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

BENZENE
2004

This fact sheet provides Canadian soil quality guidelines for benzene for the protection of environmental and human health (Tables 1a and 1b). A scientific supporting document is also available (Environment Canada 2004).

Background Information

Benzene (C_6H_6; CAS 71-43-2) is a monocyclic aromatic compound with a molecular weight of 78.11. Synonyms for benzene include benzol, carbon oil, coal naphtha, light oil, phene, and phenyl hydride (Slooff 1988).

Benzene is a clear, colourless, inflammable liquid with a sweet, aromatic odour. It is readily miscible with alcohol, chloroform, ether, carbon disulphide, carbon tetrachloride, glacial acetic acid, acetone, and oils (Slooff 1988; Budavari 1989) and it is relatively soluble in water, with a reported solubility of 1740–1870 mg·L^{-1} (at 25°C) (Shiu et al. 1990). Benzene has a relatively low octanol–water partition coefficient, in the order of 1.56–2.15, depending on temperature, pH, and pressure (Hansch and Leo 1979).

Table 1a. Soil quality guidelines for benzene (mg·kg^{-1}); 10^{-6} incremental risk.*
(see Table 1b for values calculated at an incremental cancer risk of 10^{-5})

	Land use and soil texture							
	Agricultural		Residential/ parkland		Commercial		Industrial	
	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine
Surface								
Guideline [a,b,c]	**0.0095**	**0.0068**	**0.0095**	**0.0068**	**0.030**	**0.0068**	**0.030**	**0.0068**
SQG_{HH} [b,c]	0.0095	0.0068	0.0095	0.0068	0.030	0.0068	0.030	0.0068
SQG_E	25	25	31	60	180	310	180	310
Subsoil								
Guideline [a,b]	**0.011**	**0.0068**	**0.011**	**0.0068**	**0.030**	**0.0068**	**0.030**	**0.0068**
SQG_{HH} [b]	0.011	0.0068	0.011	0.0068	0.030	0.0068	0.030	0.0068
SQG_E	62	120	62	120	360	620	360	620

Notes: SQG_E = soil quality guideline for environmental health; SQG_{HH} = soil quality guideline for human health.

* Free-phase formation, a circumstance deemed unacceptable by many jurisdictions, occurs when a substance exceeds its solubility limit in soil water. The concentration at which this occurs is dependent on a number of factors, including soil texture, porosity, and aeration porosity. Under the assumptions used for this guideline, at concentrations greater than 910 mg·kg^{-1} in coarse soil, or 970 mg·kg^{-1} in fine soil, formation of free-phase benzene will likely occur. Contact jurisdiction for guidance.

[a] Data are sufficient and adequate to calculate an SQG_{HH} and an SQG_E. Therefore the soil quality guideline is the lower of the two and represents a fully integrated *de novo* guideline for this land use.

[b] This guideline value may be less than the common limit of detection for benzene in some jurisdictions. Contact jurisdiction for guidance.

[c] CCME recommends that guideline values be based on a lifetime incremental cancer risk within the range of 10^{-4} to 10^{-7}. The SQG_{HH} presented here is based on a lifetime incremental cancer risk of 10^{-6}.

The guidelines in this fact sheet are for general guidance only. Site-specific conditions should be considered in the application of these values. The values may be applied differently in various jurisdictions. Use of some values listed in Tables 1a and 1b may not be permitted at the generic level in some jurisdictions. For example, use of subsoil values may result in land use restrictions. The reader should consult the appropriate jurisdiction before application of the values.

Table 1b. Soil quality guidelines for benzene (mg·kg^{-1}); 10^{-5} incremental risk.*
(see Table 1a for values at an incremental risk of 10^{-6})

	Land use and soil texture							
	Agricultural		Residential/ parkland		Commercial		Industrial	
	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine
Surface								
Guideline [a,b,c]	**0.030**	**0.0068**	**0.030**	**0.0068**	**0.030**	**0.0068**	**0.030**	**0.0068**
SQG_{HH} [b,c]	0.030	0.0068	0.030	0.0068	0.030	0.0068	0.030	0.0068
SQG_E	25	25	31	60	180	310	180	310
Subsoil								
Guideline [a,b]	**0.030**	**0.0068**	**0.030**	**0.0068**	**0.030**	**0.0068**	**0.030**	**0.0068**
SQG_{HH} [b]	0.030	0.0068	0.030	0.0068	0.030	0.0068	0.030	0.0068
SQG_E	62	120	62	120	360	620	360	620

Notes: SQG_E = soil quality guideline for environmental health; SQG_{HH} = soil quality guideline for human health.
* Free-phase formation, a circumstance deemed unacceptable by many jurisdictions, occurs when a substance exceeds its solubility limit in soil water. Th concentration at which this occurs is dependent on a number of factors, including soil texture, porosity, and aeration porosity. Under the assumptions use for this guideline, at concentrations greater than 910 mg·kg^{-1} in coarse soil, or 970 mg·kg^{-1} in fine soil, formation of free-phase benzene will likely occur. Contact jurisdiction for guidance.

[a] Data are sufficient and adequate to calculate an SQG_{HH} and an SQG_E. Therefore the soil quality guideline is the lower of the two and represents a fully integrated *de novo* guideline for this land use.

[b] This guideline value may be less than the common limit of detection for benzene in some jurisdictions. Contact jurisdiction for guidance.

[c] CCME recommends that guideline values be based on a lifetime incremental cancer risk within the range of 10^{-4} to 10^{-7}. The SQG_{HH} presented here is based on a lifetime incremental cancer risk of 10^{-5}.

Worldwide natural sources of benzene include discharges from petroleum seeps, forest fires, volcanic eruptions, and vegetation (Westberg et al. 1981; Slooff 1988; Environmental Science and Engineering, Inc. 1991). However, these natural emissions are low compared to anthropogenic emissions (Slooff 1988). Estimates of emissions to the Canadian environment from these sources were not found, but nonanthropogenic sources are expected to be relatively minor in Canada.

Benzene is produced in Canada primarily from petroleum refining and processing. Secondary sources include extraction from natural gas condensate and slow distillation from coal (Jacques 1990).

Benzene is used in the manufacturing of various chemicals and pharmaceuticals, notably ethylbenzene, styrene, cyclohexane, cumene, and maleic acid anhydride. It is also used as a component of solvents and paints, although there is a trend to replace it with more benign compounds (Fishbein 1984; Jacques 1990). Benzene is also a natural component of petroleum and typically makes up from 1 to 4% of gasoline (Barker et al. 1989; Kirk et al. 1991). In gasoline, benzene acts as an octane-enhancer and an antiknock agent. An estimated 39×10^9 L of gasoline were sold in Canada in 2002 for use in road motor vehicles (Statistics Canada 2003).

