Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health

POLYCYCLIC AROMATIC HYDROCARBONS 2010

This fact sheet provides Canadian soil quality guidelines for commonly occurring unsubstituted polycyclic aromatic hydrocarbons for the protection of environmental and human health (Table 1; Figure 1 and 2 provide instructions on how to implement the PAH guidelines at a contaminated site). The guideline was developed in 2008 and revised in 2010 to improve the understanding of how to implement the PAH soil quality guidelines. A detailed scientific supporting document is also available (CCME 2010). CCME soil quality guidelines for naphthalene and benzo[a]pyrene were previously developed in 1997. These 2010 values supersede the 1997 guidelines.

Background Information

The contamination of soil by polycyclic aromatic hydrocarbons (PAHs) is widespread in Canada due to the near ubiquitous nature of its major sources: namely, the release of various petroleum hydrocarbon or coal-derived products and the production of PAHs through a variety of combustion processes/types such as vehicle exhaust or a wide variety of industrial processes.

PAHs are a group of complex hydrocarbons comprised of two or more fused benzenoid rings. In addition to anthropogenic sources, some PAHs also occur naturally - primarily as combustion byproducts or the modification of plant-derived terpenoids and heterocyclic compounds. Forest fires and volcanic eruptions are natural sources of some PAHs.

In general, PAHs become increasingly less soluble in water with an increasing number of benzenoid or other rings, and increasing molecular weight. Naphthalene, a two-ring PAH, is the most soluble, with an estimated aqueous solubility of around 32 $mg \cdot L^{-1}$ at 25°C. Indeno[1,2,3-c,d]pyrene, a six-ring PAH, has a much more limited aqueous solubility at room temperature of approximately 2.2×10^{-5} $mg \cdot L^{-1}$. Lower molecular weight PAHs also tend to be more volatile (i.e., have a higher vapour pressure) and more readily partition into air from pure water (i.e., have a higher Henry's Law constant). For example, the vapour pressure and Henry's Law constant of naphthalene are 8.5×10^{-2} mm Hg and 4.83×10^{-4} $atm \cdot m^3 \cdot mol^{-1}$, respectively, while those for indeno[1,2,3-c,d]pyrene are 1.0×10^{-10} mm Hg and 1.6×10^{-6} $atm \cdot m^3 \cdot mol^{-1}$, respectively.

Much of the scientific, regulatory, and public interest in PAHs is based on the potential role of these substances as cancer-causing agents. This set of Canadian soil quality guidelines specifically addresses existing management gaps for PAH-contaminated soils in Canada where there is concern about human health risks associated with exposure to potentially carcinogenic PAHs such as benzo[a]pyrene and other PAHs with similar modes of action but of different potency, or concern about ecological non-cancer effects of the broader suite of unsubstituted PAHs.

The unsubstituted PAHs that are known or strongly suspected to act as carcinogens in humans and other mammals include:

- benz[a]anthracene,
- benzo[a]pyrene,
- benzo[b]fluoranthene,
- benzo[j]fluoranthene,
- benzo[k]fluoranthene,
- chrysene,
- dibenz[a,h]anthracene,
- benzo[g,h,i]perylene, and
- indeno[1,2,3-c,d]pyrene.

In addition to the sixteen or so "unsubstituted" PAHs that are commonly analyzed in North America in environmental samples, there are hundreds of PAH compounds containing nitrogen (N-) or sulfur (S-) atoms within the carbon rings (heterocyclics), and/or with various side chains attached to the aromatic ring structure. Alkyl-substituted PAHs, in particular, are common constituents of petrogenic (petroleum-derived) PAH mixtures. Too little is currently known, however, about the environmental fate and toxicity (either for humans or various other living organisms) to enable development of Canadian Soil Quality Guidelines for alkyl-PAHs.

PAHs are found in environmental samples almost always as complex mixtures, with minor exceptions; for example, in cases where naphthalene has been used and released in the absence of other PAH compounds. This necessitates some consideration of the risks and related environmentally-acceptable soil thresholds of the entire suite of PAHs present, not just of individual PAHs. Any possible approach for dealing with environmental risks of mixtures involves a number of trade-offs in terms of the ability of the approach to account for compositional variability across sites; toxicological variability across

Figure 1. How to apply Canadian Soil Quality Guidelines for PAHs at a contaminated site.

There is no single Canadian Soil Quality Guideline that will protect both human and environmental health from all PAHs. To ensure that both human and ecological receptors are protected, the following process must be followed (*do Steps*, **1** , **2** and **3**)

For the protection of Human Health from:

carcinogenic effects of PAHs;
benz[a]anthracene
benzo[a]pyrene
benzo[b+j+k]fluoranthene
benzo[g,h,i]perylene
chrysene
dibenz[a,h]anthracene
indeno[1,2,3-c,d]pyrene

do &

Step **1**

Calculate a Benzo[a]pyrene Total Potency Equivalents (B[a]P TPE) to ensure that **humans are protected from direct contact** with contaminated soil

Step **2**

Calculate the Index of Additive Cancer Risk (IACR) to ensure that **potable water resources are protected**

non-carcinogenic effects of PAHs (i.e. not evaluated based on carcinogenicity);
anthracene
acenaphthene
acenaphthylene
fluoranthene
fluorene
naphthalene
phenanthrene
pyrene

Protection of human health from non-carcinogenic effects of PAHs was not assessed; consult guidelines from other jurisdictions for protection.

For the protection of Environmental Health from:

non-carcinogenic effects of PAHs (i.e. not evaluated based on carcinogenicity);
anthracene
acenaphthene
acenaphthylene
benz[a]anthracene
benzo[a]pyrene
benzo[b]fluoranthene
benzo[k]fluoranthene
chrysene
dibenz[a,h]anthracene
fluoranthene
fluorene
indeno[1,2,3-c,d]pyrene
naphthalene
phenanthrene
pyrene

do

Step **3**

Compare PAHs individually to the appropriate environmental Soil Quality Guideline which were developed based on non-carcinogenic effects.

Table 1: Soil Quality Guidelines for Carcinogenic and Other PAHs ($mg \cdot kg^{-1}$)

IMPORTANT NOTE (1): Assess the hazard to human health from carcinogenic effects of PAHs by doing steps **1** and **2**. Assess the hazard to environmental health from non-carcinogenic effects of PAHs by doing step **3** (see Figure 1 and 2, and factsheet text for more detail).

IMPORTANT NOTE (2): For soil contaminated with coal tar or creosote mixtures, the calculated Benzo[a]pyrene Total Potency Equivalents (B[a]P TPE) concentration for soil samples should be multiplied by a safety factor of 3 prior to comparison with the SQG_{DH} to account for carcinogenic potential of alkylated and other PAHs present for which a Potency Equivalence Factor (PEF) does not currently exist, but which are likely to contribute to mixture carcinogenic potential.

Step		Land Use			
		Agricultural	Residential/ Parkland	Commercial	Industrial
	Guideline – see table caption IMPORTANT NOTE (1)				
	Human health guidelines based on carcinogenic effects of PAHs (see footnote c or d for carcinogenic PAHs)				
1	Direct contact (SQG_{DH}) – 10^{-6} [a]	0.6 B[a]P TPE[c]	0.6 B[a]P TPE[c]	0.6 B[a]P TPE[c]	0.6 B[a]P TPE[c]
1	Direct contact (SQG_{DH}) – 10^{-5} [b]	5.3 B[a]P TPE[c]	5.3 B[a]P TPE[c]	5.3 B[a]P TPE[c]	5.3 B[a]P TPE[c]
2	Protection of potable water (SQG_{PW})	IACR≤1.0[d]	IACR≤1.0[d]	IACR≤1.0[d]	IACR≤1.0[d]
	Environmental health guidelines based on non-carcinogenic effects of PAHs (*do not use these values to protect humans; for carcinogenic PAHs consult the Human health guidelines above; to protect humans from non-carcinogenic effects of PAHs consult guidelines from other jurisdictions; if a PAH displays both cancer and non-cancer effects to humans, protect human health based on the threat from cancer*)				
3	Anthracene (SQG_E)	2.5	2.5	32	32
3	Benzo[a]pyrene (SQG_E)	20	20	72	72
3	Fluoranthene (SQG_E)	50	50	180	180
3	Naphthalene	0.013[e]	0.013[e]	0.013[e]	0.013[e]
3	Phenanthrene	0.046[e]	0.046[e]	0.046[e]	0.046[e]
3	Benz[a]anthracene (CCME 1991)	0.1	1	10	10
3	Benzo[b]fluoranthene[f] (CCME 1991)	0.1	1	10	10
3	Benzo[k]fluoranthene[f] (CCME 1991)	0.1	1	10	10
3	Benzo[b+j+k]fluoranthene[f]	0.1	1	10	10
3	Dibenz[a,h]anthracene (CCME 1991)	0.1	1	10	10
3	Indeno[1,2,3-c,d]pyrene (CCME 1991)	0.1	1	10	10
3	Pyrene (CCME 1991)	0.1	10	100	100

Notes: SQG_{DH} = human health-based soil quality guideline for direct contact; SQG_E = soil quality guideline for environmental health; SQG_{PW} = soil quality guideline for the protection of potable water.

