column. Several arguments favour this selection. First, the narcosis mode of action applies equally well to aquatic invertebrates. Many aquatic invertebrates inhabit the sediment and may experience similar exposure to pore water as a consequence of groundwater discharge. Secondly, benthic invertebrates often contain higher lipid levels in comparison to juvenile and adult fish. This allows greater accumulation of the contaminant as a consequence of partitioning from water to the lipid phase, and is an important factor in obtaining critical body residues of contaminant from aqueous exposures. The use of salmonid embryo-larvae provide a reasonable reference for comparison to benthic invertebrates, because the embryo-larval stage has an elevated level of lipids during the yolk absorption phase. Therefore, even when salmonids are entirely absent, it is likely this species and lifestage provide adequate conservatism in the remediation criteria to also be protective of benthic invertebrates.

9.3 Exposure Assessment Modelling

9.3.1 Risk Assessment Assumptions

Physiological parameter assumptions which help to define exposure rate include:

- Soil Ingestion Rate (mg/day)
- Inhalation Rate (m^3/hr)
- Body Weight (kg)

These parameters define the intake rate of the medium in which the contaminant resides (soil ingestion rate, air inhalation rate) and the body mass into which the contaminant is dispersed on a daily basis.

Uncertainty is associated with all three variables as a consequence of biological variability. For example it is well known children are more prone to ingest soil incidently or purposefully in comparison to adults. To address this uncertainty, calculations of risk estimates were based on age-specific intake rates and the lifetime exposures were performed using iterative age-steps.

These exposure calculations were conducted in a deterministic approach; therefore, there is no opportunity to define the uncertainty in the context of probability distribution functions. However, the values employed for the weights and intake rates of the residential receptors were obtained from CEPA (1994) and are considered to be average values for Canadians of specified age categories.

To avoid under-estimatation of intake rates in a workplace setting, a separate and conservative respiration rate was employed as defined by BCE (1990). It assumes a respiration rate under a physically demanding workload of 2.1 m^3/hr., approximately double that used for the residential scenario.

9.3.2 Soil Gas (Indoor Inhalation)

9.3.2.1 Soil Gas Partitioning Model

The partitioning model used to estimate soil-water and soil gas concentrations is based on linear equilibrium partitioning assuming no NAPL is present. The upper bound for the partitioning model is the soil saturation concentration for individual chemicals. Since petroleum hydrocarbons consist of a mixture of chemicals, the actual soil saturation concentration will depend on the properties of the mixture and will be lower than for a pure-chemical due to the effect of co-solubility. The use of linear partitioning, assuming no NAPL is present, will provide conservative estimates of soil gas concentrations above saturation limits. The partitioning model also assumes that sufficient soil moisture is present to form at least a monolayer water film over soil particulates. For dry soils such as volcanic tuff deposits, sufficient water may not be present and partitioning may occur between the absorbed and soil gas phases.

9.3.2.2 Soil Gas Fate and Transport Model

The soil gas fate and transport model is based on steady-state one-dimensional (1-D) upward diffusion through soil and concrete. In addition, steady-state 1-D upward advective flow is assumed through shallow soil and the concrete floor slab. Finally, a laterally infinite, but vertically depletable contamination source is assumed.

Conservative aspects of the model include:

1) A laterally infinite contamination source.

2) No attenuation through sorption or biodegradation.

3) Steady-state mass transfer; in some cases attenuation due to the sorption and biodegradation will be significant and therefore transient conditions may prevail for part of the exposure duration.

4) Advection is assumed to occur through a cracked concrete slab only. The potential effect of floor coverings and sealants on mass transfer rates is not considered.

5) Diffusion in soil is limited to 1-D upward mass transfer. In reality, three-dimensional diffusion will occur thereby reducing upward mass flux to the underside of a building floor slab.

6) Possible mass reduction through infiltration and leaching to groundwater is not considered.

Potentially, a more sophisticated model could have been used to incorporate some or possibly all of the above factors. One disadvantage of using a more sophisticated model are that numerical modelling (i.e., finite difference or element) techniques would be required to incorporate many of the above considerations. Furthermore, due to the uncertainty associated with many of the input parameters required for such modelling, the additional effort may not be warranted where the objective is to derive generic soil criteria.

9.3.2.3 Uncertainty in Input Parameters

The quantity and quality of data currently available for input into the soil gas infiltration model varies considerably. For some parameters, the quality and quantity of data was considered to be moderate to high. Parameters in this category are Henry's Law constant (H), diffusion coefficient (D_a), solubility (S), organic carbon partitioning coefficient (k_{oc}), organic carbon content (f_{oc}), airfilled porosity (P_a), building height (H_b), building air exchange rate (AEH) and soil permeability (k). For these parameters, the default value represents the estimated <u>median value</u> for these parameters. For the remaining parameters consisting of concrete crack width (W_c), concrete crack spacing (S_c) and building underpressurization (P_b), the data quality and quantity is considered to be low.