Changes in gasoline formulations to reduce benzene content and the use of fuel-efficient vehicles or natural gas-powered vehicles were considered to likely have the greatest impact in reducing benzene emissions to the environment. A marked decrease in benzene emissions has been noted since 1975 (Jacques 1990). Through the benzene Canada-wide Standard, the CCME Ministers committed to a 30% reduction in benzene emissions from 1995 levels by 2000, plus an additional 6-kilotonne reduction in national emissions by 2010 (CCME 2001). Initiatives undertaken to achieve these targets address aspects of transportation, chemical manufacturing, natural gas dehydrators, and the oil and gas, petroleum, and steel industries. Reports indicate that this commitment is well on its way to being met, as benzene emissions in Canada decreased 39% between

1995 and 1999 (CCME 2001). Data from the National Air Pollution Surveillance Monitoring Network indicate that average levels of ambient benzene in Canada decreased by approximately 30% between 1995 and 2000 (CCME 2001).

Benzene can enter the soil by deposition from the atmosphere, leakage from underground storage tanks, seepage from waste disposal sites, and spillage of oil and gasoline during storage, transportation, and handling. Various surveys suggest that from 3 to 20% of the estimated 200 000 storage tanks in Canada are potentially leaking (Barker et al. 1989). Emissions of benzene from this source alone may be considerable, but reliable estimates of amounts entering Canadian soil were not found.

In an attempt to determine concentrations of naturally occurring benzene in soil, Environmental Science and Engineering, Inc. (1991) analyzed soil samples from seven Florida sites without a history of spills, but exposed to high ambient atmospheric levels of benzene. All samples were found to be below the 40 ppt quantitation limit.

The Ontario Ministry of Environment and Energy has reported that the 98th percentiles of benzene concentrations in rural and old urban parkland soils not impacted by a local point source of pollution are 0.040 and 0.047 $\mu g \cdot kg^{-1}$, respectively (OMEE 1993).

Benzene was detected in soil samples collected from background urban areas in the general vicinities of a Port Credit petroleum plant and a refinery in Oakville, Ontario, at concentrations ranging from <0.002 to 0.16 $mg \cdot kg^{-1}$ dry soil (Environmental Science and Engineering, Inc. 1991). Data presented in this report indicated that roughly two-thirds of the soil samples contained benzene levels below detection limits (2 $\mu g \cdot kg^{-1}$ dry soil).

Environmental Fate and Behaviour in Soil

The four primary processes that control the fate and behaviour of benzene in the environment are (1) evaporation or volatilization into the gas phase coupled with diffusive transport in the gas phase; (2) sorption to soil, particularly to organic matter; (3) biodegradation; and (4) leaching by rainwater infiltrating through the unsaturated zone and/or dissolution in groundwater.

The infiltration of spilled benzene into soil, in pure solution or as part of fuel, has been described in detail (EPS 1984; Mackay et al. 1985; Tucker et al. 1986). Essentially, the spilled liquid will fill the pores of the soil adjacent to the spill and will flow downwards at a rate governed by the hydraulic conductivity for benzene in that soil. A residual amount is left within the soil pores along the path of the saturated slug. Downward migration will continue until the volume spilled equals the volume retained within the unsaturated zone or until the plume reaches the saturated zone (water table) or an impermeable layer. At this point, downward migration virtually ceases and lateral spreading dominates. Diffusion of benzene in the unsaturated zone can also lead to removal from the subsurface to the atmosphere by transport into the gas phase (volatilization). Vapour transport can also increase the area of contamination from that originally contaminated by the spill as the gas phase diffuses through soil pores.

Volatilization from the unsaturated zone can be the major process leading to the removal of benzene from soil (Rogers et al. 1980; Korte and Klein 1982; Tucker et al. 1986; Karimi et al. 1987; Anderson et al. 1991) and is directly affected by the factors that govern its partitioning into the soil–water–air system within soil pores (Karimi et al. 1987; Chiou 1989; Sims 1990; Rutherford and Chiou 1992). In one case, volatilization was almost entirely responsible for the rapid removal of benzene from a soil, with a reported half-life of <2 d (Anderson et al. 1991). Temperature and soil porosity determine the rate of molecular diffusion, the principle process resulting in volatilization losses from the subsurface (Tucker et al. 1986; Karimi et al. 1987; Jury et al. 1990).

Partitioning of benzene between the air and water phases will change markedly with variation in temperature. As the Henry's law constant increases with increasing temperatures, losses to the atmosphere or the air phase within the soil also increase, which may in turn have implications for increasing the area of contamination (Ashworth et al. 1988).

Jury et al. (1990) compared the fate of benzene additions placed in a 30-cm-thick layer located 100 cm below the surface of a sandy soil and a clayey soil. After 1 year, the calculated mass balances were as follows: 34.3% volatilized, 38.6% degraded, and 27.1% remained in the porous sandy soil, while 0.01% volatilized, 50% degraded, and 49.99% remaining in the more compact clayey soil. In the sandy soil, benzene volatilization quickly rose to a maximum at about 30 d and remained high thereafter. Volatilization from the clayey soil did not reach a maximum during the first year, and was more than two orders of magnitude less than the flux from the sandy soil after 1 year.

Benzene will rapidly and reversibly partition between the air, water, and solids in the subsurface (Karimi et al. 1987; Chiou 1989). Although some sorption onto clays will take place, soil organic matter content largely governs the fraction retained by the solid phase (Chiou 1989; Rebhun et al. 1992). Residual petroleum hydrocarbon behaves as a component of soil organic carbon and will affect the partitioning of benzene (Tucker et al. 1986). Organic carbon acts as a partitioning medium, while the mineral matter acts as a conventional adsorbent (Chiou 1989). Water saturation also affects partitioning in soil organic matter, although to a much lesser degree (Rutherford and Chiou 1992). The effect of temperature on the partitioning of benzene has not been reported.

Degradation by aerobic microorganisms is another significant removal mechanism in the unsaturated zone. Hydrocarbon-degrading microorganisms are ubiquitous in soil, and both sorbed and vapour-phase benzene are likely biodegraded (Rosenburg and Gutnick 1980; English and Loehr 1991). To some extent, biodegradation and volatilization are competitive processes, and their relative importance varies considerably, but often sites contaminated by gasoline become anaerobic due to the high oxygen demand imposed by the organic load (Song et al. 1990). Biodegradation in the unsaturated zone practically ceases when it becomes anaerobic (Smith 1990; Aelion and Bradley 1991; Barbaro et al. 1991), but it can be enhanced by supplying air to the subsurface (Sims 1990).

The fourth significant removal process from the unsaturated zone is leaching with infiltrating rainwater (Tucker et al. 1986). Obvious factors such as annual rainfall and rate of recharge govern this process. However, leaching is only a transfer process and likely results in the migration of benzene to groundwater.