[a] SQG based on an incremental lifetime cancer risk (ILCR) of 1 in 1,000,000 (10^{-6}).

[b] SQG based on an incremental lifetime cancer risk (ILCR) of 1 in 100,000 (10^{-5}).

[c] B[a]P TPE = Benzo[a]pyrene Total Potency Equivalents, which is the sum of estimated cancer potency relative to B[a]P for all potentially carcinogenic unsubstituted PAHs. The B[a]P TPE for a soil sample is calculated by multiplying the concentration of each PAH in the sample by its B[a]P Potency Equivalence Factor (PEF), given below, and summing the products (see Figure 2 for B[a]P TPE example calculation including PAH mixtures found in coal tar or creosote).

B[a]P Potency Equivalence Factors:

Benz[a]anthracene	0.1	Benzo[g,h,i]perylene	0.01	Indeno[1,2,3-c,d]pyrene	0.1
Benzo[a]pyrene	1	Chrysene	0.01		
Benzo[b+j+k]fluoranthene	0.1	Dibenz[a,h]anthracene	1		

[d] The Index of Additive Cancer Risk (IACR) assesses potential threats to potable groundwater water quality from leaching of carcinogenic PAH mixtures from soil. The IACR is calculated by dividing the soil concentration (numerator) of each carcinogenic PAH by its soil quality guideline for protection of potable water component value (denominator) to calculate a hazard index for each PAH, and then summing the hazard indices for the entire PAH mixture, as follows (see Figure 2 for IACR example calculation):

$$IACR = \frac{[Benz(a)anthracene]}{0.33\ mg \cdot kg^{-1}} + \frac{[Benzo(b+j+k)fluoranthene]}{0.16\ mg \cdot kg^{-1}} + \frac{[Benzo(g,h,i)perylene]}{6.8\ mg \cdot kg^{-1}} + \frac{[Benzo(a)pyrene]}{0.37\ mg \cdot kg^{-1}} + \frac{[Chrysene]}{2.1\ mg \cdot kg^{-1}} + \frac{[Dibenz(a,h)anthracene]}{0.23\ mg \cdot kg^{-1}} + \frac{[Indeno(1,2,3-c,d)pyrene]}{2.7\ mg \cdot kg^{-1}}$$

[e] This value is the Soil Quality Guideline for the Protection of Freshwater Life. Users may wish to consider the application, on a site-specific basis, of this value where potential impacts to nearby surface waters are a concern (the value may be less than the common limit of detection in some jurisdictions; contact jurisdiction for guidance). If impact to surface water is not a concern, it is recommended to revert to the 1997 provisional SQG_E for naphthalene and the 1991 Interim Soil Quality Criteria for phenanthrene (see Table 2).

[f] Resolution between benzo[b]fluoranthene and benzo[k]fluoranthene gas chromatograph peaks may be difficult to achieve. When these two PAHs cannot be reported separately, report them as the sum of benzo[b+j+k]fluoranthene and compare this value to the guideline for the combined 3 isomers.

different taxa and soil types; and the possibility of non-additive effects (synergistic or antagonistic interactions, for example) of individual constituents in the mixture.

Developing soil quality guidelines for PAHs is particularly challenging because there is likely to be more than one toxicological mode of action in an exposed organism, and the causal linkages between exposure and actual effect at the whole organism level are complex and likely to involve many intermediate steps. The reader is encouraged to read the detailed scientific rationale for the development of these PAH soil quality guidelines (CCME 2008a) to better understand the inherent assumptions and limitations.

Environmental Fate and Behaviour in Soil

PAHs are relatively hydrophobic organic substances (WHO/IPCS 1998). The tendency of PAHs to partition in organic matter, onto particle surfaces, and into biological lipids (and out of aqueous environmental compartments such as groundwater) generally increases with an increase in the number of benzenoid rings in the aromatic ring structure (from 2 rings for naphthalene to 6 rings for benzo[g,h,i]perylene). Overall, the unsubstituted PAHs occur along a spectrum of hydrophobicity and lipophilicity, from naphthalene with an octanol-water partition coefficient (K_{ow}) of approximately 2×10^3 to benzo[g,h,i]perylene with a K_{ow} of 4×10^6. There are approximately three to six orders of magnitude difference between naphthalene and benzo[g,h,i]perylene in aqueous solubility, tendency to partition from hydrophobic organic matter into water, vapour pressure at room temperature, and tendency to partition between water and air (Henry's Law Constant).

The most important fate processes in soils, especially for the higher molecular weight PAHs, are adsorption and biodegradation. These PAHs remain tightly sorbed to soils, and especially the five- to six-ringed PAHs may exhibit a very limited bioavailability to terrestrial organisms based on soil contact or to aquatic organisms based on groundwater-mediated transfer.

Microbial degradation of PAHs in the soil environment is generally the most important process accounting for intermediate to long-term changes in substance levels over time (USEPA 1990; Wild *et al*. 1991). Resistance to microbial degradation in either soils or water tends to increase with the molecular weight and number of rings, as well. Whereas naphthalene tends to be readily degraded in most situations, PAHs with four, five, or six rings tends to be degraded much more slowly. In general, biodegradation in an aerobic environment occurs much more rapidly than in an anaerobic environment (Neff 1979).

Behaviour and Effects in Biota

Microbial Processes

Considerable scientific information is available on the role of microbes in the environmental biodegradation of PAHs, and on factors that influence microbial uptake and degradation rates. Total microbial abundance and biomass in soil can increase at some sites owing to the ability of heterotrophic microbial consortia to utilize the PAHs as an energy source, either alone or through co-metabolism with other substances. One aspect of PAH fate and effects that is often overlooked is the potential risks at a contaminated site associated with the presence of various microbial metabolites, such as dihydroxy-PAH.

Very few studies have been carried out on the tendency of individual PAHs or PAH-containing mixtures to adversely affect the ability of naturally-occurring mixed microbial communities to participate in the cycling within the ecosystem of energy, carbon, nitrogen, sulphur, phosphorus, and other macro- or micronutrients. PAHs in soils at individual concentrations in the low parts-per-million range have the potential to affect microbially-mediated functional processes such as nitrification rates (Sverdrup *et al*. 2002a).

Terrestrial Plants

Limited data are available on the toxicity to plants of PAHs in soils. Soil concentrations of individual PAHs that have been associated with reduced plant growth are in the range of approximately 30 to >2,000 mg·kg^{-1}. The available information, however, is generally limited to commonly tested agronomic species. Further, for each individual PAH there are generally insufficient data for enough plant species to confidently construct a plant sensitivity distribution; for many PAHs, no phytotoxicity data exist.

Plants exhibit very limited ability to accumulate PAHs from soils, and to translocate PAHs from root tissue into aboveground biomass (Simonich and Hites 1995). Low molecular weight PAHs (i.e., with two, three or four rings) may be taken up by roots and translocated within the plant, but do not appear to accumulate or magnify in concentration relative to concentrations in the soil (EPRI 1992). High molecular weight PAHs (i.e., five or more rings) may sorb to plant roots, but are not expected to translocate or accumulate within the plant (EPRI 1992). Risks to herbivores, therefore, from PAH uptake into plant tissue are likely to be very low relative to the risks associated with the incidental ingestion of soil.