For these parameters, the default parameter selected represents an estimate of the approximate upper quantile (i.e., 75th to 90th percentile) for these values.

9.3.2.4 Overall Level of Conservatism

A subjective evaluation of the sources of uncertainty suggests that the key level of conservatism of the soil gas model are (1) associated with assumed equilibrium conditions for soil vapour partitioning with no NAPL) and (2) no allowance for biodegradation and sorption during soil gas transport.

Input parameters that have both a high degree of uncertainty and which are sensitive in terms of their effect on resulting remediation criteria are most critical in terms of the derived criteria. Parameters in this category include air-filled porosity and organic carbon content.

9.3.3 Groundwater

9.3.3.1 Soil/Water Partitioning

The leaching of soil by infiltration of water through the source is modelled by the sorption partitioning of a chemical species between the solid phase (soil) and the liquid phase (leachate) in a porous medium. Hydrophobic sorption with a linear Freundlich sorption isotherm is assumed. The partition coefficient (K_d) is assumed to be equivalent to the product of the weight fraction of organic carbon (f_{oc}) and the partition coefficient of a compound between organic carbon and water (K_{oc}). Several studies have shown that this approximation for hydrophobic non-polar compounds (that includes many hydrocarbons) is physically realistic (Domenico and Schwartz, 1990). For less hydrophobic compounds (hydrophilic) such as methanol, the K_d values determined using the model of hydrophobic sorption, are likely underestimated. In these cases, the resulting leachate concentration would be considered conservatively high because absorption occurs through other mechanisms than absorption onto organic matter.

The leaching model also assumes that the upper limit of the leachate concentration is the maximum solubility of the compound. This upper limit may be quite conservative because the presence of other compounds in the source would result in co-solubility effects which would reduce the maximum solubility of individual compounds. Co-solubility effects are not included in the model. For example, the solubility of pure benzene in water is 1,750 mg/L; whereas, the solubility limit for benzene in gasoline would likely be less than 10 mg/L, depending on the actual composition of the gasoline.

The soil source is assumed to be continuous, i.e. decay of the source is not included. This assumption is conservative.

The soil/water partitioning equation assumes that sorption is linear and reversible. At high compound concentrations the former assumption may not be conservative because the absorption coefficient (K_d) may be less and the sorptive capacity of the organic matter may be exhausted. The assumption of reversible absorption is conservative because non-reversible absorption would result in reduction in compound concentrations.

9.3.3.2 Unsaturated Zone

The model assumes that the unsaturated-zone saturation is vertically uniform and that the saturated porosity is half that of the saturated zone. The hydraulic conductivity of the unsaturated zone is assumed to be half that of the saturated hydraulic conductivity. Both of these assumptions are conservative, in that they likely overestimate the groundwater velocity in the unsaturated zone.

The unsaturated zone model ignores the effects of the capillary fringe. In this zone, pressures are negative and the pores are saturated. The capillary zone effectively reduces the thickness of the unsaturated zone. However, in most relatively permeable soils such as sands and gravels, the capillary zone is generally thin and less than 0.05 m thick. The assumption of no capillary fringe, however, is non-conservative because in cases where the capillary zone is of significant thickness relative to the unsaturated zone, the unsaturated zone model underestimates the leachate velocity.

9.3.3.3 Mixing Zone

The thickness of the mixing zone was set equal to 0.1 times the length of the source in the direction of groundwater flow. This was a rather arbitary selection and the associated level of conservatism or uncertainty is not known.

9.3.3.4 Saturated Zone

The saturated zone is modelled as a two-dimensional groundwater transport on a one-dimensional groundwater flow regime (Domenico, 1987). The assumption of one-dimensional groundwater flow is conservative because flow in the two other dimensions (vertical and transverse directions) will increase the travel time and the dispersion of further disperses the compound. The assumption of two-dimensional dispersion (longitudinal and horizontal transverse) only, is conservative, because dispersion in the vertical transverse direction would generally result a reduction in the compound concentrations.

The porous medium in the saturated zone is assumed to be homogeneous and isotropic. If preferential pathways (highly permeable zone) are present, this assumption is non-conservative, because such pathways would increase the compound concentration at the receptor.