Behaviour and Effects in Biota

Soil Microbial Processes

Microbial systems hydroxylate benzene to catechol. Bacteria can either convert catechol to pyruvate and acetaldehyde by a meta-cleavage pathway or convert catechol to beta-ketoadipate via an ortho-cleavage route (Smith 1990). Anaerobic bacteria have little capacity to metabolize benzene. Anaerobic methanogenic bacteria can convert a small percentage of benzene to phenol, cyclohexanone, and other aliphatic acids, but produce little methane or carbon dioxide using benzene as a substrate (Grbić-Galić and Vogel 1987). The intermediates of benzene metabolites in bacteria are rapidly converted and do not persist (Gibson 1977).

Walton et al. (1989) reported that no effects on bacterial respiration were observed in a silt loam, but a transient decrease in respiration occurred in sandy loam after the application of 1000 µg benzene$\cdot g^{-1}$ dry soil. Respiration rates, however, were not significantly different from controls in both cases after 6 d, suggesting that soil microbial function is unlikely to be grossly impaired at this dose. Such transient effects on respiration were also observed for 15 of 18 other compounds tested, suggesting that they either become unavailable due to sorption, volatilization, or biodegradation, or that a shift in microbial populations occurs, which selects for organisms resistant to the compound tested.

Burback et al. (1994) studied the effect of benzene and its metabolites, phenol and hydroquinone, on the number of colony-forming units of a soil mycobacterium (*Mycobacterium vaccae* strain JOB-5). *M. vaccae* can catabolize benzene to phenol and subsequently to hydroquinone. Benzene and hydroquinone had no measurable effect on cell viability when added at concentrations under 100.0 mmol$\cdot L^{-1}$. Phenol, however, affected cell viability at approximately 75.0 mmol$\cdot L^{-1}$.

Terrestrial Plants

Plants have been reported to transform benzene to metabolites such as amino acids (Dumishidze and Ugrekhelidze 1969), suggesting that they may also be involved in removing benzene from soil (Cross et al. 1979). Bioaccumulation factors ranged from 4.6 to 17 and from 1.9 to 10 for barley (*Hordeum* sp.) and cress (*Cruciferae* sp.), respectively (Topp et al. 1989). Bioaccumulation factors ≥10 were measured after short exposure periods (12 d), whereas longer exposure periods (>33 d) resulted in lower (<5) bioaccumulation factors, coincident with an increase in plant-bound residue and polar metabolites. The data were difficult to interpret because it was impossible to establish whether the ^{14}C label was taken up as ^{14}C-labelled benzene or as ^{14}C-CO_2 produced from the biodegradation of benzene in soil. In closed aerated laboratory systems, it was shown that ^{14}C-labelled benzene formed 62% $^{14}CO_2$ within 1 week (Scheunert and Korte 1986).

Plants (barley, carrots, and tomatoes) directly sprayed with benzene quickly exhibited signs of cellular damage (Currier 1951). Exposure to vapours at 50 mg$\cdot L^{-1}$ air also caused loss of turgor within a few minutes. In both cases, the equivalent soil concentrations are difficult to compare with these doses or to develop into soil guidelines. Other plant data show no toxicity from benzene vapours (Cross et al. 1979).

In an attempt to establish phytotoxic levels of benzene in soil, Environment Canada conducted seedling emergence tests for both radishes *(Raphanus sativa)* and lettuce *(Lactuca sativa)* in 1995. The lowest concentrations at which adverse effects occurred were 24 and 40 mg benzene·kg^{-1} soil for radishes and lettuce, respectively, resulting in a 25% reduction in seedling emergence. Although these endpoints were used to calculate provisional soil quality guidelines in 1997, the data were suspect due to problems associated with the recovery of benzene from soil and the volatility of the compound (Environment Canada 1995).

With significant advances in techniques for determining the toxicity of highly volatile compounds, new plant toxicity tests were conducted by ESG International in 2002. Tests conducted with early northern wheatgrass (*Agropyron dasystachyum*) and alfalfa (*Medicago sativa*) examined the effects of benzene on shoot and root length and dry and wet biomass after 14 days of exposure in both coarse and fine soils. In coarse soils, the most sensitive endpoint for alfalfa was reduction of root dry mass with an IC_{25} value of 235 mg·kg^{-1}, and for northern wheatgrass the most sensitive endpoint was an IC_{25} of 73 mg·kg^{-1} for reduction of root dry mass (ESG 2002). The results for fine soils reported by ESG (2002) were recalculated by Komex (2002) to take into account volatile losses that occur between spiking the sample and introducing the plants 2 hours later. (Similar calculations had already been made by ESG for the data from the coarse soils.) Therefore, the most sensitive estimated effect concentrations in fine soils for alfalfa and northern wheatgrass were an IC_{25} of 265 mg·kg^{-1} for reduction of root length, and an IC_{25} of 199 mg·kg^{-1} for reduction of root wet mass, respectively (Komex 2002).

Terrestrial Invertebrates

No studies were found that described benzene metabolism in non-mammalian chordates and soil invertebrates. However, animals across a wide spectrum of genera are known to have hydrocarbon-oxidizing enzymes: in marine organisms, from phytoplankton (e.g., *Fucus* sp.) to molluscs (e.g., *Mytilus edulis*) to fish (e.g., *Oncorhynchus kisutch*) (Malins 1977). There are also no reports of benzene bioaccumulation in terrestrial animals.

Hartenstein (1982) reported that benzene dissolved in sludge applied to a 4-mm layer of silt loam significantly affected growth, but not survival, of the earthworm *E. foetida* at a concentration of 8% (weight/weight).

The lowest reported benzene concentrations resulting in adverse effects to soil invertebrates come from Environment Canada. The earthworm *(Eisenia foetida)* suffered 25% mortality at 161 mg benzene·kg^{-1} soil. Although these results were used for deriving provisional soil quality guidelines in 1997, the same problems associated with the phytotoxicity tests were encountered (Environment Canada 1995).
Studies commissioned by the CCME in 2001, and using advanced techniques for dealing with volatile compounds, examined the toxicity of benzene to the collembolan (*Onychiurus folsomi*) and the earthworm (*Eisenia andrei*). In coarse soils, the LC_{25} for collembolans was 63 mg·kg^{-1}, and the NOEC and LOEC for adverse effects in earthworms were 0 and 172 mg·kg^{-1}, respectively (ESG 2002). The results reported by ESG (2002) for fine soils were recalculated by Komex (2002) to take into account volatile losses that occur between spiking the sample and introducing the invertebrates 24 hours later. (Similar calculations had already been made by ESG for the data from the coarse soils.) Therefore, in fine soils the LC_{25} for collembolans was 99 mg·kg^{-1}, and the NOEC and LOEC for adverse effects in earthworms were 63 and 97 mg·kg^{-1}, respectively (Komex 2002).