Terrestrial Invertebrates

One of the primary modes of toxicity of PAHs to soil invertebrates, based on direct exposure in the soil environment, is non-polar narcosis; i.e., epidermal uptake of PAHs from soil pore water and/or dietary intake and partitioning into body lipid (Sverdrup *et al*. 2002b). More specific modes of PAH toxicity cannot be discounted, however.

Reproductive impairment in most soil invertebrates chronically exposed to PAHs or other contaminants tends to occur at much lower soil concentrations than acute or sub-chronic mortality. Most soil invertebrates are well adapted to short periods of stress (e.g., during periods of extreme cold or desiccation) and therefore have a potential to use physiological and/or behavioural stressor avoidance mechanisms. However, such mechanisms are typically accompanied by periods of non-feeding so that long-term survival, and - more specifically - fecundity, may be adversely affected. Tests on PAH-contaminated soils based on short-term mortality to earthworms, collembolans, or other soil invertebrate taxa may under-predict the true risks to soil invertebrate communities.

Given that uptake into lipids from the soil environment is likely to be a major factor for determining subsequent toxicological responses in soil invertebrates, the organic-carbon water partition co-efficient of the individual PAHs is likely to directly influence the soil concentration at which adverse effects would be observed.

As for all hydrophobic organic contaminants, the bioavailability and subsequent toxicity of PAHs to soil invertebrates exhibits high variability across different soil types. Further, there is a limited ability to predict the degree of toxicity as an alternative to using laboratory toxicity tests to measure it.

Toxicity data for various earthworm and springtail species were available for individual PAHs. For a full summary, refer to CCME (2008a).

Livestock and Wildlife

One of the major knowledge gaps in PAH ecotoxicology is in the area of effects on terrestrial vertebrate fauna, including adult life-stages of amphibians, reptiles, birds, and small to large mammalian herbivores, omnivores, and carnivores. The current understanding of potential risks of PAHs to livestock or wildlife is based almost entirely on laboratory rodent studies, which have been conducted primarily in support of a greater understanding of human health risks. A major emphasis of available research has been on cancer-type effects.

Biochemical stress responses and biomarkers of PAH exposure (e.g., hydroxypyrene in blood and urine) have been examined in a limited number of wildlife species, but the relevance of such data for predicting organism and population fitness has yet to be determined.

Possible effects of various PAHs on exposed livestock and wildlife species include but are not limited to mortality, growth, reproductive impairment, teratogenesis, endocrine disruption, liver and kidney damage, neurobehavioural changes, altered thermoregulatory ability, and cancer induction.

There is an absence in the scientific literature of observational data from chronic as opposed to sub-chronic or acute exposures, detailed wildlife epidemiological studies, or multi-generational studies.

Some indirect information is available on PAH toxicity to wildlife based on the exposures in the laboratory to whole crude oil, or in the field following large scale accidental spills of crude oil. Effects of crude oil on mallard ducks, American kestrels, and herring gulls have been examined. These studies are of limited value, however, in assessing the risks of PAH-contaminated soils.

A full summary of the available toxicity data for various PAHs on mammalian and avian species is provided in CCME (2008a).

Human and Experimental Animal Health Effects

Many major reviews of human cancer and other risks from PAHs have been completed within the last decade (WHO/IPCS 1998; ATSDR 1995; Boström *et al*. 2002; WHO 2003; WHO/IPCS 2004; others). One of the major drivers for the large degree of scientific and regulatory concern is based on the presence of PAHs in urban air particulates, and associated risks of inhalation exposures in human populations.

Total daily PAH intake for humans for the general American population was estimated by Santodonato *et al*. (1981) to vary from 0.2 to about 20 $\mu g{\cdot}day^{-1}$, excluding those individuals who are also occupationally exposed. The general population is primarily exposed via consumption of food and as a result of cigarette smoking. Charbroiled grilling and smoked meats may be a substantial source of PAH exposure in some human populations. Depending on an individual's lifestyle, the life-long cumulative intake (i.e., over 70 years or greater) of benzo[a]pyrene for non-occupationally exposed humans may add up to 29 mg, integrating respiratory, gastrointestinal and percutaneous absorption.

The emphasis herein for human health effects is on cancer endpoints for those PAHs with known or expected carcinogenic potential. There is sufficient scientific information on the mechanisms of PAH-induced genotoxicity and carcinogenicity based on *in vitro* (mammalian cell culture and bacterial culture) and *in vivo* (laboratory rodent) studies to conclude that the PAHs considered herein are known or potential carcinogens. It is recommended that Health Canada be contacted directly for guidance regarding PAHs that are not covered by this guidance.

PAHs have limited ability to bind to DNA and cause mutations until they are converted to more potent intermediates (especially PAH diol-epoxides) by cytochrome P450 oxidases (CYP1A1-type enzymes).

PAHs with two or three aromatic rings (for example, naphthalene, acenaphthene, acenaphthylene, fluorene, anthracene, phenanthrene) have been consistently shown to have very limited or no tendency to bind to the Ah-receptor, and to induce CYP enzymes such as EROD (*ethoxyresorufin-O-deethylase*) (Bosveld *et al*. 2002). It is suggested that these lighter molecular weight PAHs do not meet the structural requirements for having an affinity to bind to the Ah-receptor. Bosveld and other researchers (reviewed in Bosveld *et al*. 2002) found that benzo[k]fluoranthene was among the most potent inducers of EROD or reporter gene activity *in vitro.*

The mechanisms of PAH carcinogenesis are described in greater detail in CCME (2008a).

A major challenge in assessing the cancer risks of human exposures to PAH-containing mixtures is that no whole organism sub-chronic or chronic studies have been completed on the carcinogenicity of individual PAHs other than benzo[a]pyrene (B[a]P). It is therefore not possible to confidently and directly develop cancer slope factors for the potentially carcinogenic PAHs other than B[a]P. Instead, the evaluation of human cancer risks internationally has tended to be based on the use of B[a]P relative potencies, derived from whole animal studies with dermal, implantation, inhalation, oral or other exposure methods. The tumour incidence from studies of B[a]P is compared with incidence for the other PAHs under the same or similar conditions in order to estimate the cancer potency of the other PAHs relative to B[a]P.

Limited attempts to validate B[a]P relative potency schemes have suggested a poor relationship between the predicted and observed carcinogenicity of certain PAH-containing mixtures, notably coal tar and creosote. The tendency of benzo[a]pyrene relative potency schemes to under-estimate coal tar carcinogenicity might be due to the presence of unaccounted for carcinogens in the mixture. In particular, Harvey *et al.* (2000) and Koganti *et al*. (2001) found that 7H-benzo[c]fluorene, a major constituent of coal tars, strongly induced DNA-adduct formation. Therefore, the use of relative potency schemes may under-predict the severity of cancer risks for coal tar and creosote.

Guideline Derivation

Canadian soil quality guidelines are derived for different land uses following the process outlined in CCME (2006) using different receptors and exposure scenarios for each land use. Detailed derivations for these soil quality guidelines are provided in CCME (2008a).

Soil Quality Guidelines for Environmental Health

Environmental soil quality guidelines (SQG_E) are based on soil contact using data from toxicity studies on plants and invertebrates. In the case of agricultural use, soil and food ingestion toxicity data for mammalian and avian species are included. To provide a broader scope of protection, a nutrient and energy cycling check is calculated where the data permit. For commercial and industrial land uses, an off-site migration check is also calculated.

There were insufficient soil contact data for the PAHs, acenaphthene, acenaphthylene, benz[a]anthracene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[g,h,i]perylene, chrysene, dibenz[a,h]anthracene, fluorene, indeno[1,2,3-c,d]pyrene, phenanthrene, and pyrene, using either the preferred weight-of-evidence method (CCME 2006) or secondary derivation methods. Direct contact soil quality guidelines were calculated for fluoranthene and benzo[a]pyrene using a weight-of-evidence approach, and for anthracene based on selection of the lowest LOEC for agricultural and residential/parkland land uses and based on the geometric mean value of three suitable LOEC values for commercial and industrial land uses (Table 2).