Downgradient of the source, dilution caused by infiltration of water on to the plume or from upward flow of non-contaminated water from below the plume, are assumed to be zero. These assumptions are conservative because infiltrating non-contaminated water would reduce the compound concentration at the receptor.

9.3.3.5 Uncertainty in Selection of Input Parameters

The quantity and quality of data currently available for input into the groundwater model varies consideraby. Parameters for which the quantity and quality of data were considered to be high included: porosity, darcy velocity, and f_{oc}. For these parameters the value selected generally represented the median or a somewhat more conservative value. For the remaining parameters, the values selected were generally conservative representing approximately the upper (or lower) quartile (i.e., 75^{th} to 90^{th} percentile).

Parameters in this category include: thickness of unsaturated zone, and biodegradation half-lives.

9.4 Quality Assurance of Calculations

The quality assurance procedures utilized to verify the accuracy of calculations consisted of both internal Golder and external reviews. The soil gas infiltration model (indoor inhalation) and to a lesser degree the groundwater model were, in part, verified by PetroCanada who concurrently developed a similar spreadsheet model to assess gas infiltration and exposure.

9.5 Limitations and Recommendations for Further Development

9.5.1 Limitations of GSM Remediation Criteria and Proposed "Safety Factors"

9.5.1.1 Multi-Media Exposure

In spite of the conservative strategies employed, a notable limitation of the human generic exposure scenarios is that with the exception of concurrent exposure from soil ingestion and fugitive dust inhalation, all other exposures are modelled to occur in isolation (i.e., no multi-media exposure). While many contaminated sites tend to have only one or two major exposure pathways, multiple concurrent exposure pathways may exist depending on the source and location of the petroleum hydrocarbon.

For example, it is conceivable that in addition to a residential scenario involving contaminated soil and fugitive dust intake, subsurface contamination may also affect potable water and lead to further ingestion and perhaps inhalation and/or dermal absorption while showering. While such a scenario is plausible both in a residential or industrial scenario, there is little basis by which to apportion the total intake by each pathway that would be applicable on a province-wide basis.

Thus, in applying this approach and the remediation criteria in a regulatory capacity, consideration should be given to whether multi-media exposure is applicable for the site.

Safety Factor: *If multi-media exposure is expected, it may be necessary to invoke full risk assessment principles under Tier 4.*

9.5.1.2 Protection of Groundwater

The modelling assumptions used for deriving the GSM remediation criteria for protection of groundwater were in general somewhat conservative and targeted to protect groundwater at approximately 9 of 10 contaminated sites. Two major assumptions were soil type and distance to receptor, for which sand and a 10 m distance were selected. The model used assumed homogeneous soil conditions, which is non-conservative.

Safety Factor: *To address the potential for non-homogeneities in site soils, BCE may consider selecting a greater default distance to receptor of, for example, 30 m.*

9.5.2 Recommendations for Further Development

9.5.2.1 Soil Gas Infiltration Model

A general limitation that applies to soil gas building infiltration modelling for VOCs is the lack of available models that have been verified through previous use and field calibration. In comparison, significantly more research has been conducted for radon entry into buildings where empirical methods include the estimation of attenuation coefficients based on average measured radon concentrations in soil and buildings (Little, *et al.*, 1992), or based on the results of controlled tests where radon flux as a function of building underpressurization is measured (Nazaroff and Sextro, 1989 and Nazaroff, *et al.*, 1987). For example, based on a review of average radon data in the literature, Little *et al.* (1992) suggests that an attenuation coefficient, α, (C_{indoor}/C_{source}) equal to 0.0016 may be a reasonable first approximation for radon entry into a single dwelling house.

Johnson and Ettinger (1991) present a heuristic model for VOC soil gas infiltration which incorporates one-dimensional diffusive max flux through soil, advective and diffusive flow through building cracks and building air exchange rates. Based on input data chosen to reflect a single family dwelling, Johnson and Ettinger (1991) present attenuation coefficients for benzene calculated using various crack area to building slab areas and soil permeabilities. However, the attenuation coefficients are not verified using field data. Further applied research and calibration of soil gas infiltration models is recommended.

9.5.2.2 Groundwater Model

Components of the groundwater exposure pathway model should be verified and validated to field data and to previously validated numerical models. In particular, the assumptions used in the unsaturated and saturated zone transport models must be assessed by comparison with numerical models that fully describe three-dimensional transport and fate. Such comparisons will determine if the assumptions are conservative and the extent of this approximation.

The mixing model is not based on any field observations and the mixing zone is assigned somewhat arbitrarily. The model is essentially empirical in nature, but field observations are required to assess the validity of the assumptions used in the mixing model.

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