Livestock and Wildlife

Information on the metabolism of benzene in livestock or wildlife species is lacking. No studies on the toxic effects of benzene on mammalian wildlife, livestock or birds have been found.

Human and Experimental Animal Health Effects

The aerobic metabolism of benzene involves the enzymatic hydroxylation and oxidation of benzene, mediated by induced oxidase systems. This reaction has been detected and measured in a wide variety of organisms (Malins 1977; Fishbein 1984; Smith 1990). Bacteria and mammals use different mechanisms of benzene metabolism. In mammalian systems, including humans, the initial oxidation of benzene is performed by the mixed-function oxidase system (Fishbein 1984). The oxidized intermediate may subsequently be hydroxylated to form phenol, hydroquinone, or catechol. These in turn may be metabolized by several pathways or be excreted. Intermediates in the mammalian metabolic pathway are now considered to be the primary cause of the chronic toxicity of benzene.

With a log K_{ow} of 2.13, benzene will readily be taken up into the cell membrane. The general narcotic effects caused by the action of benzene on the membrane include inhibition of nerve transmission and an overall depression of the central nervous system function; inhibition of gas exchange and a lowered oxygen-binding capacity of hemoglobin; and inhibition of the capacity of some cell-surface receptors to bind to appropriate ligands, desensitizing the cells to hormonal responses.

Slooff (1988) reported that the acute toxic dose of benzene for rats is 41.6 g·m^{-3}, measured as the 4-h LC_{50} for inhalation of benzene. In experimental mammals, the effects of benzene show significant variation among sexes and species. Shubik et al. (1962) applied 0.05 mL of benzene to a 2-cm^2 patch on laboratory rats and rabbits three times per week. After 60 d, all the treated male rats had died, while only 52% of the treated female rats had died. Similar treatment of rabbits had no effect. Tice et al. (1980) reported that a highly sensitive strain of laboratory mice (DBA/2) also shows distinct sexual differences in the response to benzene.

Virtually all the detailed information on the chronic toxicity of benzene was derived from studies on mammals, particularly humans (Fishbein 1984; Manahan 1989). Upon entry into the circulatory system of mammals, via either inhalation or topical application, benzene will partition between the aqueous phases and lipid components of tissues.

In mammals, the major chronic effect is manifested on cells from the blood system. Chronic low-level exposure in humans results in blood disorders, such as pancytopenia, a reduction in the three types of formed elements in blood (erythrocytes, leucocytes, and platelets). Benzene is a known carcinogen, specifically causing acute myelogenous leukemia (IARC 1982). In mammalian tests (e.g., rats and mice), the carcinogenicity of benzene shows a wide range of tissue and species sensitivity (Byard 1982), with the most common effect being tumorigenicity. Acute myelogenous leukemia has not been observed in other mammals exposed to benzene (Andrews and Snyder 1991).

Health Canada has established an inhalation tolerable concentration for benzene at a 5% cancer risk for lifetime exposure of 15 mg·m^{-3} (Health Canada 1996). Therefore, the risk-specific concentration (RsC) for inhalation, evaluated at an incremental cancer risk of 10^{-6}, is 0.0003 mg·m^{-3}and for an incremental cancer risk of 10^{-5} is 0.003 mg·m^{-3}. For ingestion, Health Canada (2003) provides an oral slope factor for benzene of 0.31 (mg·kg-bw^{-1}·day^{-1})$^{-1}$. Therefore, the risk-specific dose (RsD) that would result in an incremental cancer risk of 10^{-6} is 0.0000032 mg·kg-bw^{-1}·day^{-1} and for an incremental cancer risk of 10^{-5} is 0.000032 mg·kg-bw^{-1}·day^{-1}.

Guideline Derivation

Canadian soil quality guidelines are derived for different land uses following the process outlined in CCME (1996a) using different receptors and exposure scenarios for each land use (Tables 1a and 1b). Various modifications to the 1996 protocol which were used in the Canada-Wide Standard for Petroleum Hydrocarbons in Soil (CCME 2000) were also applied in the development of these guidelines, including the derivation of guidelines for different soil textures (coarse and fine) and depths (surface soil and subsoil). As defined in the Canada-wide Standard for Petroleum Hydrocarbons, fine-grained soils are those which contain greater than 50% by mass particles less than 75 µm mean diameter (D_{50} < 75 µm). Coarse-grained soils are those which contain greater than 50% by mass particles greater than 75 µm mean diameter (D_{50} > 75 µm). Surface soil refers to the unconsolidated mineral material on the immediate surface of the earth that serves as a natural medium for terrestrial plant growth, and can extend as deep as 1.5 m. Subsoil is defined as the unconsolidated regolith material above the water table not subject to soil forming processes; this nominally includes vadose zone materials below 1.5 m depth. Detailed derivations for benzene soil quality guidelines are provided in Environment Canada (2004).

Soil Quality Guidelines for Environmental Health

Environmental soil quality guidelines (SQG_Es) are based on soil contact using data from toxicity studies on plants and invertebrates. In the case of agricultural land 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 data permit. For industrial land use, an off-site migration check is also calculated.

In the case of benzene, there are sufficient data to derive a guideline value for soil contact with plants and invertebrates (Tables 2 and 3). A nutrient and energy cycling check value was not calculated due to a lack of data. The available dataset was also not sufficient to meet the requirements of the CCME (1996) protocol for calculating the soil and food ingestion guideline; however, the process used to determine tolerable daily intakes for humans was adapted to calculate daily threshold doses for livestock. As bioconcentration of benzene into livestock fodder is not expected to be significant, a guideline was calculated only for the livestock soil ingestion (and not food ingestion) pathway. Check values for groundwater have been calculated to determine benzene soil concentrations that will be protective of freshwater aquatic life and livestock associated with groundwater discharge to surface water. These groundwater check values are not applied in the determination of the SQG_Es, but should be applied on a site-specific basis (Tables 2 and 3). An off-site migration check was not calculated for benzene with the rationale that, given the volatility and biodegradability of benzene, it is unlikely that significant amounts would remain after wind or water transport of soil.

The soil ingestion guidelines are recommended as the SQG_E for both coarse and fine surface soils with agricultural land uses. For agricultural land use subsurface soils, and for all soil types and depths on other land uses the soil contact guidelines are recommended as the SQG_E.

Soil Quality Guidelines for Human Health

Human health soil quality guidelines (SQG_{HH}s) for nonthreshold (carcinogenic) contaminants require the development of soil quality guidelines that employ a critical risk-specific dose based on lifetime incremental risks from soil ingestion. For all land uses, the adult was chosen as the receptor when considering lifetime cancer risk. For nonthreshold contaminants, human exposure should be reduced to the maximum extent possible.