Given the current limitations of our scientific understanding, the inability to calculate direct soil contact soil quality guidelines for the majority of the PAHs may be of little practical significance to the overall achievement of environmental protection goals at Canadian contaminated sites. The direct soil contact soil quality standards recently promulgated as the Canada-Wide Standards for Petroleum Hydrocarbons (PHC CWS) might account for contributions to toxic responses of soil invertebrates and plants for several of these unsubstituted PAHs as well as alkyl-substituted forms. The PHC CWS were derived using newly generated ecotoxicity data on a fractioned Federated crude oil in a standardized (OECD) soil type as well as a relatively fine-grained Chernozem loam soil. No corrections were made for the presence of PAHs in the petroleum mixtures.

More work is required, however, to establish the relevance of the PHC CWS to managing PAH risks to soil organisms. Those with responsibility for contaminated sites investigation and management may need to look beyond the generic guidance for protecting soil ecological functioning if there exists a contaminant mixture which exhibits very high PAH concentrations relative to other petroleum-derived hydrocarbons.

Soil quality guidelines for the protection of freshwater life (SQG_{FL}) were derived using the CCME (2006) protocol for all PAHs for which CCME water quality guidelines for the protection of aquatic life exist (naphthalene, acenaphthene, fluorene, anthracene, phenanthrene, pyrene, fluoranthene benz[a]anthracene, and benzo[a]pyrene). For the remaining PAHs, an attempt was made to calculate SQG_{FL} values by assuming a narcosis-type mode of action in the aquatic receiving environment and a Critical Body Residue-based threshold for chronic effects equivalent to 3.0 mmol PAH·kg^{-1} lipid (Di Toro *et al*. 2000). This derivation procedure is beyond the guidance provided in CCME (2006), but is virtually identical to the procedure used in the derivation of aquatic life protective soil concentration thresholds for the PHC CWS (CCME 2008b). Only one additional SQG_{FL} was determined using the critical body residue approach, and that was for acenaphthylene.

For agricultural and residential/parkland land uses, soil and food ingestion by cows as a representative livestock species, and mule deer, meadow voles and American robins as representative wildlife species, were considered. For most PAHs, only a provisional soil and food ingestion guideline (SQG_I) could be derived, due to lack of sufficient data (with the exception of naphthalene for which a full SQG_I was derived) (Table 2). The SQG_I values presented in Table 2 are for the protection of secondary consumers (based on soil and food ingestion for American robins). SQG_Is for the protection of primary consumers are orders of magnitude higher (see CCME 2008a for SQG_Is for primary consumers). Note that the provisional SQG_I values were not used in determining the overall SQG_E.

For protection of the non-human environment, soil quality guidelines recommended for agricultural, residential/ parkland, commercial and industrial sites are outlined in Table 2.

Soil Quality Guidelines for Human Health

Human health soil quality guidelines (SQG_{HH}) for non-threshold (carcinogenic) contaminants require the development of soil quality guidelines that employ a critical risk-specific dose (RsD), based on incremental lifetime cancer risks (ILCRs) from exposure to PAH-contaminated soil. For all land uses, the adult was chosen as the receptor when considering lifetime cancer risk. For non-threshold contaminants, human exposure should be reduced to the maximum extent possible. Some jurisdictions in Canada have adopted an "essentially negligible" ILCR of 10^{-5} (or 1 in 100,000) for managing risks of carcinogenic contaminants, while other jurisdictions use an ILCR of 10^{-6} (or 1 in 1,000,000). In light of this, soil quality guideline calculations were undertaken using both a 10^{-5} and 10^{-6} ILCR. Both of these incremental risks above background fall within the range considered to be "essentially negligible" in the derivation of MACs (Maximum Acceptable Concentrations) for carcinogenic chemicals in drinking water (Health and Welfare Canada 1989).

Various check mechanisms are applied, if relevant, to the preliminary human health soil quality guidelines in order to provide them with a broader scope of protection, such as the potential to adversely impact humans through the consumption of groundwater, agricultural crops and livestock.

A soil quality guideline for the protection of potable water (SQG_{PW}) was derived for potentially carcinogenic PAHs. An off-site migration check was not carried out, since the preliminary SQG_{HH} for commercial and industrial land uses were the same as for the more sensitive land uses. Nor was a produce, meat and milk check carried out, since PAHs exhibit very limited potential for food-web mediated transfer.

For protection against cancer risks in humans, it is recommended that the benzo[a]pyrene Total Potency Equivalents (B[a]P TPE) in soil be established at a threshold value of 0.6 mg·kg^{-1} for an ILCR of 10^{-6} and 5.3 mg·kg^{-1} for an ILCR of 10^{-5} for all land uses.

In 1996, Health Canada developed a human health protective soil quality guideline for benzo[a]pyrene with a value of 1.5 mg·kg^{-1} (CCME 1999). Of all possible human exposure pathways, the 1996 guideline accounted only for the oral exposure route, and was based on a risk-specific dose (RsD) of 0.000435 μg benzo[a]pyrene·kg bw^{-1}·day^{-1} for an incremental cancer risk of 10^{-6}, based in turn on a cancer slope factor of 2.3 $(mg·kg^{-1}·day^{-1})^{-1}$.

This calculation was revised herein to also account for possible dermal and particulate inhalation uptake of benzo[a]pyrene from site soils. The critical study (Neal and Rigdon 1967) consulted by Health Canada (1996) and adopted herein used an orally administered, not absorbed, dose. A relative absorption factor for inhalation and ingestion is assumed to be 100%, by default. This factor assumes that the bioavailability of PAHs in soil will be the same as the bioavailability of PAHs in the food administered to the test animals in the critical study used to derive the risk specific dose. The magnitude of dermal absorption is not expected to be similar to oral absorption. Therefore a dermal absorption factor of 34% was derived based on the available literature.

Shatkin *et al*. (2002) developed a fugacity model to predict dermal uptake of benzo[a]pyrene from soil, and compared the model predictions with nine experimental data points, which agreed within a factor of two. An upper bound estimate based on this study for dermal absorption over a 24 h period is 34%, which is the modeled mean plus one standard deviation.

The B[a]P TPE is calculated for potentially carcinogenic PAHs by multiplying their concentrations in soil by the following B[a]P Potency Equivalence Factors (B[a]P PEFs) and summing the products.

B[a]P PEFs

Benz[a]anthracene	0.1
Benzo[a]pyrene	**1**
Benzo[b+j+k]fluoranthene	0.1
Chrysene	0.01
Benzo[g,h,i]perylene	0.01
Dibenz[a,h]anthracene	1
Indeno[1,2,3-c,d]pyrene	0.1

The cancer risk for the combined exposure to potentially carcinogenic PAHs is assumed to be additive, but this is a source of uncertainty. The soil B[a]P TPE is intended to ensure that incremental lifetime cancer risk from soil ingestion, inhalation and dermal exposure does not exceed 1 x 10^{-6} or 1 x 10^{-5}. Initially, an uncertainty factor was considered for application in deriving the B[a]P TPE, since limited attempts to validate B[a]P relative potency schemes have shown a potential for the under-prediction of human cancer risks. It was felt that an uncertainty factor was not justified for most contaminant mixture types. However, a 3-fold uncertainty factor should be applied to soils contaminated with coal tar or creosote to account for the risks associated with other potentially carcinogenic PAHs present, but not included in the PEF scheme. In practice, the B[a]P TPE concentration for such site soils should be multiplied by a factor of three (3) prior to comparison with the SQG_{DH}. In cases where site information is insufficient to determine whether PAH contamination has resulted from a coal tar or creosote source, the uncertainty factor should be applied.

The above-listed PEFs were also used to produce B[a]P equivalent values in potable water for benz[a]anthracene, benzo[b+j+k]fluoranthene, chrysene, benzo[g,h,i]perylene, dibenz[a,h]anthracene, and indeno[1,2,3-c,d]pyrene (CCME 2008a). The PAHs were treated individually, since different compounds within PAH mixtures would be expected to exhibit differing potential for groundwater-mediated transport (i.e., based on orders of magnitude difference in organic carbon-water (K_{OC}) partition co-efficients). Therefore, soil-to-potable water-based risks of individual PAHs were modeled to derive soil quality guideline for the protection of potable water (SQG_{PW}) component values for individual carcinogenic PAHs. It should be noted that the individual SQG_{PW} component values are not stand alone soil quality guidelines. Rather, each has been incorporated into the "Index of Additive Cancer Risks" (IACR) equation, to account for the combined effects of individual PAHs in the mixture (Tables 1 and 2). The resulting IACR value is equivalent to a hazard index and should not exceed a value of 1.0. Therefore, the final SQG_{PW} is expressed as IACR $\leq$ 1.

Although not specified in the CCME (2006) protocol, a set of soil PAH threshold values was also calculated for human health risks based on acute exposures of infants potentially engaged in pica soil ingestion. The soil PAH thresholds were calculated assuming short-term PAH exposures only, via oral ingestion, and threshold mechanisms of toxicity as opposed to non-threshold (carcinogenic) ones. Toddlers (6 months to 4 years of age) have been observed to engage in "pica" soil ingestion. Per U.S. EPA guidance, it was assumed that a child involved in pica soil ingestion may consume a maximum of 5,000 mg soil·day^{-1}. ATSDR (1995) did not develop any acute oral Minimal Risk Levels (MRLs) for PAHs due to the absence of guiding studies. However, there are four ATSDR (1995) MRLs developed for intermediate exposures (15 to 364 days): acenaphthene: 0.6 mg·kg^{-1} day^{-1}, anthracene: 10 mg·kg^{-1}·day^{-1}, fluoranthene: 0.4 mg·kg^{-1}·day^{-1} and fluorene: 0.4 mg·kg^{-1}·day^{-1}. The calculated soil threshold values for the four individual PAHs based on pica exposure in infants were all greater than 1,000 mg·kg^{-1}. Pica and other types of acute exposure, therefore, are not deemed to be of concern for these unsubstituted PAHs based on the currently available toxicological data.

Soil Quality Guidelines for Carcinogenic and Other PAHs

The soil quality guidelines for PAHs are intended to be protective of both environmental and human health. In contrast to normal practice where the lower of either the human health or environmental values drive the final soil quality guideline, the recommendation is that soil samples be assessed for carcinogenic effects to humans and non-carcinogenic effects to ecological receptors separately, by (1) Converting to B[a]P equivalents for comparison with the SQG_{DH}, (2) Calculating an IACR and comparing the value to 1, and (3) Comparing soil sample concentrations for individual PAHs against the most conservative guideline developed based on non-carcinogenic effects for that land use (Table 1 and 2).

It should be noted that, although petroleum hydrocarbons (PHCs) contain PAHs, the Canada-wide Standard for Petroleum Hydrocarbons (CCME, 2008) was not developed to address the issue of carcinogenicity. Remediation of contaminated soils to meet the PHC standards will not necessarily mean that the PAH soil quality guidelines for human health protection will be met, and vice versa.

SQG for freshwater life protection (Table 2) were derived for the majority of commonly analyzed, unsubstituted PAHs, and tend to be much lower than other preliminary SQG for either human health or environmental protection. They were nonetheless determined to be greater than expected background soil PAH concentrations in other than highly urbanized and industrialized regions of Canada. The SQG_{FL} are not reflected in the overall SQG (except for naphthalene and phenanthrene), but users may wish to consider their application on a site-specific basis where potential impacts on nearby surface water are a concern.

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Table 2. Soil Quality Guidelines for Carcinogenic and Other PAHs ($mg \cdot kg^{-1}$)

IMPORTANT NOTE (1): There is no single final Soil Quality Guideline (SQG_F) for any of the PAHs included in this guideline that will protect both human and environmental health. To ensure that both human and ecological receptors are protected, the user must (1) calculate a Benzo[a]pyrene Total Potency Equivalents (B[a]P TPE) to ensure that humans are protected from direct contact with soil contaminated with carcinogenic PAHs, (2) calculate the Index of Additive Cancer Risk (IACR) to ensure that potable water resources are protected from carcinogenic PAHs, and (3) consider all relevant guidelines to protect ecological receptors from non-carcinogenic effects, in this table, for the land use in question.

IMPORTANT NOTE (2): For soil contaminated by coal tar or creosote mixtures, the calculated Benzo[a]pyrene Total Potency Equivalents (B[a]P TPE) concentration for soil samples should be multiplied by a safety factor of 3 prior to comparison with the SQG_{DH} to account for carcinogenic potential of alkylated and other PAHs present for which a Potency Equivalent Factor (PEF) does not currently exist, but which are likely to contribute to mixture carcinogenic potential.

		Land Use			
		Agricultural	Residential/ Parkland	Commercial	Industrial
	Guideline (SQG_F)–see table caption, IMPORTANT NOTE 1				
Human health guidelines/check values	**Human health guidelines/check values based on carcinogenic effects of PAHs** (potentially carcinogenic PAHs are benz[a]anthracene, benzo[a]pyrene, benzo[b+j+k]fluoranthene[m], benzo[g,h,i]perylene, chrysene, dibenz[a,h]anthracene, and indeno[1,2,3-c,d]pyrene)				
	SQG_{HH}	NC	NC	NC	NC
	Direct contact[a] (SQG_{DH}) – ingestion, inhalation, and dermal exposures				
	1×10^{-6} incremental lifetime cancer risk	0.6 B[a]P TPE[b]	0.6 B[a]P TPE[b]	0.6 B[a]P TPE[b]	0.6 B[a]P TPE[b]
	1×10^{-5} incremental lifetime cancer risk	5.3 B[a]P TPE[b]	5.3 B[a]P TPE[b]	5.3 B[a]P TPE[b]	5.3 B[a]P TPE[b]
	Protection of indoor air quality (SQG_{IAQ})	NC	NC	NC	NC
	Off-site migration (SQG_{OM-HH})	-	-	NC	NC
	Protection of potable water (SQG_{PW})	IACR≤1.0[c]	IACR≤1.0[c]	IACR≤1.0[c]	IACR≤1.0[c]
	Produce, meat, and milk (SQG_{FI})	NC	NC	-	-
Environmental health guidelines/check values	**Environmental health guidelines/check values based on non-carcinogenic effects of PAHs** (*do not use these values to protect humans; for carcinogenic PAHs consult the Human health guidelines above; to protect humans from non-carcinogenic effects of PAHs consult guidelines from other jurisdictions; if a PAH displays both cancer and non-cancer effects to humans, protect human health based on the threat from cancer*)				
	Environmental health guideline values for Acenaphthene				
	SQG_E[d]	NC	NC	NC	NC
	Soil contact (SQG_{SC})	NC	NC	NC	NC
	Soil and food ingestion (SQG_I)	21.5[e]	21.5[e]	-	-
	Protection of freshwater life[f] (SQG_{FL})	0.28[g]	0.28[g]	0.28[g]	0.28[g]
	Interim Soil Quality Criteria (CCME 1991)	no value	no value	no value	no value
	Environmental health guideline values for Acenaphthylene				
	SQG_E[d]	NC	NC	NC	NC
	Soil contact (SQG_{SC})	NC	NC	NC	NC
	Soil and food ingestion (SQG_I)	NC	NC	-	-
	Protection of freshwater life[f] (SQG_{FL})	320[h]	320[h]	320[h]	320[h]
	Interim Soil Quality Criteria (CCME 1991)	no value	no value	no value	no value