CCME (1996a) notes that regulatory decisions for contaminated land management in Canada have reflected incremental cancer risks in the range of 10^{-4} to 10^{-7}. Since 1996, Canadian jurisdictions have generally settled on 10^{-5} or 10^{-6} incremental cancer risk for modeled exposures supporting tabular numerical guidelines. The decision to apply guidelines at either of these conventional incremental risks or some alternative value is a policy, rather than a scientific, issue to be decided by individual jurisdictions. For convenience, CCME provides guideline values for *non-drinking water pathways* at both 10^{-5} and 10^{-6} incremental risk levels.

With respect to soil quality guidelines to protect groundwater as a source of potable water, the CCME SQGTG employs the Canadian Drinking Water Guidelines (when available) as acceptable or desirable (in the case where groundwater contamination is present in excess of the guidelines) target concentrations in groundwater. As these water quality guidelines are regulatory limits in many jurisdictions, no evaluation or position is taken on the risk levels associated with those water guideline concentrations. Rather, they are employed as target concentrations from which to derive a soil quality concentration that should not result in leaching to or contamination of groundwater in excess of the water quality guideline. As a result, no range in acceptable risk levels is associated with soil quality guidelines derived to protect groundwater as a source of potable water. Note, however, that the 10^{-5} to 10^{-6} incremental cancer risk range discussed above corresponds to the range considered “essentially negligible” in the derivation MACs for carcinogenic chemicals in drinking water (Health and Welfare Canada 1989).

Ingestion and dermal contact guidelines were calculated for all surface soils, but these two pathways were considered not applicable in subsoils, unless the ground is disturbed. Soil inhalation guidelines were not calculated for any of the land uses or soil types. However, checks were calculated for inhalation of vapour from indoor air. A groundwater check value was calculated to determine benzene soil concentrations that will be protective of drinking water.

The SQG_{HH} is the lowest of the various human health guidelines and check values. Therefore, for benzene managed to a lifetime incremental cancer risk of 10^{-6}, the indoor vapour inhalation values are recommended as the SQG_{HH} for all land uses in coarse surface soils, and for agricultural and residential/parkland land uses in coarse subsoils (Tables 2 and 3). For all other scenarios, including where benzene is managed to a lifetime incremental cancer risk of 10^{-5} (Tables 2 and 3) the groundwater check for the protection of drinking water is recommended as the SQG_{HH}.

Soil Quality Guidelines for Benzene

The soil quality guidelines are intended to be protective of both environmental and human health and are taken as the lower of the SQG_{HH} and SQG_E. For all land uses and soil types, the guideline is the soil concentration calculated for the SQG_{HH} (Tables 1a and 1b).

Because there are sufficient data to derive an SQG_{HH} and an SQG_E for each land use, the soil quality guideline represents a fully integrated *de novo* guideline for each land use. The interim soil quality criteria for benzene (CCME 1991), and the soil quality guidelines for benzene derived in 1997, are superseded.

CCME (1996b) provides guidance on potential modifications to the final recommended soil quality guideline when setting site-specific objectives.

Table 2. Soil quality guidelines and check values for benzene (mg kg^{-1}) in surface soil.

SURFACE SOIL	Land Use							
	Agricultural		Residential/ Parkland		Commercial		Industrial	
	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine
Guideline – 10^{-6} incremental risk	0.0095[a]	0.0068[a]	0.0095[a]	0.0068[a]	0.030[a]	0.0068[a]	0.030[a]	0.0068[a]
Guideline – 10^{-5} incremental risk	0.030[a]	0.0068[a]	0.030[a]	0.0068[a]	0.030[a]	0.0068[a]	0.030[a]	0.0068[a]
Human health guidelines/check values – 10^{-6} incremental risk								
SQG_{HH}	0.0095[b]	0.0068[b]	0.0095[b]	0.0068[b]	0.030[b]	0.0068[b]	0.030[b]	0.0068[b]
Soil ingestion guideline	11	11	11	11	11	11	11	11
Soil dermal contact guideline	25	25	25	25	25	25	25	25
Soil inhalation guideline	NC	NC	NC	NC	NC	NC	NC	NC
Inhalation of indoor air check (basement)	0.015	0.21	0.015	0.21	---	---	---	---
Inhalation of indoor air check (slab on grade)	0.0095	0.21	0.0095	0.21	0.030	0.28	0.030	0.28
Off-site migration check	---	---	---	---	---	---	NC[c]	NC[c]
Groundwater check (drinking water)	0.030	0.0068	0.030	0.0068	0.030	0.0068	0.030	0.0068
Produce, meat and milk check	NC[d]	NC[d]	NC[d]	NC[d]	---	---	---	---
Human health guidelines/check values – 10^{-5} incremental risk								
SQG_{HH}	0.030[b]	0.0068[b]	0.030[b]	0.0068[b]	0.030[b]	0.0068[b]	0.030[b]	0.0068[b]
Soil ingestion guideline	110	110	110	110	110	110	110	110
Soil dermal contact guideline	250	250	250	250	250	250	250	250
Soil inhalation guideline	NC	NC	NC	NC	NC	NC	NC	NC
Inhalation of indoor air check (basement)	0.15	2.1	0.15	2.1	---	---	---	---
Inhalation of indoor air check (slab on grade)	0.095	2.1	0.095	2.1	0.30	2.8	0.30	2.8
Off-site migration check	---	---	---	---	---	---	NC[c]	NC[c]
Groundwater check (drinking water)	0.030	0.0068	0.030	0.0068	0.030	0.0068	0.030	0.0068
Produce, meat and milk check	NC[d]	NC[d]	NC[d]	NC[d]	---	---	---	---
Environmental health guidelines/check values								
SQG_E	25[e]	25[e]	31[f]	60[f]	180[f]	310[f]	180[f]	310[f]
Soil contact guideline	31	60	31	60	180	310	180	310
Soil and food ingestion guideline	25	25	---	---	---	---	---	---
Nutrient and energy cycling check	NC[g]	NC[g]	NC[g]	NC[g]	NC[g]	NC[g]	NC[g]	NC[g]
Off-site migration check	---	---	---	---	---	---	NC[c]	NC[c]
Groundwater check (livestock)	1.7[h]	NC[i]	---	---	---	---	---	---
Groundwater check (aquatic life)	1.0[j]	NC[i]	1.0[j]	NC[i]	1.0[j]	NC[i]	1.0[j]	NC[i]
Interim soil quality criterion (CCME 1991)	0.05		0.5		5		5	

Notes: NC=not calculated; ND-not determined; SQG_E=soil quality guideline for environmental health; SQG_{HH}=soil quality guideline for human health. 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] Data are sufficient and adequate to calculate an SQG_{HH} and an SQG_E. Therefore the soil quality guideline is the lower of the two and represents a fully integrated *de novo* guideline for this land use, derived in accordance with the soil protocol (CCME 1996a). The corresponding interim soil quality criterion (CCME 1991) is superseded by the soil quality guideline.

[b] The SQG_{HH} is the lowest of the human health guidelines and check values.