Continued…

		Land Use			
		Agricultural	Residential/ Parkland	Commercial	Industrial
Environmental health guidelines/check values	**Environmental health guideline values for Anthracene**				
	SQG_E[d]	2.5[p]	2.5[p]	32[p]	32[p]
	Soil contact (SQG_{SC})	2.5	2.5	32	32
	Soil and food ingestion (SQG_I)	61.5[e]	61.5[e]	-	-
	Protection of freshwater life[f] (SQG_{FL})	NA[g,i]	NA[g,i]	NA[g,i]	NA[g,i]
	Interim Soil Quality Criteria (CCME 1991)	no value	no value	no value	no value
	Environmental health guideline values for Benz[a]anthracene				
	SQG_E[d]	NC	NC	NC	NC
	Soil contact (SQG_{SC})	NC	NC	NC	NC
	Soil and food ingestion (SQG_I)	6.2[e]	6.2[e]	-	-
	Protection of freshwater life[f] (SQG_{FL})	NA[g,i]	NA[g, i]	NA[g, i]	NA[g, i]
	Interim Soil Quality Criteria (CCME 1991)	0.1[j]	1[j]	10 [j]	10 [j]
	Environmental health guideline values for Benzo[a]pyrene				
	SQG_E[d]	20[k]	20[k]	72[k]	72[k]
	Soil contact (SQG_{SC})	20	20	72	72
	Soil and food ingestion (SQG_I)	0.6[e]	0.6[e]	-	-
	Protection of freshwater life[f] (SQG_{FL})	8800[g]	8800[g]	8800[g]	8800[g]
	Provisional SQG_E (CCME 1997)	0.7	0.7	1.4	1.4
	Environmental health guideline values for Benzo[b]fluoranthene[r]				
	SQG_E[d]	NC	NC	NC	NC
	Soil contact (SQG_{SC})	NC	NC	NC	NC
	Soil and food ingestion (SQG_I)	6.2[e]	6.2[e]	-	-
	Protection of freshwater life[f] (SQG_{FL})	NA[h,i]	NA[h,i]	NA[h,i]	NA[h,i]
	Interim Soil Quality Criteria (CCME 1991)	0.1[j]	1[j]	10 [j]	10 [j]
	Environmental health guideline values for Benzo[k]fluoranthene[r]				
	SQG_E[d]	NC	NC	NC	NC
	Soil contact (SQG_{SC})	NC	NC	NC	NC
	Soil and food ingestion (SQG_I)	6.2[e]	6.2[e]	-	-
	Protection of freshwater life[f] (SQG_{FL})	NA[h,i]	NA[h,i]	NA[h,i]	NA[h,i]
	Interim Soil Quality Criteria (CCME 1991)	0.1[j]	1[j]	10 [j]	10 [j]
	Environmental health guideline values for Benzo[g,h,i]perylene				
	SQG_E[d]	NC	NC	NC	NC
	Soil contact (SQG_{SC})	NC	NC	NC	NC
	Soil and food ingestion (SQG_I)	NC	NC	-	-
	Protection of freshwater life[f] (SQG_{FL})	NA[h,i]	NA[h,i]	NA[h,i]	NA[h,i]
	Interim Soil Quality Criteria (CCME 1991)	no value	no value	no value	no value

Continued...

		Land Use			
		Agricultural	Residential/ Parkland	Commercial	Industrial
Environmental health guidelines/check values	**Environmental health guideline values for Chrysene**				
	SQG_E[d]	NC	NC	NC	NC
	Soil contact (SQG_{SC})	NC	NC	NC	NC
	Soil and food ingestion (SQG_I)	6.2[e]	6.2[e]	-	-
	Protection of freshwater life[f] (SQG_{FL})	NA[h,i]	NA[h,i]	NA[h,i]	NA[h,i]
	Interim Soil Quality Criteria (CCME 1991)	no value	no value	no value	no value
	Environmental health guideline values for Dibenz[a,h]anthracene				
	SQG_E[d]	NC	NC	NC	NC
	Soil contact (SQG_{SC})	NC	NC	NC	NC
	Soil and food ingestion (SQG_I)	NC	NC	-	-
	Protection of freshwater life[f] (SQG_{FL})	NA[h,i]	NA[h,i]	NA[h,i]	NA[h,i]
	Interim Soil Quality Criteria (CCME 1991)	0.1[j]	1[j]	10[j]	10[j]
	Environmental health guideline values for Fluoranthene				
	SQG_E[d]	50[p]	50[p]	180[p]	180[p]
	Soil contact (SQG_{SC})	50	50	180	180
	Soil and food ingestion (SQG_I)	15.4[e]	15.4[e]	-	-
	Protection of freshwater life[f] (SQG_{FL})	NA[g,i]	NA[g,i]	NA[g,i]	NA[g,i]
	Interim Soil Quality Criteria (CCME 1991)	no value	no value	no value	no value
	Environmental health guideline values for Fluorene				
	SQG_E[d]	NC	NC	NC	NC
	Soil contact (SQG_{SC})	NC	NC	NC	NC
	Soil and food ingestion (SQG_I)	15.4[e]	15.4[e]	-	-
	Protection of freshwater life[f] (SQG_{FL})	0.25[g]	0.25[g]	0.25[g]	0.25[g]
	Interim Soil Quality Criteria (CCME 1991)	no value	no value	no value	no value
	Environmental health guideline values for Indeno[1,2,3-c,d]pyrene				
	SQG_E[d]	NC	NC	NC	NC
	Soil contact (SQG_{SC})	NC	NC	NC	NC
	Soil and food ingestion (SQG_I)	NC	NC	-	-
	Protection of freshwater life[f] (SQG_{FL})	NA[h,i]	NA[h,i]	NA[h,i]	NA[h,i]
	Interim Soil Quality Criteria (CCME 1991)	0.1[j]	1[j]	10[j]	10[j]
	Environmental health guideline values for Naphthalene				
	SQG_E[d]	NC	NC	NC	NC
	Soil contact (SQG_{SC})	NC	NC	NC	NC
	Soil and food ingestion (SQG_I)	8.8	8.8	-	-
	Protection of freshwater life[f] (SQG_{FL})	0.013[g,l]	0.013[g,l]	0.013[g,l]	0.013[g,l]
	Provisional SQG_E (CCME 1997)	0.6[n]	0.6[n]	22[n]	22[n]
	Environmental health guideline values for Phenanthrene				
	SQG_E[d]	NC	NC	NC	NC
	Soil contact (SQG_{SC})	NC	NC	NC	NC
	Soil and food ingestion (SQG_I)	43.0[e]	43.0[e]	-	-
	Protection of freshwater life[f] (SQG_{FL})	0.046[g,l]	0.046[g,l]	0.046[g,l]	0.046[g,l]
	Interim Soil Quality Criteria (CCME 1991)	0.1[o]	5[o]	50[o]	50[o]

Continued…

		Land Use			
		Agricultural	**Residential/ Parkland**	**Commercial**	**Industrial**
Environmental health guidelines/check values	**Environmental health guideline values for <u>Pyrene</u>**				
	SQG_E[d]	NC	NC	NC	NC
	Soil contact (SQG_{SC})	NC	NC	NC	NC
	Soil and food ingestion (SQG_I)	7.7[e]	7.7[e]	-	-
	Protection of freshwater life[f] (SQG_{FL})	NA[g,i]	NA[g,i]	NA[g,i]	NA[g,i]
	Interim Soil Quality Criteria (CCME 1991)	0.1[q]	10[q]	100[q]	100[q]
	The following guidelines/check pathways were evaluated for all PAHs appearing in the environmental section				
	Livestock Watering (SQG_{LW})	NC	-	-	-
	Irrigation Water (SQG_{IR})	NC	-	-	-
	Nutrient and energy cycling check (SQG_{NEC})	NC	NC	NC	NC
	Off-site migration check (SQG_{OM-E})	-	-	NC	NC

Notes: NA = not applicable; NC = not calculated; SQG_E = soil quality guideline for environmental health; SQG_{HH} = soil quality guideline for human health; SQG_I = soil quality guideline for protection of livestock and wildlife based on soil and food ingestion; SQG_{IR} = soil quality guideline for the protection of irrigation water; SQG_{IAQ} = soil quality guideline for the protection of indoor air quality; SQG_F = final soil quality guideline (for protection of environmental and human health); SQG_{LW} = soil quality guideline for protection of livestock based on water consumption; SQG_{NEC} = soil quality guideline check value for the protection of nutrient and energy cycling; SQG_{PW} = soil quality guideline for the protection of potable groundwater; SQG_{OM-E} = soil quality guideline check value for off-site migration of soils in consideration of environmental health risks; SQG_{OM-HH} = soil quality guideline check value for off-site migration of soils in consideration of human health risks; SQG_{SC} = soil quality guideline for soil contact by soil-dependent organisms (e.g., plants and invertebrates). The dash indicates a guideline/check value that is not part of the exposure scenario for this land use and therefore is not calculated.

[a] Guideline values for toddler pica soil ingestion have also been calculated for benzo[a]pyrene, acenaphthene, fluorene, anthracene and fluoranthene, but are several orders of magnitude higher than the direct contact guidelines. For more details on the pica guidelines, refer to section 7.1.4 of the scientific supporting document (CCME, 2008a).

[b] B[a]P TPE = Benzo[a]pyrene Total Potency Equivalents, which is the sum of estimated cancer potency relative to B[a]P for all potentially carcinogenic unsubstituted PAHs. The B[a]P TPE for a soil sample is calculated by multiplying the concentration of each PAH in the sample by its B[a]P Potency Equivalence Factor (PEF), given below, and summing these products (see Figure 2 for B[a]P TPE example calculation including PAH mixtures found in coal tar or creosote). B[a]P PEFs are order of magnitude estimates of carcinogenic potential and are based on the World Health Organization (WHO/IPCS 1998) scheme, as follows:

Benz[a]anthracene	0.1	Benzo[g,h,i]perylene	0.01	Indeno[1,2,3-c,d]pyrene	0.1
Benzo[a]pyrene	1	Chrysene	0.01		
Benzo[b+j+k]fluoranthene	0.1	Dibenz[a,h]anthracene	1		

[c] The Index of Additive Cancer Risk (IACR) assesses potential threats to potable groundwater water quality from leaching of carcinogenic PAH mixtures from soil. The IACR is calculated by dividing the soil concentration (numerator) of each carcinogenic PAH by its soil quality guideline for protection of potable water component value (denominator) to calculate a hazard index for each PAH, and then summing the hazard indices for the entire PAH mixture, as follows (see Figure 2 for IACR example calculation):

$$\text{IACR} = \frac{[Benz\,(a)\,anthracene\,]}{0.33\ \text{mg}\cdot kg^{-1}} + \frac{[Benzo\,(b+j+k)\,fluoranthene\,]}{0.16\ \text{mg}\cdot kg^{-1}} + \frac{[Benzo\,(g,h,i)\,perylene\,]}{6.8\ \text{mg}\cdot kg^{-1}} + \frac{[Benzo(a)\,pyrene]}{0.37\,\text{mg}\cdot\text{kg}^{-1}} + \frac{[Chrysene]}{2.1\,\text{mg}\cdot\text{kg}^{-1}} + \frac{[Dibenz(a,h)anthracene]}{0.23\ \text{mg}\cdot\text{kg}^{-1}} + \frac{[\text{Indeno}(1,2,3-\text{c,d})\text{pyrene}]}{2.7\,\text{mg}\cdot\text{kg}^{-1}}$$

The potable water component values were derived using a drinking water Maximum Allowable Concentration of 0.00001 mg/L for benzo(a)pyrene and the B[a]P PEFs listed in footnote b above, and the soil-to-groundwater model described in Appendix C of CCME (2006).

[d] The SQG_E is based on the lowest of the available environmental health guidelines (soil contact, soil and food ingestion, or protection of freshwater life). For PAHs where a soil contact guideline was not available, an overall SQG_E was not calculated.

[e] This guideline is considered provisional because minimum data requirements, as outlined in CCME (2006), were not met. The value is presented for users to consider applying at their own discretion, but it has not been used to determine the overall SQG_E recommended here.

[f] Modeling assumptions include the absence of biodegradation of PAHs in the subsurface environment, a highly conservative assumption.

[g] SQG_{FL} for freshwater life protection back-calculated based on CCME (2006) protocol, using pre-existing CCME Water Quality Guidelines (Freshwater Life) (CCME 1999).

[h] SQG_{FL} for freshwater life protection back-calculated from theoretically derived freshwater life thresholds based on baseline (narcosis-type) toxicity along with a Critical Body Residue (CBR) approach, assuming an internalized dose for aquatic life of 3.0 mmol PAH·kg^{-1} lipid is a threshold for chronic, non-lethal toxicity.

[i] A freshwater life protective guideline could not be calculated based on the assumed generic site/soil properties and the K_{OC} of the PAH, since the concentration in groundwater at the point of leaching would need to far exceed the solubility limit to account for a concentration that approaches the toxicity threshold at a point 10 m down-gradient.

[j] The interim soil quality criterion (CCME 1991) is retained as the environmental soil quality guideline for this land use because there was insufficient/inadequate data to calculate an SQG_E or provisional SQG_E. Consult the human health guidelines/check values to assess the human hazard of PAH mixtures containing this PAH.

[k] The SQG_E is based on the soil contact guideline value. The 2008 benzo[a]pyrene SQG_E replaces the 1997 provisional benzo[a]pyrene SQG_E. Consult the human health guidelines/check values to assess the human hazard of PAH mixtures containing this PAH.

[l] Users may wish to consider the application, on a site-specific basis, of the Soil Quality Guideline for the Protection of Freshwater Life where potential impacts on nearby surface water are a concern. This guideline value may be less than the common limit of detection in some jurisdictions. Consult appropriate jurisdiction for further guidance.

[m] Benzo[b]fluoranthene and benzo[j]fluoranthene tend to strongly co-elute under most gas chromatographic conditions. Furthermore, resolution between benzo[b]fluoranthene, benzo[j]fluoranthene, and benzo[k]fluoranthene is difficult to achieve when all three isomers are present in the soil matrix. Therefore, these three isomers have been considered together in deriving SQG_{HH} values.

[n] Data were insufficient/inadequate to update the 1997 provisional SQG_E and no attempt was made to calculate a SQG_{HH} or provisional SQG_{HH}, therefore the 1997 provisional SQG_E is retained as the soil quality guideline for the protection of environmental health for this land use. However, if there is concern for potential impacts to water bodies, the Soil Quality Guideline for the Protection of Freshwater Life (SQG_{FL}) should be applied. Consult other jurisdictions for the protection of human health from naphthalene.

[o] Data were insufficient/inadequate data to calculate an SQG_E or provisional SQG_E and no attempt was made to calculate a SQG_{HH}, or provisional SQG_{HH}, therefore the interim soil quality criterion (CCME 1991) is retained as the environmental soil quality guideline for this land use. However, if there is concern for potential impacts to water bodies, the Soil Quality Guideline for the Protection of Freshwater Life (SQG_{FL}) should be applied. Consult other jurisdictions for the protection of human health from phenanthrene.

[p] The SQG_E is based on the soil contact guideline value.

[q] Data were insufficient/adequate data to calculate an SQG_E or provisional SQG_E and no attempt was made to calculate a SQG_{HH}, or provisional SQG_{HH}, therefore the interim soil quality criterion (CCME 1991) is retained as the environmental soil quality guideline for this land use. Consult other jurisdictions for the protection of human health from pyrene.

[r] Resolution between benzo[b]fluoranthene and benzo[k]fluoranthene gas chromatograph peaks may be difficult to achieve. When these two PAHs cannot be reported separately, report them as the sum of benzo[b+j+k]fluoranthene and compare this value to the guideline for benzo[b]fluoranthene.

Figure 2. Example of how to apply Canadian Soil Quality Guidelines for PAHs at a contaminated site

PAH concentration in soil (mg/kg dry weight) collected from a contaminated industrial site (fictitious data).

Acenaphthene	0.63	**Benzo[g,h,i]perylene**	**0.67**
Anthracene	1.4	**Chrysene**	**1.6**
Benz[a]anthracene	**4.5**	**Dibenz[a,h]anthracene**	**0.22**
Benzo[a]pyrene	**0.69**	**Indeno[1,2,3-c,d]pyrene**	**0.81**
Benzo[b]fluoranthene	**0.64**	Naphthalene	0.66
Benzo[k]fluoranthene	**0.62**	***(potentially carcinogenic PAHs are in bold)***	

Step **1**

To ensure that humans are protected from direct contact with soil contaminated with carcinogenic PAHs, calculate the **Benzo[a]pyrene Total Potency Equivalents (B[a]P TPE)** using the following Equation (see factsheet text and Table 1, footnote c, for more details);

$$B[a]P\ TPE = \sum_{i=1}^{n} (C_i \times PEF_i)$$

where,

B[a]P TPE = concentration of the carcinogenic-PAH mixture, expressed as a total potency equivalent of B[a]P
n = number of carcinogenic PAHs (with an available PEF value)
C_i = concentration of carcinogenic-PAH compound *i*
PEF_i = potency equivalence factor for the carcinogenic-PAH compound *i* (unitless) (see Table 1, footnote c)

Take only the carcinogenic PAHs from the above table and calculate the B[a]P TPE as follows;