[c] Given the volatility and biodegradability of benzene, it is unlikely that significant amounts would remain after wind or water transport of soil, and so this pathway was not evaluated.

[d] This check is intended to protect against chemicals that may bioconcentrate in human food. Benzene is not expected to exhibit this behaviour, and so this pathway was not evaluated.

[e] The SQG_E is based on the lower of the soil contact guideline and the soil and food ingestion guideline.

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

[g] Data are insufficient/inadequate to calculate the nutrient and energy cycling check for this land use.

[h] This environmental groundwater check value is provisional because at the time of derivation there was no Canadian Water Quality Guideline for the protection of livestock watering for benzene upon which to base it. For details on the derivation see the scientific supporting document (Environment Canada 2004). This check value is not used in determining the national soil quality guideline, but is provided as a reference for site-specific application.

[i] The environmental groundwater check value has not been determined because calculations show that in 100 years groundwater migration through fine soils will be less than 10 metres. For site specific calculations where the protection of potable groundwater pathway is active, a hydraulic conductivity of 32 m year^{-1} should be assumed, if adequate measured data are not available.

[j] This environmental groundwater check value is not used in determining the national soil quality guideline, but is provided as a reference for site-specific application.

Table 3. Soil quality guidelines and check values for benzene (mg kg^{-1}) in subsoil.

SUBSOIL	**Land Use**							
	Agricultural		**Residential/ Parkland**		**Commercial**		**Industrial**	
	Coarse	**Fine**	**Coarse**	**Fine**	**Coarse**	**Fine**	**Coarse**	**Fine**
Guideline – 10^{-6} incremental risk	0.011[a]	0.0068[a]	0.011[a]	0.0068[a]	0.030[a]	0.0068[a]	0.030[a]	0.0068[a]
Guideline – 10^{-5} incremental risk	0.030[a]	0.0068[a]	0.030[a]	0.0068[a]	0.030[a]	0.0068[a]	0.030[a]	0.0068[a]
Human health guidelines/check values – 10^{-6} incremental risk								
SQG_{HH}	0.011[b]	0.0068[b]	0.011[b]	0.0068[b]	0.030[b]	0.0068[b]	0.030[b]	0.0068[b]
Soil ingestion guideline	NC	NC	NC	NC	NC	NC	NC	NC
Soil dermal contact guideline	NC	NC	NC	NC	NC	NC	NC	NC
Soil inhalation guideline	NC	NC	NC	NC	NC	NC	NC	NC
Inhalation of indoor air check (basement)	0.015	0.21	0.015	0.21	---	---	---	---
Inhalation of indoor air check (slab on grade)	0.011	0.22	0.011	0.22	0.032	0.29	0.032	0.29
Off-site migration check	---	---	---	---	---	---	NC[c]	NC[c]
Groundwater check (drinking water)	0.030	0.0068	0.030	0.0068	0.030	0.0068	0.030	0.0068
Produce, meat and milk check	NC[d]	NC[d]	NC[d]	NC[d]	---	---	---	---
Human health guidelines/check values – 10^{-5} incremental risk								
SQG_{HH}	0.030[b]	0.0068[b]	0.030[b]	0.0068[b]	0.030[b]	0.0068[b]	0.030[b]	0.0068[b]
Soil ingestion guideline	NC	NC	NC	NC	NC	NC	NC	NC
Soil dermal contact guideline	NC	NC	NC	NC	NC	NC	NC	NC
Soil inhalation guideline	NC	NC	NC	NC	NC	NC	NC	NC
Inhalation of indoor air check (basement)	0.15	2.1	0.15	2.1	---	---	---	---
Inhalation of indoor air check (slab on grade)	0.11	2.2	0.11	2.2	0.32	2.9	0.32	2.9
Off-site migration check	---	---	---	---	---	---	NC[c]	NC[c]
Groundwater check (drinking water)	0.030	0.0068	0.030	0.0068	0.030	0.0068	0.030	0.0068
Produce, meat and milk check	NC[d]	NC[d]	NC[d]	NC[d]	---	---	---	---
Environmental health guidelines/check values								
SQG_E	62[e]	120[e]	62[f]	120[f]	360[f]	620[f]	360[f]	620[f]
Soil contact guideline	62	120	62	120	360	620	360	620
Soil and food ingestion guideline	NC	NC	---	---	---	---	---	---
Nutrient and energy cycling check	NC[g]	NC[g]	NC[g]	NC[g]	NC[g]	NC[g]	NC[g]	NC[g]
Off-site migration check	---	---	---	---	---	---	NC[c]	NC[c]
Groundwater check (livestock)	1.7[h]	NC[i]	---	---	---	---	---	---
Groundwater check (aquatic life)	1.0[j]	NC[i]	1.0[j]	NC[i]	1.0[j]	NC[i]	1.0[j]	NC[i]
Interim soil quality criterion (CCME 1991)	0.05		0.5		5		5	

Notes: NC=not calculated; ND-not determined; SQG_E=soil quality guideline for environmental health; SQG_{HH}=soil quality guideline for human health. 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] Data are sufficient and adequate to calculate an SQG_{HH} and an SQG_E. Therefore the soils quality guideline is the lower of the two and represents a fully integrated *de novo* guideline for this land use, derived in accordance with the soil protocol (CCME 1996a). The corresponding interim soil quality criterion (CCME 1991) is superseded by the soil quality guideline.

[b] The SQG_{HH} is the lowest of the human health guidelines and check values.

[c] Given the volatility and biodegradability of benzene, it is unlikely that significant amounts would remain after wind or water transport of soil, and so this pathway was not evaluated.

[d] This check is intended to protect against chemicals that may bioconcentrate in human food. Benzene is not expected to exhibit this behaviour, and so this pathway was not evaluated.

[e] The SQG_E is based on the lower of the soil contact guideline and the soil and food ingestion guideline.

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

[g] Data are insufficient/inadequate to calculate the nutrient and energy cycling check for this land use.

[h] This environmental groundwater check value is provisional because at the time of derivation there was no Canadian Water Quality Guideline for the protection of livestock watering for benzene upon which to base it. For details on the derivation see the scientific supporting document (Environment Canada 2004). This check value is not used in determining the national soil quality guideline, but is provided as a reference for site-specific application.

[i] The environmental groundwater check value has not been determined because calculations show that in 100 years groundwater migration through fine soils will be less than 10 metres. For site specific calculations where the protection of potable groundwater pathway is active, a hydraulic conductivity of 32 m year^{-1} should be assumed, if adequate measured data are not available.

[j] This environmental groundwater check value is not used in determining the national soil quality guideline, but is provided as a reference for site-specific application.

References

Aelion, C.M., and P.M. Bradley. 1991. Aerobic biodegradation potential of subsurface microorganisms from a jet fuel-contaminated aquifer. Appl. Environ. Microbiol. 57:57–63.

Anderson, T.A., J.J. Beauchamps, and B.T. Walton. 1991. Organic chemicals in the environment: Fate of volatile and semivolatile organic chemicals in soil: Abiotic vs. biotic losses. J. Environ. Qual. 20:420–424.

Andrews, L.S., and R. Snyder. 1991. Toxic effects of solvents and vapours. In: Casarett and Doull's toxicology: The basic science of poisons, M.O. Amdur, J. Doull, and C.D. Klaassen, eds. Pergamon Press, New York.

Ashworth, R.A., G.B. Howe, M.E. Mullins, and T.N. Rogers. 1988. Air–water partitioning coefficients of organics in dilute aqueous solution. J. Hazard. Mater. 18:25–36.

Barbaro, J.R., J.F. Barker, L.A. Lemon, R.W. Gillham, and C.I. Mayfield. 1991. *In situ* cleanup of benzene in groundwater by employing denitrifying bacteria. Canadian Petroleum Products Institute, Ottawa.

Barker, J.F., E.A. Sudicky, C.I. Mayfield, and R.W. Gillham. 1989. Petroleum hydrocarbon contamination of groundwater: Natural fate and *in situ* remediation, a summary report. PACE Report No. 89-5. Petroleum Association for Conservation of the Canadian Environment, Ottawa.

Budavari, S. (ed.). 1989. The Merck index: An encyclopedia of chemicals, drugs, and biologicals. 11th ed. Merck and Co. Inc., Rahway, NJ.

Burback, B.L., J.J. Perry, and L.E. Rudd. 1994. Effect of environmental pollutants and their metabolites on a soil mycobacterium. Appl. Microbiol. Biotechnol. 41:134–136.

Byard, J.L. 1982. Detection and evaluation of potential hazards to human health. In: Genetic toxicology: An agricultural perspective, R.A. Fleck and A. Hollaender, eds. Plenum Publishing Corp., New York.

CCME (Canadian Council of Ministers of the Environment). 1991. Interim Canadian environmental quality criteria for contaminated sites. CCME, Winnipeg.

———. 1996a. A protocol for the derivation of environmental and human health soil quality guidelines. CCME, Winnipeg. [A summary of the protocol appears in Canadian environmental quality guidelines, Chapter 7, Canadian Council of Ministers of the Environment, 1999, Winnipeg.]

———. 1996b. Guidance manual for developing site-specific soil quality remediation objectives for contaminated sites in Canada. CCME, Winnipeg. [Reprinted in Canadian environmental quality guidelines, Chapter 7, Canadian Council of Ministers of the Environment, 1999, Winnipeg.]

———. 2000. Canada-Wide Standards for Petroleum Hydrocarbons (PHC) in Soil: Scientific Rationale, Supporting Technical Document. Canadian Council of Ministers of the Environment, Winnipeg.

———. 2001. Benzene Canada-wide Standard: Phase 1 National Summary. Annual Progress Report – December 2001. Canadian Council of Ministers of the Environment, Winnipeg.

Chiou, C. 1989. Theoretical considerations of the partition uptake of nonionic organic compounds by soil organic matter. In: Reactions and movement of organic chemicals in soils, B.L. Sawhney and K. Brown, eds. Soil Sci. Soc. Am. Spec. Publ. No. 22. Soil Science Society of America Inc., Madison WI.

Cross, A.J., J.C. McFarlane, and C.W. Frank. 1979. Benzene vapor depletion in the presence of plants. EPA-600/3-79-096. U.S. Environmental Protection Agency, Monitoring Systems Research and Development Division, Environmental Monitoring and Support Laboratory, Las Vegas, NV.

Currier, H.B. 1951. Herbicidal properties of benzene and certain methyl derivatives. Hilgardia 20:383–405.

Dumishidze, S.V., and D.S.H. Ugrekhelidze. 1969. Degradation of benzene in tea plants. Doklady Academii Nauk SSSR 184:228

English, C.W., and R.C. Loehr. 1991. Degradation of organic vapors in unsaturated soils. J. Hazard. Mater. 28:55–63.

Environment Canada. 1995. Toxicity testing of National Contaminated Sites Remediation Program priority substances for the development of soil quality guidelines for contaminated sites. Environmental Conservation Service, Evaluation and Interpretation Branch, Guidelines Division, Ottawa. Unpub.

———. 2004. Canadian soil quality guidelines for benzene. Scientific supporting document. National Guidelines and Standards Office, Environmental Quality Branch, Environment Canada, Ottawa.

Environmental Science and Engineering, Inc. 1991. Naturally occurring benzene, toluene and xylenes in soils. Health and Environmental Sciences Departmental Report. American Petroleum Institute, Washington, DC.

EPS (Environmental Protection Service). 1984. Benzene: Environmental and technical information for problem spills. Environment Canada, Environmental Protection Service, Environmental Protection Programs Directorate, Technical Services Branch, Ottawa.

ESG International Inc. 2002. Quantification of the exposure concentrations and toxicity of BTEX compounds in soil. Report prepared for the Soil Quality Guidelines Task Group, Canadian Council of Ministers of the Environment. Report #G1603 – June 2002.

Fishbein, L. 1984. An overview of environmental and toxicological aspects of aromatic hydrocarbons. I. Benzene. Sci. Total Environ. 40:189–218.

Gibson, D.T. 1977. Biodegradation of aromatic petroleum hydrocarbons. In: Fate and effects of petroleum hydrocarbons in marine ecosystems and organisms, D.A. Wolfe, ed. Pergamon Press, Oxford.

Grbić-Galić, D., and T.M. Vogel. 1987. Transformation of toluene and benzene by mixed methanogenic cultures. Appl. Environ. Microbiol. 53:254–260.

Hansch, C., and A. Leo. 1979. Substitute constants for correlation analysis in chemistry and biology. John Wiley and Sons, New York.

Hartenstein, R. 1982. Effect of aromatic compounds, humic acids and lignins on growth of the earthworm *Eisenia foetida*. Soil Biol. Biochem. 14:595–599.

Health and Welfare Canada. 1989. Derivation of maximum acceptable concentrations and aesthetic objectives for chemicals in drinking water. In: Guidelines for Canadian drinking water quality:

Supporting documentation. Prepared by the Federal-Provincial Subcommittee on Drinking Water, May 1989.

Health Canada. 1996. Health-based tolerable daily intakes/ concentrations and tumorigenic doses/concentrations for priority substances. Health Canada, Environmental Health Directorate, Health Protection Branch. 96-EHD-194.

Health Canada. 2003. Federal contaminated site risk assessment in Canada. Part II: Health Canada toxicological reference values (TRVs). Version 1.0, October 3, 2003. Environmental Health Assessment Services, Safe Environments Program, Health Canada, Ottawa.

IARC (International Agency for Research on Cancer). 1982. Benzene. IARC Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Humans, vol. 29. Lyon, France.