See Note 2 below for an explanation of this value

B[a]P TPE = $(4.5\ mg\cdot kg^{-1} \times 0.1) + (0.69\ mg\cdot kg^{-1} \times 1) + (1.26\ mg\cdot kg^{-1} \times 0.1) + (0.67\ mg\cdot kg^{-1} \times 0.01) + (1.6\ mg\cdot kg^{-1} \times 0.01) + (0.22\ mg\cdot kg^{-1} \times 1) + (0.81\ mg\cdot kg^{-1} \times 0.1)$
$= 1.6\ mg\cdot kg^{-1}$

Compare the B[a]P TPE of 1.6 mg·kg^{-1} to the SQG_{DH} in Table 1 with the desired level of acceptable risk. If the PAH mixture is found in soil co-contaminated with coal tar or creosote, the B[a]P TPE should be multiplied by a safety factor of 3 before comparison to the SQG_{DH}, as follows; B[a]P TPE = $1.6\ mg\cdot kg^{-1} \times 3 = 4.8\ mg\cdot kg^{-1}$

Step **2**

To ensure that potable water resources are protected from carcinogenic PAHs, calculate the **Index of Additive Cancer Risk (IACR)** using the following equation (see factsheet text and Table 1, footnote d, for more details);

$$IACR = \frac{[Benz(a)anthracene]}{0.33\ mg\cdot kg^{-1}} + \frac{[Benzo(b+j+k)fluoranthene]}{0.16\ mg\cdot kg^{-1}} + \frac{[Benzo(g,h,i)perylene]}{6.8\ mg\cdot kg^{-1}} + \frac{[Benzo(a)pyrene]}{0.37\ mg\cdot kg^{-1}} + \frac{[Chrysene]}{2.1\ mg\cdot kg^{-1}} + \frac{[Dibenz(a,h)anthracene]}{0.23\ mg\cdot kg^{-1}} + \frac{[Indeno(1,2,3-c,d)pyrene]}{2.7\ mg\cdot kg^{-1}}$$

Take only the carcinogenic PAHs from the above table and calculate the IACR as follows;

See Note 2 below for an explanation of this value

IACR = $(4.5\ mg\cdot kg^{-1}/0.33\ mg\cdot kg^{-1}) + (1.26\ mg\cdot kg^{-1}/0.16\ mg\cdot kg^{-1}) + (0.67\ mg\cdot kg^{-1}/6.8\ mg\cdot kg^{-1}) + (0.69\ mg\cdot kg^{-1}/0.37\ mg\cdot kg^{-1}) + (1.6\ mg\cdot kg^{-1}/2.1\ mg\cdot kg^{-1}) + (0.22\ mg\cdot kg^{-1}/0.23\ mg\cdot kg^{-1}) + (0.81\ mg\cdot kg^{-1}/2.7\ mg\cdot kg^{-1})$
= 25

The resulting IACR value, in this case = 25, is equivalent to a hazard index and should not exceed a value of 1.0 (Table 1 shows that the SQG_{PW} should be ≤ 1).

Note that for both the B[a]P TPE and IACR calculations;

1. no carcinogenic PAH should be left out of the calculations. If PAHs are suspected at a site, soil samples should be analyzed for the full suite of carcinogenic PAHs. If analysis returns non-detects, and until further guidance, enter ½ the detection limit into the formulas. Consult the appropriate jurisdiction to confirm that this advice does not conflict with program policy for dealing with non-detects at contaminated sites.

2. if concentrations of benzo[b]fluoranthene, benzo[j]fluoranthene, and benzo[k]fluoranthene are reported separately, they should be summed together and expressed as a single value for benzo[b+j+k]fluoranthene. In this example, benzo[b+j+k]fluoranthene = 0.64 mg·kg^{-1} + 0.62 mg·kg^{-1} = 1.26 mg·kg^{-1}

Step **3** To protect environmental health from non-carcinogenic effects of PAHs (i.e. hazard assessed based on non-carcinogenic modes of action), compare individual PAHs to the appropriate Soil Quality Guideline (SQG) in the bottom half of Table 1.

At this point, the cancer hazard to humans from potentially carcinogenic PAHs has been assessed by calculating the B[a]P TPE and IACR in Steps 1 and 2, respectively, above. Now the non-carcinogenic hazard of PAHs must be assessed. Note that the non-carcinogenic hazard posed by PAHs to humans was not assessed; consult guidelines from other jurisdictions for protection. Additionally, if a PAH displays both cancer and non-cancer effects to humans, protect human health based on the threat from cancer.

Take all PAH concentration data from the industrial site, and compare it to the appropriate environmental SQG from Table 1(excerpt of which is provided below);

	Land Use			
	Agricultural	Residential/ Parkland	Commercial	Industrial
Anthracene (SQG_E)	2.5	2.5	32	32
Benzo[a]pyrene (SQG_E)	20	20	72	72
Fluoranthene (SQG_E)	50	50	180	180
Naphthalene	0.013[e]	0.013[e]	0.013[e]	0.013[e]
Phenanthrene	0.046[e]	0.046[e]	0.046[e]	0.046[e]
Benz[a]anthracene (CCME 1991)	0.1	1	10	10
Benzo[b]fluoranthene[f] (CCME 1991)	0.1	1	10	10
Benzo[k]fluoranthene[f] (CCME 1991)	0.1	1	10	10
Benzo[b+j+k]fluoranthene[f]	0.1	1	10	10
Dibenz[a,h]anthracene (CCME 1991)	0.1	1	10	10
Indeno[1,2,3-c,d]pyrene (CCME 1991)	0.1	1	10	10
Pyrene (CCME 1991)	0.1	10	100	100

Results of comparison between PAHs at industrial site and available SQGs to protect environmental health;

Acenaphthene : There is no SQG for the protection of environmental health reported in Table 1 for this PAH. However, Table 2 provides value(s) for individual environmental soil pathway(s) that could be developed. Consult guidelines from other jurisdictions for the protection of humans from non-carcinogenic effects of this PAH. This conclusion would also apply to acenaphthylene and fluorene if it were present at the site.

Anthracene : The value indicated by the arrow is valid for the protection environmental health from non-carcinogenic effects of this PAH. Consult guidelines from other jurisdictions for the protection of humans from non-carcinogenic effects of this PAH.

Benz[a]anthracene : The value indicated by the arrow is valid for the protection of environmental health from non-carcinogenic effects of this PAH. For human health, the hazard posed by this PAH is assessed solely based on its carcinogenic potential (see Steps 1 and 2).

Benzo[a]pyrene : Same conclusion as for benz[a]anthracene.

Benzo[b]fluoranthene : Same conclusion as for benz[a]anthracene. Additionally, if benzo[b]fluoranthene and benzo[k]fluoranthene cannot be reported separately, report them as the sum of benzo[b+j+k]fluoranthene and compare this value to the guideline for the combined 3 isomers reported in Table 1.

Benzo[k]fluoranthene	: Same conclusion as for benzo[b]fluoranthene.
Benzo[g,h,i]perylene	: There is no SQG reported for the protection of environmental health (Table 1), or individual environmental soil pathways (Table 2) for this PAH. For human health, the hazard posed by this PAH is assessed solely based on its carcinogenic potential (see Steps 1 and 2).
Chrysene	: There is no SQG for the protection of environmental health reported in Table 1 for this PAH. However, Table 2 provides value(s) for individual environmental soil pathway(s) that could be developed. For human health, the hazard posed by this PAH is assessed solely based on its carcinogenic potential (see Steps 1 and 2).
Dibenz[a,h]anthracene	: Same conclusion as for benz[a]anthracene.
Indeno[1,2,3-c,d]pyrene	: Same conclusion as for benz[a]anthracene.
Naphthalene	: The value indicated by the arrow is valid for the protection of environmental health from non-carcinogenic effects of this PAH. Consult guidelines from other jurisdictions for the protection of humans from non-carcinogenic effects of this PAH.

Reference listing:

Canadian Council of Ministers of the Environment. 2010. Canadian soil quality guidelines for the protection of environmental and human health: Carcinogenic and Other PAHs. In: Canadian environmental quality guidelines, 1999, Canadian Council of Ministers of the Environment, Winnipeg.

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Excerpt from Publication No. 1299; ISBN 1-896997-34-1

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