Jacques, A.P. 1990. National inventory of sources and emissions of benzene (1985). Report EPS 5/AP/1. Environment Canada, Ottawa.

Jury, W.A., D. Russo, G. Streile, and H. El Abd. 1990. Evaluation of volatilization by organic chemicals residing below the soil surface. Water Resour. Res. 26:13–20.

Karimi, A.A., W.J. Farmer, and M.M. Cliath. 1987. Vapour-phase diffusion of benzene in soil. J. Environ. Qual. 16:38–43.

Kirk, R.E., D.F. Othmer, M. Grayson, and D. Eckroth. 1991. Kirk-Othmer encylopedia of chemical technology. 4th ed. John Wiley, New York.

Komex. 2002. Derivation of revised benzene, toluene, ethylbenzene, and xylenes soil guidelines. Prepared by Komex International Ltd. for the Soil Quality Guidelines Task Group of the Canadian Council of Ministers of the Environment.

Korte, F., and W. Klein, 1982. Degradation of benzene in the environment. Ecotoxicol. Environ. Saf. 6:311–327.

Mackay, D.M., P.V. Roberts, and J.A. Cherry. 1985. Transport of organic contaminants in groundwater. Environ. Sci. Technol. 19:384–392.

Malins, D.C. 1977. Biotransformation of petroleum hydrocarbons in marine organisms indigenous to the arctic and subarctic. In: Fate and effects of petroleum hydrocarbons in marine organisms and ecosystems, D.A. Wolfe, ed. Pergamon Press, Oxford.

Manahan, S.E. 1989. Toxicological chemistry: A guide to toxic substances in chemistry. Lewis Publishers, Chelsea, MI.

OMEE (Ontario Ministry of Environment and Energy). 1993. Ontario typical range of chemical parameters in soil, vegetation, moss bags and snow. Version 1.0a. PIBS 2792. Standards Development Branch, Phytotoxicology Section, Toronto.

Rebhun, M., R. Kalabo, L. Grossman, J. Manka, and Ch. Rav-Acha. 1992. Sorption of organics on clay and synthetic humic-clay complexes simulating aquifer processes. Water Res. 26:79–84.

Rogers, R.D., J.C. McFarlane, and A.J. Cross. 1980. Adsorption and desorption of benzene in two soils and montmorillonite clay. Environ. Sci. Technol. 14:457–460.

Rosenberg, E., and D.L. Gutnick. 1980. The hydrocarbon-oxidizing bacteria. In: The prokaryotes: A handbook on habitats, isolation, and identification of bacteria, M.P. Starr, H. Stolp, H.G. Trüper, A. Balows, and H.G. Schlegel, eds. Springer-Verlag, Berlin.

Rutherford, D.W., and C.T. Chiou. 1992. Effect of water saturation in soil organic matter on the partition of organic compounds. Environ. Sci. Technol. 26:965–970.

Scheunert, I., and F. Korte. 1986. Comparative laboratory and outdoor studies on the behaviour of ^{14}C-labelled chlorinated benzenes in soil. In: Contaminated soil, J.W. Assink and W.J. van den Brink, eds. Nijhoff, Dordrecht, Netherlands.

Shiu, W.Y., K.C. Ma, D. Mackay, J.N. Seiber, and R.D. Wauchope. 1990. Solubilities of pesticide chemicals in water. Part I, Environmental physical chemistry. Rev. Environ. Contam. Toxicol. 116:1–11.

Shubik, P., U. Saffiotti, W. Lijinsky, G. Pietra, H. Rappaport, B. Toth, C.H. Raha, L. Tomatis, R. Feldman, and H. Ramahi. 1962. Studies on the toxicity of petroleum waxes. Toxicol. Applied Pharmacol. (Supp. 4) 4:1–62.

Sims, R.C. 1990. Soil remediation techniques at uncontrolled hazardous waste sites: A critical review. J. Air Waste Manage. Assoc. 40:704–732.

Slooff, W. 1988. Integrated criteria document: Benzene. Report No. 758476003. National Institute of Public Health and Environmental Hygiene, Bilthoven, Netherlands.

Smith, M.R. 1990. The biodegradation of aromatic hydrocarbons by bacteria. Biodegradation 1:191–206.

Song, H.G., X. Wang, and R. Bartha. 1990. Bioremediation potential of terrestrial fuel spills. Appl. Environ. Microbiol. 56:652–656.

Statistics Canada. 2003. Sales of fuel used for road motor vehicles, provinces and territories. CANSIM Table 405-0002. www.statcan.ca/english/Pgdb/trade37c.htm.

Tice, R.T., D.L. Costa, and R.T. Drew. 1980. Cytogenetic effects of inhaled benzene in murine bone marrow: Induction of sister chromatid exchanges, chromosomal aberrations, and cellular proliferation inhibition in DBA/2 mice. Proc. Nat. Acad. Sci. (U.S.). 77:2148–2152.

Topp, E., I. Scheunert, and F. Korte. 1989. Kinetics of the uptake of ^{14}C-labelled chlorinated benzenes from soil by plants. Ecotoxicol. Environ. Saf. 17:157–166.

Tucker, W.A., C.T. Huang, and R.E. Dickinson. 1986. Environmental fate and transport of benzene in Florida groundwater. American Petroleum Institute, Washington, DC.

Walton, B.T., T.A. Anderson, M.S. Hendricks, and S.S. Talmage. 1989. Physicochemical properties as predictors of organic chemical effects on soil microbial respiration. Environ. Toxicol. Chem. 8:53–63.

Westberg, H., K. Sexton, and D. Flyckt. 1981. Hydrocarbon production and photochemical ozone formation in forest burn plumes. J. Air Pollut. Control Assoc. 31:661.

This fact sheet was originally published in the working document entitled "Recommended Canadian Soil Quality Guidelines" (Canadian Council of Ministers of the Environment, March 1997, Winnipeg). A revised and edited version was presented in "Canadian Environmental Quality Guidelines" (CCME 1999). In 2002-04, new guidelines were developed for benzene, and the fact sheet was revised again.

Reference listing:

Canadian Council of Ministers of the Environment. 2004. Canadian soil quality guidelines for the protection of environmental and human health: Benzene (2004). In: Canadian environmental quality guidelines, 1999, Canadian Council of Ministers of the Environment, Winnipeg.

For further scientific information, contact:

Environment Canada
National Guidelines and Standards Office
351 St. Joseph Blvd.
Gatineau, QC K1A 0H3
Phone: (819) 953-1550
Facsimile: (819) 953-0461
E-mail: ceqg-rcqe@ec.gc.ca
Internet: http://www.ec.gc.ca/ceqg-rcqe

For additional copies, contact:

CCME Documents
Toll-Free Phone: (800) 805-3025
Internet: http://www.ccme.ca

Aussi disponible en français.

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